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Cycle XXXIII

Design of eco-sustainable bituminous mixtures for road pavements

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1 Introduction

Sustainability is clearly becoming a popular word in the environmental policy and research arena. "Sustainable development," "sustained use of the biosphere," and "ecological sustainability" are terms increasingly used by institutions and individuals concerned with the relationships between humans and the global environment.

Environmental sustainability is responsibly interacting with the planet to maintain natural resources and avoid jeopardizing the ability for future generations to meet their needs.

Environmental sustainability is concerned with issues such as:

- **Long-term health of ecosystems**. Protecting the long-term productivity and health of resources to meet future economic and social needs, e.g. protecting food supplies, farmland and fishing stocks.
- **Intergenerational decision making**. When making economic decisions, we should focus on implications for future generations, and not just the present moment. For example, burning coal gives a short-term benefit of cheaper energy, but the extra pollution imposes costs on future generations.
- **Renewable resources**. Diversifying into energy sources that do not rely on non-renewable resources. For example, solar and wind power.
- **Prevent the consequences of man-made global warming**. Policies to ensure the environment of the planet does not deteriorate to a point where future generations face water shortages, extreme weather events, excess temperature.

- **Protection of species diversity and ecological structure**. Sometimes medicines require elements within specific plant species. If some species go extinct, it limits future technological innovation
- **Treating environmental resources as if they have intrinsic rights and value**. In other words, we shouldn't just rely on a monetary value, i.e. we should protect rainforests because they deserve to be protected rather than using a cost-benefit analysis of whether we gain financially from protecting rainforests
- **Targeting social welfare/happiness and environmental sustainability above crude measures of progress such as GDP (Gross Domestic Product).**

In the civil engineering sector and in particular in road construction, attention is increasingly being focused on the need for "sustainable development" which reflects the growing trend from one hand to reduce the amount of materials taken to landfills, on the other to conserve and reuse non-renewable resources (suitably treated) instead of raw materials that should be preserved in nature.

There are now numerous materials that have been studied for possible use in the body of embankments and in road pavements. They come from:

- Road construction or building sector itself such as:
  - recovery bituminous mixture (milled)
  - construction and demolition waste.
- Other industries and available in such quantities as to be able to meet the need for large volumes of materials required by construction road like:
  - rubber from end-of-life tires (rubber powder)
  - the broken glass
  - waste plastic materials
  - waste from sugar factories.

Additional alternative materials that can be used in addition to or in place of natural aggregates and fillers are some types of slag, in particular:

- slag from steelworks
- foundry sands
- fly ash
- waste produced by the processing of mining coal.

Of more limited use, as they are present only locally, there are some alternative resulting materials from marble processing and from the processing of sugar beet.
Their use is aimed at favouring not only a reduction in environmental discomfort but also an economic and energy saving deriving from the costs necessary for disposal and/or landfilling.
Ultimately, the main objectives to be pursued are to ensure that their use does not entail risks to health or the environment, does not penalize road performance, is not excessively burdensome and does not compromise a possible reuse or recycling of materials from the road itself.

A policy strongly aimed at encouraging the recycling and reuse of materials already present is widely implemented in areas where all the materials used in road construction are difficult to find, an incentive that is not so strong where there is sufficient availability.

The use of alternative materials from other production cycles requires in any case a careful examination capable of determining:

- compliance for a specific use, in terms of mechanical performance
- the method for implementation
- procurement costs and treatment methods.

In fact, the assessment of the suitability of an alternative material must be carried out through laboratory tests, designed to define its physical and chemical properties, and mechanical tests both in the laboratory and on site, to evaluate its behaviour in operation, even in different environmental conditions.

An analytical and systematic methodology that evaluates the environmental footprint of a product or service, along its entire life cycle is the Life Cycle Assessment (LCA). The use of LCA is the methodology that it places as the basis of all actions aimed at increasing the sustainability of products and supply chains, since it helps to understand the impact generated on the environment by products, services, events, economic systems and production chains.

The aim of this thesis is to enhance local resources by reusing secondary raw materials in the construction of sustainable infrastructures. In particular, the Reclaimed Asphalt Pavement (RAP), Jet grouting waste (JW) and plastic waste (PW) were investigated.

The JG is derived from soil consolidation during underground roadway tunnel construction. During soil consolidation works, the waste of jet grout is expelled together with extracted soil that is replaced by the grout column; the mass solidifies on the ground surface and it is called jet grouting waste.

To date, the use of JW is recognized in Italy as laid down by Italian Ministerial Decree of 05/02/1998 "Identification of non-hazardous waste subject to simplified recovery procedures under Articles 31 and 33 of Legislative Decree no. 22 of 5 February 1997" for concrete grout and road infrastructure construction, specifically for the layers making up embankments, as well as for foundation or sub-base after being subjected to environmental compatibility analysis.

Every year about 8 million tonnes of plastic waste are discharged into the sea and the presence of additives seriously speeds up the decomposition process causing an increase of the pollutants into the surrounding environment. In the light of both reduce the pollutants and increase the strength of bituminous mixtures the introduction of plastic waste into bitumen was carried out.

The study carried out during the PhD course involved, on the one hand, an investigative examination conducted at the road materials laboratory "La.Stra." at the Department of Civil, Construction and Environmental Engineering of the University of Naples "Federico II" the reuse of the aforementioned waste as secondary raw materials in bituminous blends and a second exploratory phase both from an environmental and a decisional point of view.

The research was divided into several phases as follows:

1. Following the main results available in scientific literature on Cold Bituminous Mixtures (CBM) and mastics, the first part of the research presented here aims to bridge a gap in the laboratory protocol for mixing the cold bituminous mastics and to appreciate the main differences in relation to hot bituminous mastics, in particular when the JW is added. Different mastics were prepared based on a filler-to-bitumen ratio of 0.3, 0.4 and 0.5 by weight. The fillers adopted were of the limestone (LF) and jet grouting waste (JW) types, while neat bitumen 50/70 (B50/70) was adopted for hot mastics, and bituminous emulsion (BE) made up of 60% neat bitumen and 40% water was used for the cold ones; mixing was carried out without adding cement traying to substitute it with JW in the cold bituminous mixture production, since the JW is also a mixture made up of cement. A rheological investigation was carried out in terms of Frequency sweep (FS) test and Multiple Stress Creep and Recovery MSCR test.
2. With the aim to provide a broad-based experimental-methodological approach to the reuse of plastic waste (PW) materials as an alternative filler in hot bituminous mastics, laboratory tests focused on analysis of the rheological behaviour of bituminous mastics by examining three of their basic properties (i.e. the physical properties of filler, the ring and ball of the mastics, and their dynamic viscosity) and advanced features such as shear modulus G* (storage and loss

shear modulus), phase angle, and recoverable and non-recoverable creep compliance by means of a MSCR test were carried out. Four main comparisons were carried out as follows: a) mastics made up of PW and neat 50/70 bitumen (B5070) vs B5070; b) mastics made up of PW and B5070 vs mastics made up of traditional limestone filler (LF) and B5070, keeping the weight ratios used at point a constant; c) mastics made up of PW and B5070 vs PmB 10/40-70 hard modified bitumen (HMB) (since PW also modifies bitumen); d) mastics made up of PW, B5070 and a small quantity of LF vs mastics made up of PW and B5070.

From the above, it follows that one of the main objectives of the research was to prepare mastics able to meet or exceed the performance of a) traditional limestone mastics (three solutions made up of 10%, 15%, and 20% LF by the total weight of B5070) and, on the other hand, b) the high performance hard modified bitumen (PmB 10/40-70) used here.

A comparison of all the solutions in the light of the results achieved was carried out in order to suggest the most appropriate mastic solutions made up of plastic waste materials.

3. With the aim to work on an integrated laboratory methodological approach for introducing marginal materials into mix design for a bituminous base layer in a road pavement, the research presented focused on mixing and analyzing four different asphalt mixtures: 1) a traditional Hot Mix Asphalt (HMA) obtained by adopting virgin limestone aggregates and neat 50/70 penetration bitumen; 2) HMA containing JW (HMAJ); 3) Cold mix asphalt containing RAP and limestone aggregates (CRA) and 4) Cold mix asphalt containing JW, RAP and limestone aggregates (CRAJ). The possibility of re-using JW in a hot mixture or when it is added to RAP in a cold mix asphalt instead of a portion of virgin aggregates was evaluated by analyzing main mechanical and volumetric properties. The volumetric properties were evaluated in terms of air voids content, while the mechanical properties were established by measuring the Indirect tensile Strength (ITS), moisture sensitivity (ITSR), stiffness modulus and resistance to permanent deformations by cyclic compression tests with confinement, also in compliance with some test suggestions provided by UNI TS 11688/2017
4. With the aim to create a complete procedure for the comparative analysis of the solutions supporting the decision makers that takes into account not only the mechanical variables linked to the performance of the mixtures which were investigated through the laboratory phase, but also in terms of environmental sustainability an LCA was applied in the condition of an extraordinary maintenance work on an existing road pavement and the laying of a new contiguous section located under a tunnel by providing four alternative design solutions of

flexible pavement containing as base layer the four bituminous mixtures mentioned in the above point.

5. To identify the most appropriated solution a sensitivity analysis was implemented to validate the robustness of the results of the Multiple Criteria Decision Analysis (MCDA) by varying the MCDA methods (Utility, Multipol, Evaluation Based on Distance from Ideal Solution (EDIS) and Elimination Et Choix Traduisant la Realité (ELECTRE) methods), the weight vectors (a total of 48 vectors) and the sets of considered criteria (a total of 40 different configurations) to detect the solution with the best compromise between the parameters classified as predictors of the best performances.

2 Circular economy

In a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimised, and when a product reaches the end of its life, it is used again to create further value. This can bring major economic benefits, contributing to innovation, growth and job creation.

A circular economy encourages sustainability and competitiveness in the long term. It can also help to:

- preserve resources–including some which are increasingly scarce, or subject to price fluctuation
- save costs for European industries
- unlock new business opportunities
- build a new generation of innovative, resource-efficient European businesses – making and exporting clean products and services around the globe
- create local low and high-skilled jobs
- create opportunities for social integration and cohesion

2.1 A new economic model for the European Union

An indispensable component of the European Union's efforts to develop a sustainable, competitive and low-carbon economy is the transition to a circular economy system, in which the materials and energy used to manufacture products maintain their value for as long as possible, waste is minimized and as few resources as possible are used.

According to a recent study on the circular economy, the European economy constitutes a "surprising" model of waste in the creation of value with its production and disposal system ("disposable" model). In 2012, for example, 60% of waste materials was deposited in landfill or incinerated, while only 40% was recycled or reused. In terms of value, Europe has lost 95% of its material and energy value, while the recycling of materials and energy recovery from waste has recovered only 5% of the original values of raw materials. Steel, polyethylene terephthalate (PET), and paper loses in any case from 30 to 75% of the material value incorporated in the cycle before use [1].

The transition to a circular economy therefore responds to both an environmental and an economic logic. It could in fact ease pressures on the environment, with positive effects on ecosystems, biodiversity and human health. By way of example, according to the Commission's estimates, the full implementation of waste management objectives would reduce sea pollution by 27% by 2030 [2].
It could also increase the security of energy supplies, since the EU currently imports roughly half of the resources it consumes in raw materials equivalent. In addition, businesses would have the potential to make savings on materials expenses (between 250 and 465 billion euros per year, or between 12% and 23% of materials expenses, according to the Ellen MacArthur Foundation [3]) as well as to benefit from organizational innovations and produced requests.

In order to make the transition to a circular economy, it is necessary to intervene at all stages of the value chain: from the extraction of raw materials to the design of materials and products, from production to distribution and consumption of goods, from repair regimes, remanufacturing and reuse for waste management and recycling.

2.1.1 The communication entitled "Towards a circular economy"

The program for a zero waste Europe (COM (2014) 398) [2] is aimed at promoting the transition from a linear to a more circular economy (see Figure 2.1). The communication indicates that new opportunities for growth and Employment. Innovative design, better and more resilient products, more efficient and sustainable production processes, forward-looking business models and technical advances to turn waste into a resource would, in the Commission's view, contribute to increasing efficiency, context that should make it possible to transform the circular economy into reality, with better interconnected policies, intelligent regulation and active support for research and innovation activities.

Figure 2.1 Transition from linear to circular economy

European Commission presented the new circular economy package. Compared to the 2014 proposals, an integrated approach is anticipated that goes beyond the focus on waste and includes actions to promote the circular economy at every stage of the value chain, from production to repair to secondary products, involving all actors, both from side of production and consumption.

Specific actions will concern some areas identified as priority: plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based products.

2.1.2 Measures foreseen in the production phase

The circular economy begins in the very early stages of the product life cycle. Both the design phase and the production processes affect the procurement of resources, their use and the generation of waste throughout the entire life cycle of the product.

The new Commission proposals aim to:

- Support repairability, durability and recyclability through product specifications as part of future work plans to implement the Ecodesign Directive
- Propose requirements aimed at simplifying the disassembly, reuse and recycling of electronic screens
- Work towards better enforcement of material product warranties and examine possibilities for improvement as well as address false green labels
- Act in the field of Green Public Procurement (GPP)
- Prepare guidelines on best practices for waste management and resource efficiency in industrial sectors
- Publish guidelines and promote best practices on extractive waste to improve the recovery of raw materials

2.1.3 Measures related to specific sectors

Plastic

The goal is to increase the recycling of plastic; currently the use of plastic is growing but recycling is not keeping up: less than 25% of the plastic waste collected is recycled, while about 50% is placed in landfills.

The Commission intends to:

- Adopt a strategy on plastics to address issues such as recyclability, biodegradability, the presence of hazardous substances in some plastics and marine litter.
- Propose a more ambitious target for the recycling of plastic packaging in the revised legislative proposal on waste.

Construction and demolition sectors

Construction and demolition are among the sectors that generate the largest volumes of waste in Europe: each year it produces one tonne per capita, or 500 million tons across the EU. Valuable materials are not always identified and recovered. Improving waste management in this sector can significantly affect the circular economy.

The Commission intends to:

- Undertake a series of actions aimed at recovering valuable resources as well as ensuring adequate waste management in this sector, as well as facilitating the assessment of the environmental performance of buildings.
- Develop pre-demolition guidelines to increase high-value recycling in the sector as well as voluntary recycling protocols aimed at improving quality and increasing trust in recycled building materials.

2.1.4 The new proposals on waste management

The new legislative proposals on waste stem from the need to improve resource efficiency and ensure that the European Union does not continue to lose, as is currently the case, a significant amount of potential secondary raw materials present in the waste stream.

The proposals are accompanied by an impact assessment, which is the same that accompanied the proposal presented in July 2015, which states that, by combining the various strategic options regarding waste management, the following results can be achieved:

- reduction of administrative burdens;
- job creation in the order of over 170,000 by 2035;
- reduction of greenhouse gas emissions, avoiding the release of over 600 million tons between 2015 and 2035;
- reintroduction of secondary raw materials into the EU economy, thus reducing dependence on the import of raw materials.

Among the main changes introduced by the proposed amendment to the directive 2008/98/EC [4] on waste it is report:

- the obligation to increase the recycling of municipal waste by at least 60% by weight by 2025 and by at least 65% by 2030;
- the obligation to increase preparedness for reuse, recycling and backfilling of non-hazardous construction and demolition waste by 70% by 2020;
- the inclusion of new definitions including "municipal waste", "construction and demolition waste", "backfilling" and "final recycling process";
- new provisions on extended producer responsibility regimes that define some minimum requirements in order to overcome the differences between the various states members;
- new waste prevention provisions providing for the adoption by Member States of measures aimed, inter alia, at encouraging the use of resource efficient products which are main sources of raw materials and to reduce the production of waste in processes inherent to industrial production as well as waste food;
- the strengthening of the traceability mechanisms of hazardous waste through specific registers.

In this regard, even taking into account the most recent changes in national legislation on the subject, it seems appropriate to acquire the Government's notice on the possible impact of the Commission's proposals on national law.

- the ban on throwing small waste in public places;
- the simplification of registration obligations for small entities or businesses that collect or transport small quantities of non-hazardous waste;

- the improvement of the quality, reliability and comparability of statistics through the use by Member States of the most recent methodology developed by the European Commission and the national statistical institutes.

2.1.5 The role of design

Design plays a fundamental role in the development of products that reflect the principles of the circular economy as much as possible. During the conception, design and development phase, decisions are made that can significantly affect the sustainability or otherwise of the product during its life cycle. Therefore, it is necessary that in the conception and design phase appropriate preliminary assessments are carried out configuring possible market scenarios in order to assess the environmental sustainability and economic sustainability requirements. The development of a new product must take place following the principles of eco-design and through the use of tools that allows to evaluate the different environmental impacts.

A fundamental thing in a design process is to rationalize the use of material resources (efficiency in the use of materials), trying to replace non-renewable materials with renewable, recycled, permanent recycled, biodegradable and compostable materials. Enhance local resources to reduce the environmental impacts of transport and create a local product identity. The need is to "create" new materials that best contemplate sustainability and circularity. Knowledge of the environmental and social characteristics of the materials is essential to avoid pursuing design choices that do not favor the circularity of production process resources: to minimize the production of processing waste or to ensure that these are managed as by-products.

Recyclability is an important factor that serves to facilitate the recovery and recycling of components and related materials, thus avoiding sub-assemblies of multi-material components that cannot be recycled.

Maintenance must be encouraged that allows the extension of the life cycle of the product itself. And in particular to look for material solutions that do not contain hazardous substances to make products more easily recyclable, also taking as a reference the European legislation on chemicals [5].

During the recycling process, it must be avoided that there is an alteration of the characteristics of the materials such as not to allow a new use. A reduction in the quality of the material inevitably leads to a lower economic value of the same.

Only produce what can be "recycled": in the new paradigm, no more waste is generated that cannot be recycled or residues that cannot be reused in other production cycles.

2.1.6 The concept of "waste"

The concept of "waste", although in the past it has allowed the solution of problems that cannot otherwise be solved, is no longer relevant if one goes towards a policy of minimizing waste. The challenge of the transition to the circular economy is to consider what is now waste as an element, a "brick" for a new production cycle. Consequently, a profound revision of Community legislation appears, in the light of the concept of circular economy, increasingly unavoidable. If the green economy already considered rejection a solution and no longer a problem, even today the rejection itself is subject to meticulous regulation, which significantly limits many of its intrinsic potential, in particular through rules that provide for restrictions in terms of management and handling. If in the past restrictive provisions for waste management were justified by what was considered the real problem of waste, namely their abandonment, without evaluating its potential, today, paradoxically, the concept of waste could be limited only to what "does not it has an economic value" for the market; just think of materials such as used mineral oils, for which there is a market that sets an almost official quotation that is used for exchanges, and which have been the subject of international "disputes" for their acquisition, or goods for which collection is regulated by law (as in the case of consortia provided for by current environmental legislation for particular waste streams). Considering these cases, restrictive legislation should be provided only for what is destined for abandonment, in order to prevent dispersion into the environment, while today it is also extended to noble materials and in high demand.

The revision of the community legislation will therefore have to go beyond the changes that led, in 2008, to the provision of a partial strategy to exit the concept of waste, which also materialized with the recognition of by-products and the cessation of the qualification of waste.

Once the necessary regulatory change has been made, the following must be identified:

- Waste streams for which the qualification of waste is no longer required but which can be recirculated in the production and economic system as new raw materials or products.
- Waste streams currently not reused or recycled due to legislative, authorization, organizational, economic, competitive obstacles, etc. For these flows it is necessary to set up ad hoc working groups to effectively intervene in removing the causes that hinder circularity in these sectors.

- Waste streams currently not reusable or recyclable. On these flows it is necessary to intervene to activate applied research capable of developing new materials or products to be reintroduced into production cycles, find new systems and new market outlets or provide for the progressive elimination from the market or replacement with others that are reusable or recyclable.

As already mentioned, the transition from a "cradle to grave" economy to the circular economy already represents a moment of strong change in the materials management strategy with the tools available (termination of the qualification of waste and identification of by-products) and represents a strong impulse in the identification of new waste streams to be subjected to "end-of-waste" (EoW) processes and in the recognition of new by-products, especially as a result of the recent enactment of the decree by-products [2].

To reach the new paradigm, it is important that in the transition phase work is done on the tools that can give certainty to operators regarding the qualification of by-product of the production residues they generate by establishing, for example, a unitary and updated national legislative framework for the EoW. On the one hand, for specific types of waste, the EoW decrees have not yet been issued, with the exception of the decree on excavated earth and rocks and, pending the same, reliance is still being placed on the previous mechanisms for terminating the qualification of waste that appear now outdated, while the absence of an effective EoW mechanism is severely penalizing the recycling and recovery sector. This mechanism, in fact, constitutes the "reward" for those who carry out the recycling and recovery of waste by transforming it into the so-called "secondary raw materials", that is, into materials that can be reused in economic cycles, thus helping to reduce the consumption of raw materials and the amount of waste to be disposed in the landfill.

The cessation of the qualification of waste therefore becomes the main tool for the implementation of the much-desired recycling society, a declared objective of the community bodies, and marks an important step forward in today's waste legislation in order to put an end to the concepts antiquated (and consumerist) of "all refusal" and "refusal forever". To this end, also to favor the saving of natural raw materials, it is necessary to identify the priority waste flows on which to intervene and prepare the relative decrees so that the materials resulting from high quality recovery operations can be introduced again on the market and be in able to compete with virgin raw materials with full dignity, with an immaculate "criminal record" and without trailing behind a discriminating origin. This will only be possible if they are granted the same legal status as a product.

On the contrary, as long as an object or a substance retains - despite being the result of high-quality recovery operations - the legal status of “waste”, they will not be able to compete with raw materials

and consequently result in severe discrimination. It is therefore easy to understand how the absence of an effective national EoW mechanism is severely penalizing the recovery sectors.
Similarly, to the issue of the cessation of the qualification of waste, too often the possibility of considering a residue as a by-product and assigning it to new production cycles clashes with the fear of being able to prove that the residue is a by-product and not a refusal to the control authorities. To do this, it is appropriate to assist operators in verifying the conditions that allow residues to be qualified as by-products and to provide for standardized criteria for as many residual streams as possible in order to give certainty to producers of the residue and to the control authorities.

2.2 Green Public Procurement and Minimum Environmental Criteria

The Green Public Procurement (GPP), thanks to the provisions of the Procurement Code on the mandatory application of the Minimum Environmental Criteria (MEC), has become one of the main environmental and production policy tools capable of reducing environmental impacts, rationalizing and reducing public spending is able to promote innovative companies from an environmental point of view. Indeed, through this precious lever on the demand side, the market is influenced, stimulating qualification and environmental innovation paths by Italian companies, strengthening their competitiveness.

Thanks to GPP, enhancing the quality and performance of products, their energy efficiency during use, safety in terms of limits to the presence of hazardous substances, the recycled content, repairability, durability of the products themselves, and more environmental impacts are reduced, but some economic indicators are improved: both by rationalizing public spending, and by encouraging new economic activities that deal with aspects and issues valued by MEC (repair and recovery, use of recycled materials, energy replacements and matter coming from non-renewable sources with those coming from renewable sources, enhancement of the bio-economy…).
It therefore becomes strategic to ensure that there is full application of this tool by the Public Administration. The powerful market lever represented by public purchases can become one of the main tools for directing production towards circular economy models. In fact, for example, while the MECs on the "urban waste management service" enhance the quality of separate collection, other MECs stimulate the demand for products made with materials derived from separate collection (eg urban furniture items or the management service public parks, or office furniture). Again, some MECs provide services (for example, "rental") instead of supplies, while others, such as the MEC document

for the supply of toner and inkjet cartridges, partly include the purchase of cartridges. “Remanufactured”, they promote the preparation for the reuse of used cartridges and the reduction of the quantity of cartridges to be disposed in the landfill.

In general, it should be emphasized that MECs have complementary and synergistic prescriptions. Their joint application allows for the simultaneous implementation of the various indications referred to in all the Communications of the European Commission, in particular those on the circular economy and the efficient use of resources. With the new procurement code, the issue of the cost of a product/service must be referred to the cost along the life cycle (the so-called Life cycle costing), which includes in addition to the costs of using the product and its disposal also those related environmental externalities. The issues related to "circularity" must, therefore, also be addressed in the tender by highlighting the lower costs of products that better meet the objectives of the circular economy.

The application of considerations and criteria of a social nature in public administration tenders is also of significant importance, not only for ethical and social implications, but also for economic and environmental ones. The application of these criteria, especially in some product areas, allows to guarantee, at the same time, better working conditions in Italy and abroad and the control of the environmental quality of production systems, thus also reducing unfair competition for goods produced thanks to scarce checks on working conditions and polluting emissions from production.

The social requirements must be an essential element in every tender to ensure that purchases, not only those of the Public Administration, have a form of guarantee of compliance with all labour regulations and declarations on human rights.

2.3 Measure the circularity of a product

Measuring the circularity of a product or service must be the goal of all companies to take note of the quantities and types of natural resources used, among other things, in terms of:

- renewable and non-renewable
- recycled, permanently recycled and recyclable
- biodegradable and compostable
- economic and environmental sustainability of the product

It is a question of creating an "input" "output" budget considering the entire life cycle of the product. The approach can be gradual both in considering the types of resources to be inventoried (material, energy), and for the degree of detail (involvement or not of suppliers or other subjects in the supply chain). The inventory phase must be very accurate in order to avoid approximations that can create high margins of error in the calculation methodology. The inventory data useful for the production phase are already in the possession of the companies as they represent the specifications of each individual product. In addition to the production data, those relating to packaging, the use phase (maintenance and replacement of components), and finally those of disposal and recycling (for competence held by municipal companies, consortia or national bodies) must be taken into consideration.

Durability, frequency of use or reuse and sharing of the product, are requirements that must necessarily be considered in the evaluation of circularity, as they allow to obtain indications on the effectiveness of use of the product. There may be difficulties in comparing physical indicators (such as materials used and waste generated), with usage indicators (eg load factor) and in the context of physical indicators having to include both material and energy resources.

One solution to the problem is to adopt KPIs (Key Performance Indicators), which allow to relate all five key elements of the Circular Economy and therefore both physical and usage factors to arrive at a single, unambiguous result. For each phase of the product life cycle, in addition to the data of the resources used and the methods of use, the economic data must be taken into account that allows to evaluate the cost-effectiveness of the process. In this way, it is possible for companies to define market scenarios by intervening, for example, on the choice of materials or on the method of selling the asset as a product or as a service.

The choice of the best solution to pursue can only be identified through the definition of market scenarios where, through environmental and economic assessments and resource use flows, it is possible to identify possible implications and criticalities of the system, obtaining in this provides useful indications for the changes to be made. The economic component, alongside the physical one, allows to obtain an overall picture in terms of circularity and therefore to concretely evaluate, for example, if the choice to use certain resources guarantees greater durability, repairability and recyclability to the product.

The measurement of circularity is an approach that runs alongside other environmental impact assessment tools for products and/or services, such as the Life Cycle Assessment or the Carbon Footprint. The measurement of circularity is an essential requirement to give substance to the actions to be pursued in the field of circular economy, towards greater transparency for the market and for the consumer. From this it follows that:

- taxation and public incentive actions can refer to the results obtained with this measurement. If, for the legislator, taxation and incentives must be instruments of "reward", then this must be a driving force that, on the one hand, recognizes the achievement of a result for the company and on the other must push towards sustainable market demand. To do all this it is essential for the legislator to establish punctual and recognizable criteria on the method of assigning merit and therefore, measuring the circularity of a product or service, can be the solution to be pursued. In this way it is easier for the legislator to have a general framework of the system and to establish priorities on which to act also through forms of incentives aimed at the consumer during the purchase phase.
- The consumer, as the main player in the entire economy of the country, must be actively involved in pursuing responsible and sustainable actions when purchasing a product. To do this it is necessary to enable the consumer himself to understand and evaluate the "circularity" of a product. Communication must be simple, recognizable and transversal for different product categories in order to allow the consumer to understand and compare information.

3 Legislative framework

The proposed experimental study coincides with the objectives of Legislative Decree of 3 April 2006 no. 152 "Regulations on environmental matters" - published in the Official Gazette no. 88 of 14 April 2006 - ordinary supplement no. 96 - with specific reference to art. 179 (priority criteria in waste management), 180 (prevention of waste production) and 181 (waste recovery), where a greater commitment is required by public administrations in the waste management process for their reintroduction into working process as by-products, proposing additions to the contract conditions for specific works in favour of competitors, which demonstrate a rational use of materials recovered from waste. This confirms the provisions of Legislative Decree 18 April 2016 n. 50 "New code of public contracts" where technical specifications and contractual clauses to be integrated are requested in the project and tender documentation, to the advantage of economically advantageous offers respecting minimum environmental criteria (MEC) proposed by competitors.

3.1 Legislative Decree of 3 April 2006 no. 152

Part four of the Legislative Decree of 3 April 2006 no. 152 regulates the management waste and remediation of polluted sites, including in implementation Community directives, in particular the Directive 2008/98/EC, including measures to protect the environment and human health, preventing or reducing the negative impacts of waste generation and management, reducing impacts overall use of resources and improving their effectiveness.

Article 179 deals with the criteria in waste management, in particular it is stated that:

1. The waste management takes place in compliance with the following hierarchy:
   a) prevention

  b) preparation for reuse
  c) recycling
  d) other types of recovery, for example energy recovery disposal.
2. The hierarchy establishes, in general, an order of priority of what constitutes the best environmental option. In compliance with the hierarchy measures must be adopted to encourage the options that guarantee the best overall result, taking into account health, social and economic impacts, including technical feasibility and economic viability.
3. With reference to individual waste streams it is allowed exceptionally, depart from the order of priority referred to in paragraph 1 if this is justified, in compliance with the precautionary and sustainability principle, on the basis of a specific analysis of the overall impacts of the production and management of such waste both from an environmental and health point of view, in terms of life cycle, and from a social and economic point of view, including technical feasibility and the protection of resources.
4. With one or more decrees of the Minister for the Environment and for the Protection of the Territory and the Sea, in agreement with the Minister of Health, the options that guarantee, in accordance with 'to the provisions of paragraphs 1 to 3, the best result in terms of protection of human health and the environment.
5. Public administrations pursue, in the exercise of their respective competences, initiatives aimed at promoting compliance with the waste treatment hierarchy referred to in paragraph 1, in particular by:
   a) The promotion of the development of clean technologies, which allow a more rational use and a greater saving of natural resources
   b) The promotion of the technical development and the placing on the market of products conceived in such a way as not to contribute or to contribute as little as possible, for their manufacture, use or disposal, to increase the quantity or harmfulness of waste and pollution risks
   c) Promoting the development of appropriate techniques for the elimination of hazardous substances contained in waste in order to facilitate its recovery
   d) The determination of contract conditions that envisage the use of materials recovered from waste and substances and objects produced, even if only partially, with materials recovered from waste in order to favour the market for said materials
   e) The use of waste for the production of fuels and the subsequent use and, more generally, the use of waste as another means of producing energy.

6. In compliance with the waste treatment hierarchy, measures aimed at recovering waste through preparation for reuse, recycling or any other material recovery operation are adopted with priority over the use of waste as a source of energy.
7. Public administrations promote the analysis of the life cycle of products on the basis of uniform methodologies for all types of products established by ISPRA guidelines, eco-balances, the disclosure of information also pursuant to the legislative decree of 19 August 2005, n. 195, the use of economic instruments, criteria for public tender procedures, and other necessary measures.
8. The Administrations concerned shall fulfil the obligations referred to in this article with the human, instrumental and financial resources available under current legislation, without new or greater charges for public finance.))

The article 180 deals with the prevention of waste generation, in particular stated that in order to promote prevention and prevention as a priority reduction of waste production and harmfulness; initiatives referred to in Article 179 concern in particular:

a) The provision of clauses for calls for tender or letters of invitation that enhance the skills and technical skills in the field of prevention of waste generation;
b) The promotion of program agreements and contracts or protocols in agreement also experimental aimed at prevention and reduction of the quantity and dangerousness of waste;

Reuse of products and preparation for reuse of waste are dealt with in Article 180 bis where it is defined that Public administrations promote, in the exercise of respective competences, initiatives aimed at promoting reuse of products and preparation for reuse of waste. Such initiatives can also consist of:

a) Use of economic instruments;
b) Logistical measures, such as the establishment and support of accredited repair / reuse centers and networks;
c) Adoption, as part of the procedures for the assignment of public contracts, of suitable criteria, pursuant to article 83, paragraph 1, letter e), of the legislative decree 12 April 2006, n. 163, and provision of the conditions referred to in articles 68, paragraph 3, letter b), and 69 of the same decree; to this end the Minister the environment and the protection of the territory and the sea adopts within six months from the date of entry into force of this provision the implementing decrees referred to in Article 2 of the Minister for the Environment and of the protection of the territory and the sea on 11 April 2008, published in the Official Gazette n. 107 of 8 May 2008;

d) Definition of quantitative objectives;
e) Educational measures;
f) Promotion of program agreements.

In finally the article 181 states that by 2020 the preparation for re-use, the recycling and other types of material recovery, including operations replenishment using waste as a substitute for other waste non-hazardous materials, construction and demolition waste, excluding natural material defined in 17 05 04 of the list of waste shall be increased to at least 70% in weight terms.

3.2 Minimum Environmental Criteria (MEC)

The Minimum Environmental Criteria (MEC) are the environmental requirements that allow the identification of the design solution, the product or the best service from an environmental point of view throughout the entire life cycle, are defined within the framework of the Plan for environmental sustainability of consumption in the public administration sector and adopted by Decree of the Minister of the Environment for the Protection of the Territory and the Sea (Interministerial Decree of 11 April 2008 and confirmed with the Decree of 10 April 2013. The Plan aims to increase the dissemination of "Green Public Procurement", or Green Purchases, or, according to what established by the European Union, the process through which Public Administrations purchase goods and services having less impact on the environment during their life cycle. Thanks to the promotion and use of GPP, public authorities they can influence the market by stimulating the industry to develop green technologies that cover the entire cycle of life of the products: from production to supply, up to transport, use, and disposal.

The obligation of GPP was introduced for the first time by art. 68 bis in Legislative Decree n. 163/2006 s.m.i.. The PA, in order to make green purchases, must comply with the indications provided for the Minimum Environmental Criteria (MEC) annually indicated by the Ministry of the Environment in special lists that identify the categories of goods and services, the environmental impacts and the volumes of spending.

The national legislation governs the MEC and their effectiveness under Article 18 of Law 221/2015e, of the art. 34 bearing "Energy and environmental sustainability criteria" provided for by Legislative Decree 50/2016 "Procurement Code" (amended by Legislative Decree 56/2017), which required it to be mandatory for all contracting stations.

The obligation ensures that the national policy on green public procurement is incisive not only in the objective of reducing environmental impacts, but in the objective of promoting more sustainable, "circular" production and consumption models and in spreading employment "Green", at the same time rationalizing consumption and spending review.

MECs are divided into 17 categories of supplies and assignments, in addition to the minimum environmental criteria for the assignment of design services and works for the new construction, renovation and maintenance of public buildings, which govern the selection of candidates, the technical specifications for buildings or groups of buildings, from the technical specifications of the construction site to those of the building components up to the award criteria and the conditions of execution.

3.2.1 Definition structure and procedure

The MEC documents, each in its specificity, have a similar basic structure.

In the Introduction, the environmental and social legislation of reference, suggestions proposed to the contracting authorities for the analysis of needs, further indications relating to the completion of the related tender and, where the definition of a document of technical support, the approach followed for the definition of the MEC.

The Object of the contract highlights environmental sustainability and, where present, social sustainability, in order to indicate the presence of environmental and possibly social requirements in the tender procedure. The contracting authorities should always indicate in the subject of the contract the ministerial decree approving the environmental criteria used.

The actual Minimum Environmental Criteria are defined for some or all of the stages of definition of the tender procedure in particular for:

- Selection of candidates: these are subjective qualification requirements designed to prove the candidate's technical ability to perform the contract in order to cause the least possible damage to the environment
- Technical specifications: as defined by art. 68 of Legislative Decree. 50/2016, "define the characteristics envisaged for works, services or supplies. These characteristics may also refer to the specific process or method of production or performance of the works, supplies or services requested, or to a specific process for another phase of their life cycle even if these

factors are not part of their substantial content, provided that they are linked to the subject of the contract and proportionate to its value and objectives ".

- Reward criteria: that is, requirements aimed at selecting products / services with better environmental performance than those guaranteed by the technical specifications, to which to assign a technical score for the purpose of awarding according to the offer at the best value for money.
- Contractual clauses: provide information to execute the assignment or supply in the best way from an environmental point of view.

Each environmental criterion also reports, in the Verifications section, the means of proof to demonstrate compliance.

The environmental criteria are identified starting from a market analysis of the sector concerned and drawing on a wide range of requirements, including those proposed by the European Commission in the European GPP toolkit ("toolbox") or among those indicated by the regulations that impose certain environmental standards.

The definition of MEC makes use of technical working groups composed of representatives and experts from the public administration and central purchasing bodies, research bodies, universities, as well as the representatives of the trade associations of the economic operators in the reference sector. The MEC thus elaborated are subsequently shared in the Management Committee and sent as an attachment to the Decree of the Minister of the Environment for the Protection of the Territory and the Sea, to the Ministers of Economic Development and the Economy of Finance to acquire any observations. The final document is adopted by Decree of the Minister of the Environment and published in the Official Gazette

3.2.2 Application of Minimum Environmental Criteria in public tenders for supplies and in the awarding of services: Legislative Decree of 18 April 2016 no. 50

The legislative decree was adopted in implementation of the directives 2014/23/EU, 2014/24/EU and 2014/25/EU on the award of concession contracts, on public procurement and on the procurement procedures of supplying entities in special sectors water, energy, transport and postal services, as well as on the reorganization of the regulations in force regarding public contracts relating to works, services and supplies.

In the Article 34, which deals with the criteria of energy and environmental sustainability, it is established that the minimum environmental criteria defined by the decree are also taken into consideration for the purposes of drafting the tender documents for the application of the economically advantageous offer criterion , pursuant to article 95, paragraph 6 and that by decree of the Minister for the Environment and for the Protection of the Territory and the Sea, the gradual increase of the percentage of 50% of the auction base value may also be envisaged indicated by the paragraph.

In the article 38, the environmental criteria and social sustainability in the design and assignment activity are defined as rewarding criteria in the definition of the qualification of the purchasing body that concerns the complex of activities that characterize the process of acquiring a good, service or work.

3.3 Environmental Ministerial Decree of 5 February 1998

The Environmental Ministerial Decree of 05/02/98, with subsequent amendments introduced by the Ministerial Decree January 9, 2003, by the D.M. 27 July 2004 and by the D.M. 5 April 2006, n. 186, establishes the list of recovery activities which, pursuant to art. 31 and 33 of Legislative Decree 22/97, may be subjected to simplified procedures on the basis of specific conditions and technical standards which must establish in particular as follow:

a) The maximum quantities that can be used
b) The origin, types and characteristics of the waste, as well as the specific conditions of use of the same
c) The requirements necessary to ensure that waste is recovered without endangering human health and without using processes and methods that could harm the environment

The activities, procedures and methods of recovery of each of the types of waste identified by this Decree must not constitute a danger to human health and harm the environment, and in particular must not:

a) Create risks for water, air, soil and for fauna and flora
b) Cause inconvenience from noise and odours
c) Damage the landscape and entire sites of particular

Annexes 1, 2 and 3 define the general technical standards which identify the types of non-hazardous waste and establish, for each type of waste and for each activity and method of its recovery, the specific conditions under which the of these activities is subject to the simplified procedures referred to in art. 33, of the Legislative Decree of 5 February 1997, n. 22, and subsequent amendments and additions.

The activities, procedures and methods of recovery of each type of waste, governed by the decree, must comply with the regulations in force regarding the protection of human health and the environment, as well as safety in the workplace, and in particular:

- The waste water resulting from the waste recovery activities governed by the Decree must comply with the prescriptions and limit values established by law no. 319 and by the legislative decrees 27 January 1992, no. 132, no. 133, and subsequent amendments and additions
- The atmospheric emissions resulting from the recovery activities governed by this Decree must, although not provided for by the decree itself, comply with the provisions of the Decree of the President of the Republic no. 203, and subsequent amendments and additions.

The simplified procedures governed by the Decree apply exclusively to the specified recovery operations and to the waste identified by the respective codes and described in the annexes.

The activities, procedures and methods of recycling and recovery of material identified in Annex 1 must guarantee the obtaining of products or raw materials or secondary raw materials with product characteristics compliant with the technical regulations of the sector or, in any case, in the forms usually marketed. In particular, the products, raw materials and secondary raw materials obtained from the recycling and recovery of the waste identified by the Decree must not have dangerous characteristics higher than those of the products and materials obtained from the processing of virgin raw materials.

The products, raw materials and secondary raw materials obtained from recovery activities that are not effectively and objectively intended for use in consumption or production cycles remain subject to the waste regime.

The use of waste in recovery activities is subject to the simplified procedures provided for by art. 33, of the Legislative Decree of 5 February 1997 no. 22, provided that:

a) The waste is not dangerous;
b) It is provided for and governed by a specific project approved by the competent authority;

c) It is carried out in compliance with the technical standards and the specific conditions provided for by the Decree for the single type of waste used
d) It is compatible with the chemical - physical, hydrogeological and geomorphological characteristics of the area to be recovered

The sampling of waste for the purpose of its chemical-physical characterization must be carried out in such a way as to obtain a representative sample according to the criteria developed by the IRSA-CNR 64, analytical methods on sludge, volume 3 of January 1985, as applicable. The analyses on these samples, for the purposes of characterizing the waste, must be carried out according to standardized methods or methods recognized as valid at national, Community or international level. The analyses must be carried out at least at each start of the activity and, subsequently, every two years and, in any case, whenever substantial changes occur in the waste recovery process.

The leaching tests, if required, must be performed on a sample obtained in the same physical form as foreseen in the final conditions of use and must be performed according to the procedures set out in Annex 3 to this Decree. The transfer tests must be carried out at least every start of business and, subsequently, every two years and, in any case, every time substantial changes occur in the waste recovery process.

3.4 The life cycle Assessment

The Life Cycle Assessment (LCA) is a method that evaluates the set of interactions that a product or service has with the environment, considering its entire life cycle which includes the pre-production phases (therefore also the extraction and production of materials), production, distribution, use (therefore also reuse and maintenance), recycling and final disposal. Thanks to the impetus deriving from European policies on environment, energy, resources and waste, LCA is increasingly becoming a necessary tool for defining public policies and for the competitiveness of businesses. At the European level, LCA represents, to date, an element of qualification in all fields where an assessment of sustainability is required. It is a methodology that allows to evaluate the ecological advantages of a product, through the quantification of the environmental impacts connected to the production processes and other activities of the company. As for the information provided to the consumer, the LCA can be of support to increase the truthfulness of the message on the ecological characteristics of a product, which acquires credibility as it is accompanied by numerical data on the impacts.

The LCA procedure is internationally standardized by the EN ISO 14040 and 14044 standards. The LCA (as defined by the ISO 14040 standard) considers the environmental impacts of the case examined on human health, the quality of the ecosystem and the depletion of resources. The objectives of this methodology are to define a complete picture of the interactions with the environment of a product or service, helping to understand the environmental consequences directly or indirectly caused and therefore daring to those who have the decision-making power (who has the task to define the regulations) the information necessary to define the behaviors and environmental effects of an activity and identify opportunities for improvement in order to reach the best solutions to intervene on the reduction of the environmental impact.

The two main regulatory references that represent the main methodological standard for the execution of an LCA analysis applied in a general way, not referred to road works, will be analyzed in detail below, since there is still no specific legislation in the national and European context.

3.4.1 EN ISO 14040- 14044

The increased awareness of the importance of protecting the environment and the possible impacts associated with the products/services manufactured and consumed has increased interest in the development of methods to better understand and reduce these impacts. One of these techniques under development is Life Cycle Assessment (LCA). The LCA can support:

- the identification of opportunities to improve the environmental performance of products in the different stages of their life cycle
- information to those who make decisions in industry and in governmental or non-governmental organizations (for example strategic planning, choice of priorities, design or redesign of products or processes)
- the choice of relevant environmental performance indicators with the related measurement techniques
- marketing (for example, the implementation of an ecological label system, an environmental claim or the production of an environmental product declaration).

For LCA professionals, ISO 14044 describes in detail the LCA implementation requirements. LCA deals with environmental aspects and potential environmental impacts throughout the product life cycle, understood as consecutive and interconnected phases of a product system, from the acquisition of raw materials through manufacturing and use, up to the treatment of end of life, recycling and final disposal (i.e. “from cradle to grave”).

The LCA study involves four phases, represented with the related connections in Figure 3.1.

- Phase 1: the objective and scope definition
- Phase 2: the inventory analysis
- Phase 3: the impact assessment
- Phase 4: the interpretation

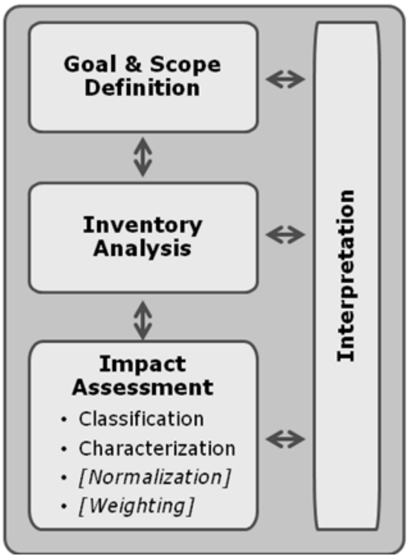


Figure 3.1 Stages of an LCA (ISO 14044)

The objective indicates the reasons for the study and the audience to whom the analysis is intended. The field of application, including the limits of the system and the level of detail of the LCA, depends on the subject and the intended use of the study. The depth and breadth of the LCA can differ considerably depending on the objective of a particular LCA. The scope includes the definitions of the product system studied, the functional unit, the system boundary, the allocation procedures, the selected impact categories, the methodologies for assessing the impacts and their interpretation, the quality requirements of the data and assumptions underlying the analysis.

The **life cycle inventory analysis** phase (LCI phase - "Life Cycle Inventory") is the second phase of the LCA. This is the inventory of incoming and outgoing data relating to the system to be studied. The LCI implies the collection of the data necessary to achieve the objectives of the defined study.

The **life cycle impact assessment** phase (LCIA phase - "Life Cycle Impacts Assessment") is the third phase of the LCA. The purpose of the LCIA is to provide additional information to help evaluate the LCI results of the product system in order to achieve a better understanding of their environmental significance.

The **Life cycle interpretation** is the final stage of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed, according to the definition of the goal and scope, as a basis for conclusions, recommendations and decisions.

There are cases in which the objective of the LCA can be met by carrying out a single inventory analysis and interpretation. This is generally known as the LCI study. EN ISO 14040 covers two types of studies: **life cycle assessment** studies (LCA studies) and **life cycle inventory** studies (LCI studies).

In general, information obtained through an LCA or LCI study can be used as part of a much more comprehensive decision-making process. Comparing the results of different LCA or LCI studies is only possible if the hypotheses and context of each study are equivalent. Therefore, EN ISO 14040 contains several requirements and recommendations to ensure transparency on these topics.

LCA is one of several existing environmental management techniques (for example: risk assessment, environmental performance assessment, environmental audit and environmental impact assessment) and may not be the most suitable technique to be used in all situations. The LCA generally does not deal with the economic and social aspects of a product, but the life cycle approach and methodologies described in EN ISO 14040 can be applied to these other aspects.

LCA is a relative approach, structured around a functional unit. The functional unit defines what is studied. All subsequent analyzes are then related to the functional unit, as all the input and output elements of the LCI and the LCIA profile are related to the functional unit.

As reported by the EN ISO 14040, the basic characteristics of the life cycle assessment methodology are listed:

- the LCA systematically examines the environmental aspects and the impacts of the product systems, from the acquisition of raw materials to final disposal, in accordance with the defined objective and field of application
- the relative nature of the LCA is due to the functional unit characteristic of the methodology
- the degree of detail and the temporal extension of the LCA are a function of the objective and field of application
- the LCA methodology is open to welcome updates on the state of the art of technology
- there is no single method for conducting LCA. Organizations have the flexibility to practically implement LCA in accordance with EN ISO 14040

- LCA is different from many other techniques (such as environmental performance assessment, environmental impact assessment and risk assessment), however it can use information collected by other techniques
- the LCA does not provide for the assessment of specific or absolute environmental impacts for the following reasons: the environmental impacts are related to a reference unit, there is an intrinsic uncertainty in their modeling and, in most cases, they are expected impacts in future time
- the LCI and LCIA phases provide a perspective on the environmental problems and resources required of one or more product systems
- the LCIA assigns the LCI results to the impact categories. For each category, a life cycle impact category indicator is selected and the result of this indicator is calculated
- the LCIA profile provides information on environmental problems associated with the elements entering and leaving the product system
- there is no scientific basis for reducing LCA results to a single score or number, since weighting requires the choice of values
- Life cycle interpretation requires the use of a systematic process to identify, qualify, verify, evaluate and present conclusions based on the results of the LCA in order to meet the requirements described in the objective and scope of study
- the interpretation of the life cycle also provides for the identification of links between the LCA and other environmental management techniques, underlining the strengths and limitations of the LCA in relation to the definition of its objective and scope.

The object of the LCA is therefore the product system, understood as a system having one or more functions and divided into a series of unitary processes. The unit processes are connected to each other by flows of intermediate products and/or waste to be treated, they are connected with other product systems by product flows and with the environment by elementary flows.

Dividing the product system into unitary component processes makes it easier to identify the elements entering and leaving the product system itself. The level of detail of the modeling that is required to meet the objective of the study determines the boundary of a unitary process. Elementary flows can include the use of resources and releases into the air, water and soil associated with the system. These data are the results of the LCI and constitute the input element for the LCIA.

The system boundary determines the unit processes that must be included in the LCA. It is necessary to establish which unitary processes to include in the study and the level of detail with which these unitary processes are to be studied.

EN ISO 14040 lists the unitary processes that must be included in the system boundary:

- acquisition of raw materials
- main process sequence
- distribution and transport
- production and use of fuels, electricity and heat
- use and maintenance of the product
- disposal of waste and process products;
- recovery of products after use (including energy recovery)
- manufacture of auxiliary materials
- manufacture, maintenance and disposal of main equipment.

The elimination of life cycle stages, processes, incoming or outgoing flows is allowed only if it does not significantly change the overall conclusions of the study and, in any case, must be appropriately justified. In particular, in the practice of LCA, various exclusion criteria are used, listed below according to the definitions of EN ISO 14044:

- mass: all the input elements that cumulatively contribute, in a way greater than a defined percentage, to the mass flow of the product system to be modeled must be included in the study
- energy: all the input elements that cumulatively contribute, in a greater than a defined percentage, to the input energy flow of the product system to be modeled must be included in the study
- environmental relevance: all input elements that contribute more than a quantity defined by the system data collected specifically for their environmental relevance must be included in the study.

The qualitative and quantitative data to be included in the inventory must be collected for each unit process included within the system boundaries. The collected data, whether measured, calculated or estimated, are used to quantify the input and output elements of a unitary process. When data is collected from those published in public sources, reference must be made to the source.

Since the data collection could cover different communication sources and published references, to achieve a uniform and consistent understanding of the product system to be modelled, measures need to be taken, including:

- drawing of non-specific process flow diagrams, which describe all the unitary processes to be included in the model, with their interrelationships
- detailed description of each unitary process with respect to the factors that influence the input and output elements
- list of flows and relevant data for the operating conditions associated with each unitary process
- development of a list specifying the units of measurement used;
- description of the data collection and calculation techniques required for all data.

The macro categories into which data can be classified include:

- incoming energy elements, incoming raw materials, auxiliary materials or other incoming physical entities
- products, co-products and waste
- releases into the air, water and soil
- other environmental aspects.

All calculation procedures must be explicitly documented and assumptions must be clearly indicated and justified. The same calculation procedures should be consistently applied throughout the study. The incoming and outgoing elements related to combustible materials, for example oil, gas or coal, can be transformed into incoming and outgoing energy streams by multiplying them by the related heat of combustion. In this case it must be recorded whether the highest or lowest calorific value has been used.

The inputs and outputs must be allocated to the different products according to clearly defined procedures, which must be documented and justified together with the allocation procedure. The sum of the elements allocated in input and output of a unit process must be equal to the elements in input and output before the allocation of the unit process.

The allocation process is performed according to the following procedure:

Step 1: Wherever possible, allocation should be avoided by splitting the unit process to be allocated into two or more subprocesses and linking the inbound and outbound data related to those subprocesses, or by expanding the product system to include additional functions relating to co-products.

Step 2: Where the allocation cannot be avoided, the input and output elements of the system should be divided among its different products or functions so that they reflect the underlying physical relationships between them.

Step 3: Where physical relationships alone cannot be established or used as a basis for allocation, the inputs should be allocated between products and functions in a way that reflects the other relationships between them (e.g. in proportion to the economic value of the products).

The allocation procedures must be applied uniformly to the similar input and output elements of the considered system.

For reuse and recycling, additional processing is required for the following reasons:

- reuse and recycling may imply that the incoming and outgoing elements associated with the unitary processes for the extraction and treatment of raw materials and the final disposal of products are shared by more than one system of products
- reuse and recycling can change the properties inherent to the materials
- specific attention should be paid to the recovery processes when defining the system boundary.

Product systems that provide for recycling and reuse operations can be closed-loop, i.e. the material is recycled within the same product system, or open-loop, i.e. the material is intended to be reused in another recycling system products.
Different allocation processes are applicable to reuse and recycling, in particular:

- a closed-loop allocation process is applied to closed-loop product systems. It also applies to open-cycle product systems where there are no changes in the properties inherent to the recycled material. In such cases, the use of secondary material replaces the use of virgin materials
- for open-loop product systems, where the material is recycled into other product systems and the material undergoes a change in its properties, an open-loop allocation process is applied.

Such allocation procedures for divided unit processes should use as a basis for the allocation, if possible, in order: the physical properties, the economic value or the number of subsequent uses of the recycled material.

The LCA phase must be carefully planned to comply with the objective and scope of the LCA study. The LCIA phase must take into account the following sources of uncertainty:

- quality of LCI data as a function of the objective and field of application
- system boundary and data excluded, as the results of the LCI must be sufficient to calculate the results of the indicators for the LCIA
- environmental relevance of the LCIA results, which can be reduced due to the functional unit and the aggregation and allocation procedures.

The LCIA phase therefore includes the collection of the results of the indicators for the different impact categories, which together represent the LCIA profile for the product system.
The LCIA is made up of mandatory and optional elements. The mandatory elements are the following:

- selection of impact categories, category indicators and characterization models
- assignment of LCI results to the selected impact categories (classification)
- calculation of category indicator results (characterization).

When selecting impact categories, category indicators and characterization models in the LCA, reference must be made to the information and related sources. This also applies to the definition of new impact categories, category indicators and characterization models. The selection of impact categories must reflect a complete set of environmental problems related to the product system studied, taking into account the objective and field of application. In addition, for each category indicator, the environmental mechanism and the characterization model that relate it to the results of the LCI must be described.

For each defined impact category, the mandatory elements of the LCIA are:

- the identification of the purpose of the category, or on which environmental aspect the impact category affects
- the definition of the category indicator, understood as a quantifiable chemical phenomenon that causes an environmental impact
- the identification of the appropriate LCI results that can be assigned to the impact category, taking into account the category indicator and the identified purposes;
- the identification of the model and characterization factors.

Furthermore, the purposes of the categories and their environmental relevance must be defined. In addition to these mandatory elements, EN ISO 14044 also includes a series of recommendations, such as the international recognition of the impact categories, category indicators and characterization models used and their technical and scientific validity.

The LCIA classification phase involves the assignment of the LCI results to the impact categories and should take into account the following aspects:

- the direct assignment of the LCI results relating to a single impact category
- identification of the results

After the characterization and before the other optional elements of the LCIA, the elements entering and leaving the product system must be represented by:

- the compilation of the results of the category indicators for the different impact categories, known as the LCIA profile
- inventory results that have not been assigned to impact categories, for example due to low environmental relevance
- data that are not elementary inventory flows.

Some of the optional elements of the LCIA reported by the EN ISO 14044 are the normalization of the category indicators with respect to a reference value, the classification by grouping of the impact categories, the weighting (assignment of weights to the different impact categories and aggregation of the results of the weighted indicators) and the analysis of data quality.

The applications of LCA in the field of environmental management tools include, among others:

- environmental management systems and the assessment of environmental performance such as the identification of the significant environmental aspects of a product
- environmental labels and declarations (ISO 14020, ISO 14021 and ISO 14025)
- the integration of environmental aspects in the design and development of a product (ISO/TR 14062)
- the inclusion of environmental aspects in product standards (ISO Guide 64)
- environmental communication (ISO 14063)

4 Literature review

According to the latest report of the International Solid Waste Association around 4 billion tons of waste are produced each year worldwide. It was observed how one half concerns urban waste and the other one special waste, derived from industrial and production activities. Even if there are no univocal estimates, complicit the growth of the world population and the economic development, in the next 10-15 years it could arrive to an increase of this production also of 50%.

In the field of road pavements, many researches are investigating the re-use of raw materials into bituminous mixtures such as waste bleaching clay, landle furnace slag, recycled bricks and waste glass powder [6] [7] [8] [9]; in particular, the studies identified in the literature deal with different approach of recovery both from a technology and multiscale point of view (see Figure 4.1) to make comparable mechanical behaviour with the traditional mixtures.

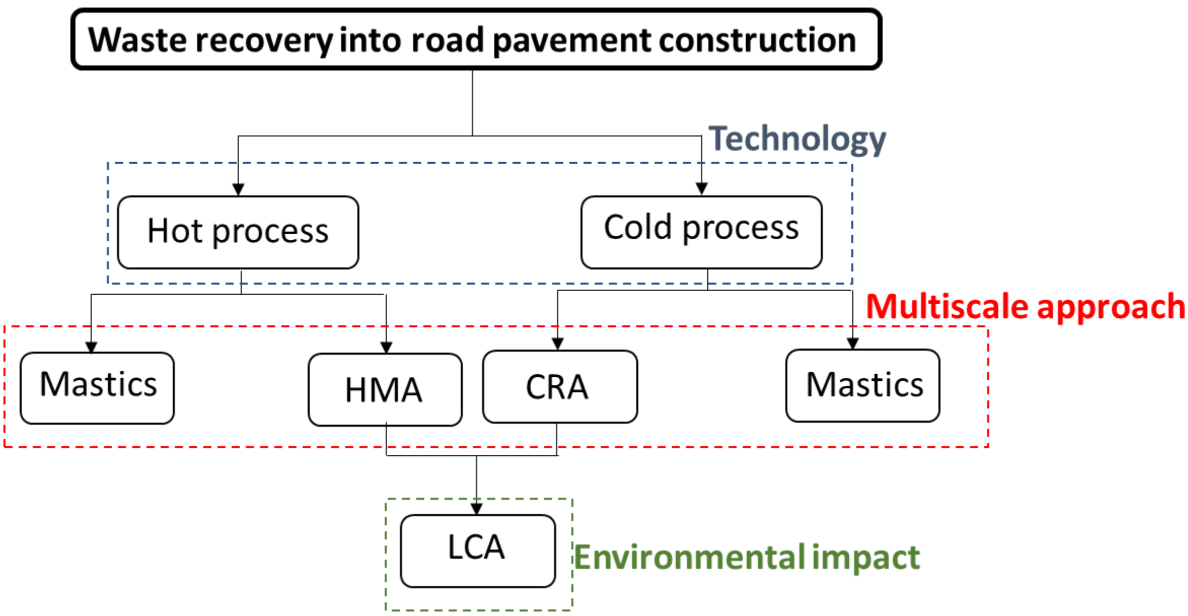


Figure 4.1 Flow diagram of waste recovery into bituminous blends

From the literature review, asphalt mixtures are mainly divided into four scales, including binder, mastic, mortar (or fine aggregate matrix, FAM) and mixtures [10] (see Figure 4.2).

To achieve universally sustainable results of road infrastructures effort not only the mechanical response is enough but environmental impact has to be assessed. Many researchers are traying to investigate from an environmental point of view the road pavement by applying LCA method.

For the purpose of the present research, as described in the previous section 1, the literature study was focused on the mixture and mastics assessment that includes the reemployment of secondary raw materials, to capture the innovative aspects deriving from the study addressed by this research.

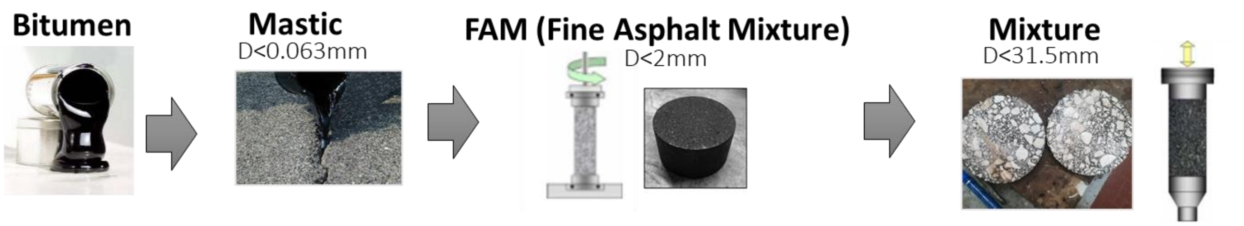


Figure 4.2 Multiscale approach for the study of bituminous mixtures

4.1 Experimental evaluation of alternative materials into bituminous mixtures

Nowadays there are many studies on use of waste materials in addition to or in place of a conventional filler in the production of HMA. From a mechanical point of view the mixtures with alternative filler showed best mechanical performance in comparison to the traditional one.

Ossa et al. [11] studied the effects of construction and demolition waste aggregates (CDWA) into mix design of hot bituminous blend for urban pavements. In particular, the wheel tracking test returned a significant reduction of the rut depth at 10,000 cycles when CDWA quantities reaches are more than 20%.

Mistry et al. [12] investigated the addition of rice husk and fly ashes as filler to HMA showing a better performance in terms of Indirect Tensile Strength (ITS) and Indirect Tensile Strength Ratio (ITSR) and a reduction of optimum bitumen content of 7.5% in comparison to a traditional mixture when filler content is equal to 4%.

Kareem et al. [13] obtained higher dynamic modulus at high test temperature (40°C) with bituminous mixtures containing double coated recycled concrete aggregates, as well as it was observed by some

researchers [14][15] when alternative fillers (hydrated lime, cement bypass dust and waste plastic bottles) are introduced into hot bituminous mixtures.
Pattanaik et al. [16] evaluated the mechanical properties of open-graded (OGFC) mixtures with different percentages of Electric Arc furnace (EAF) steel slag as a substitution for natural coarse aggregates. Mechanical properties were evaluated through static creep test, dynamic creep test, indirect tensile stiffness modulus test, Hamburg wheel tracking test and indirect tensile fatigue tests where OGFC mixtures with 75% substitution of coarse natural aggregates with EAF steel slag presented the best performance. The results compared to the traditional mixture with 0% EAF returned 72% and 66% lower accumulated Strain and Rut depth, respectively, while 100%, 78% and 376% higher Recovery strain, Stiffness modulus and fatigue life.

A topic of fundamental importance today is the high percentage of plastic waste that is still landfilled and incinerated. To encourage plastic recycling, investments are being promoted dedicated to the renewal of materials and production techniques aimed at the reuse of plastic materials. Therefore, many researchers are focusing their study on the effect of plastic waste into hot bituminous mixtures through dry and wet process, where the dry process consists to put the plastics waste into the mixture production as aggregate while the wet process the PW acts as bitumen modifier.
Almeida et al. [17] attempted to use dry process to add Low-density polyethylene (LDPE) flakes collected from urban waste to hot bituminous mixtures; they compared the effect of LDPE modification on both fatigue cracking and rutting resistance before and after an aging process and demonstrated that, while there was a negligible effect on the fatigue cracking resistance, the introduction of 6% LDPE by the weight of bitumen led to a 66% decrease of the rut depth with respect to the control mixture in unaged conditions, and a further 30% reduction in aged conditions.
Ahmadinia et al. [18] added grinded Polyethylene Terephthalate (PET) particles passing 1.18 mm sieve by means of the dry process and determined that 6% PET by the weight of bitumen was able to maximize Marshall Quotient. A slightly different blending procedure led El-Naga et al. [19] to find the optimum Marshall Quotient in correspondence of 12% crushed PET by the weight of bitumen; they previously melted PET particles at a temperature of 300°C in a special container and then added the melted PET to the aggregates and blended with bitumen.
Considering the Stone Mastic Asphalt (SMA) stiffness, Baghaee Moghaddam et al. [20] found out that asphalt mixtures containing 1% PET by weight of aggregates resulted in a 12.4% reduction of Indirect Tensile Stiffness Modulus (ITSM) (at 20°C and 250 kPa applied stress) when compared to a traditional SMA. They attributed this result to the fact that most PET particles do not melt during mixture fabrication, but they change their microstructure into a crystalline structure, increasing the

elastic deformation of the mixture. However, the higher flexibility of the PET-modified mixtures resulted in a 124.8% increase in fatigue life (Nf) assessed with Indirect Tensile Fatigue test (ITFT) according to EN 12697-24 at 250 kPa stress level, compared to the traditional SMA. Moreover, the modification of bituminous mixtures with crushed PET waste usually results in a high resistance to permanent deformation, with remarkable recovery after 1800 cycles with loading time of 1 hour at temperature 30ºC as shown by Rahman et al. [21] who produced modified asphalt mixture for wearing course with concentrate of recycled PET pallet content range between 5 and 25% of the weight of asphalt mixture with sieve size from 2.36mm to 1.18mm and 5% weight of bitumen content.
Ziari et al. [22] evaluated the rutting performance of asphalt mixtures that include various percentages of PET (0%, 0.25%, 0.5%, 0.75%, 1% by weight of aggregates) and various PET sizes (10×2.5, 20×2.5, and 30×2.5 mm) through dynamic creep test and Hamburg wheel tracking device found that with the increase of PET content and the increase in dynamic load, the produced stresses were absorbed with PET particles leading to delay in rutting phenomenon.

The materials present in old asphalt pavements may have value, even when the pavements have reached the end of their service lives. Recognizing the value of those existing aggregate and asphalt resources increased the use of RAP in new asphalt pavements. Additionally, the interest in the use of RAP has increased dramatically since the recent price increases in crude oil and energy in general. By reusing aggregate and asphalt from deteriorated pavements, the need for new materials is appreciably reduced and the overall cost of the improved pavement will be less. Furthermore, several studies showed that asphalt mixes containing RAP can have equivalent performance to virgin mixes a reduce the environmental impact [23].
The benefits connected to the use of RAP are related to the possibility of substituting the natural aggregates and the virgin binder of an asphalt concrete mixture, reducing the negative impact of the effects deriving from the production process of HMA without seriously affect desired mechanical properties. A standard procedure to optimize and verify a mixture containing RAP does not exist [24], nevertheless is largely required.
Sangiorgi et al. [25], for example, investigated static and dynamic mechanical properties of bituminous mixtures when cold reclaimed asphalt (CRA) is set up to 100% of RAP for a base layer of pavement; they observed that this solution, compared to HMA doesn't negatively affect performance of mixture, water susceptibility and thermal sensitivity.
Lyu et al. [26] found through experimental investigations one of the proper solutions for introduce CRA into bituminous mixtures by analysing some properties at high temperature (60°C), moisture

stability (Marshall Stability and ITSR) and fatigue damage as follows: 3.8% emulsified asphalt, 2% cement and 80% RAP.

Arshad et al [27] studied the effect of CRA added to recycled concrete aggregates into a base/subbase layer of a flexible pavement; they showed that an increase of the resilient modulus and constrained modulus appears when the RAP contents varied from 0 to 50%. In addition, Gómez-Meijide and Pérez [28] evaluated the mechanical properties of cold bituminous mixtures containing 100% of Construction and demolition waste aggregates (CDWA), demonstrating how ITS increases up to 12.8% or higher (15% water and 5% bitumen on the weight of dry aggregates) compared to a traditional HMA. Many studies [29] [30] [31] [32] are focused on the characterization of the curing process of CRA mixture.

Graziani et al. [33] aimed to investigate two mixtures with 3.3% of bituminous emulsion and two cement dosages of 1% and 2.5%, respectively, analysing the best curing period to achieve proper and constant mechanical properties. In time, increasing cement dosage from 1% to 2.5% it was observed a clear effect on the long-term values of mechanical properties. In fact, the stiffness increased until the 28th day from 3341 MPa to 6612 MPa and from 4154 MPa to 7726 MPa, for curing temperature at 25°C and 40°C, respectively. Analogously, ITS increased from 0.38 MPa to 0.58 MPa and from 0.42 MPa to 0.60 MPa, for curing temperature at 25°C and 40°C, respectively.

In conclusion, the literature study found that to date various alternative materials have been reused as fillers in mastics or as aggregates in mixtures, showing an increase in the mechanical performance of the mixtures compared to those traditionally used.

4.2 Effect of alternative materials on performance of hot and cold bituminous mastics

The different composition of the engineering materials at different scales generate a multiscale phenomenon. The size effect has significant influence on the material performance in particular when the 0.063 sieve passing size is combined with the binder to make the mastic. The rheological properties of bituminous mastics are very influenced by the filler, so it’s important to predict the performance of bituminous mastics with different filler [34].

Rochlani et al. [35] compared the rheology properties and mechanical performance of four mastics fabricated with the same base bitumen and four different fillers (dolomite, granodiorite, limestone and rhyolite). The main objective of the investigation was to measure the impact that the filler exerts on the mechanical response of the bitumen, as well as on the fatigue, rutting and low temperature performance. All the results were presented in a simplified performance diagram (see Figure 4.3) to visualize how the mastic properties differ depending on the filler used, and to propose a performance ranking system for selecting the most appropriate filler that could enhance the properties of the material. Overall, the performance diagram showed that the mastics behaved quite differently, with the Granodiorite being the most suitable filler for the base bitumen investigated, because it had the highest stiffening effect on the bitumen, while the aging susceptibility was the lowest. Furthermore, the Granodiorite mastic also exhibited the best fatigue and rutting resistance performance among all the materials.

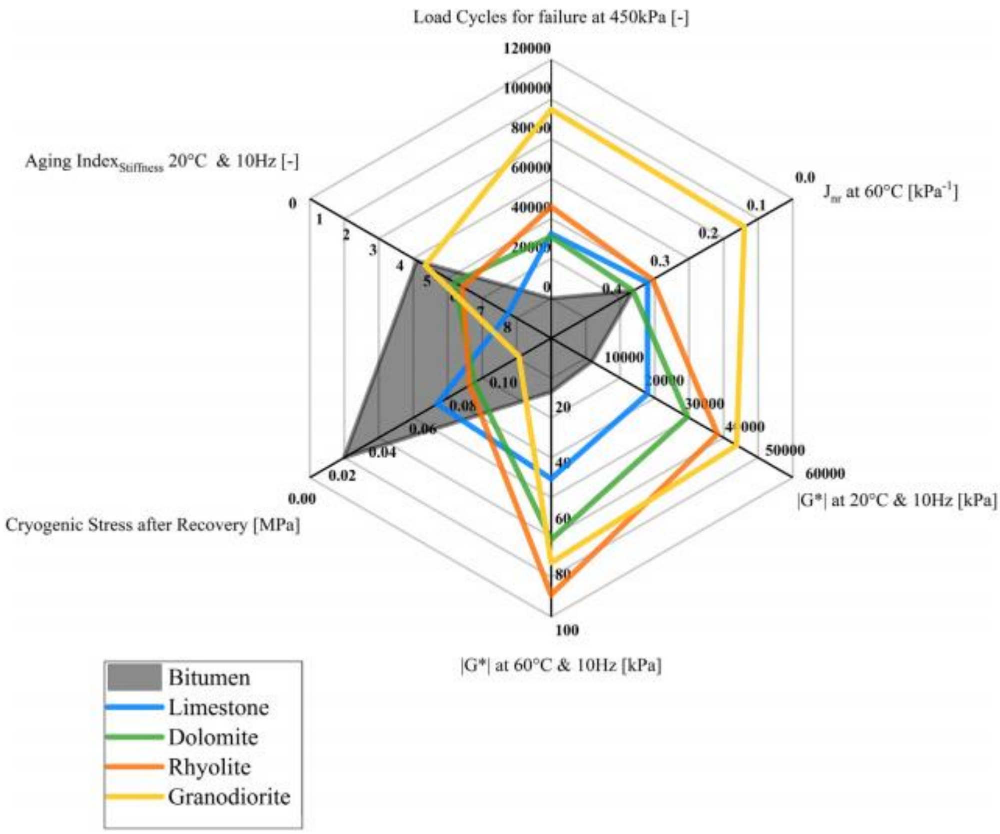


Figure 4.3 Performance diagram of birtuminos mastics [35]

Pan et al. [36] evaluated the thermal properties of bituminous mastics made up of three different fillers as limestone, cenospheres and graphite since the mastics played a vital role in the heat conduction of a cool pavement. In total, 9 mastic samples were prepared where the cenosphere or graphite replaced part of limestone filler (control mastics) by 25%, 50%, 75% and 100% by the weight of mastics. The rheological tests were carried out to evaluate the Shear modulus (G*) and the rutting index G*/sinδ to evaluate the deformation resistance of mastic under the vehicle load. The G* increased with the addition of cenospheres for a content belove 50%, therefore an increase of ratio in rutting resistance was showed when compared the alternative mastics with the traditional one. The results recommended to apply on the top layer of the cool pavement a mastics made up of 50%

limestone mastics and 50% cenospheres by the weight of bitumen and for sub-layer a mastics with 100% graphite by the weight of bitumen.

Rochlani et al. [37] investigated the feasibility of using waste ceramic powder as an alternative filler in mastic. The base bitumen and two kinds of fillers, limestone and ceramic, were blended to prepare mastics with the binder-filler mass ratio of 1:1 The dynamic shear rheometer (DSR) was used to study the rheological parameters through the Frequency sweep test, rutting resistance with MSCR test and fatigue performance using the stress-controlled test. The results showed that the bitumen has a lower stiffness than the mastics, in particular the limestone had 1.9 times the terminal stiffness of bitumen, while ceramic was 3.4 times larger; the strain level at fatigue life of 100,000 load cycle and the Jnr value of the mastic with ceramic were 15% and 84% lower than the traditional mastic.

Many studies have focused on investigating the properties of the mastics with reference to cold bituminous mixture with RA.

Godenzoni et al. [38] evaluated the effects of different mineral fillers on the linear viscoelastic (LVE) properties of cold bituminous mastics. The shear modulus was measured on bituminous mastics prepared with calcium carbonate and cement as filler at filler-to-bitumen volume ratios of 0.15 and 0.3. It has been shown that G* values are higher for mastics containing cement than those containing calcium carbonate as an added mineral; specifically, G* increases with a higher cement concentration ratio and LVE behaviour evolves from that of liquid material to that of solid material.

Some studies have shown that the Multi Stress Creep and Recovery (MSCR) method is the most appropriate for measuring the rutting resistance performance of asphalt binder. Indeed, it is widely accepted that, compared to the existing Superpave rutting factor G*/sin δ (δ= phase angle), non-recoverable creep compliance $\bar{J}_{nr}$ following the MSCR test is more closely related to the rutting resistance performance of asphalt mixture [39].

Vignali et al. [40] have measured to what extent cement and limestone filler contents affect the rutting response of two mastics produced using cationic bituminous emulsion: 1) 75% bitumen and 25% cement, and 2) 75% bitumen, 12.5% filler, and 12.5% cement per volume. The results have confirmed that the presence of limestone filler improves mastic stiffness at high temperatures with a G* higher than mastic with cement; this was confirmed by the MSCR results, where the mastic containing limestone filler accumulated less deformation at both test temperatures (46°C and 58°C) and both stress levels (0.1 kPa and 3.2 kPa).

Garilli et al. [41] focused on asphalt emulsion cement (AEC) mastic mixing to evaluate the behaviour of cold in-place recycling in the phase of coexistence of viscoelastic and brittle materials using a bending beam rheometer (BBR). The authors proposed introducing glass microspheres to act as an "inert solid skeleton" in the production of AEC mastics for BBR prismatic beams, to study the interaction between bituminous emulsion and cement in thin film and to limit the specimens' shrinkage and warpage during the curing period.

In conclusion, the possibility of reusing RAP through a cold technology to replace traditional aggregates in new blends was demonstrated, obtaining the same performance as a hot-produced blend made up of only virgin aggregates.

4.2.1 Plastic waste effect on the bitumen

Many studies revealed that physical and chemical reaction of polymers with bitumen were significantly important in the modification process; Low- and high-temperature properties of modified bitumen were improved considerably, therefore, the researchers are traying to reemploy the plastic waste into bitumen as a polymer modifier to improve the performance of bitumen.

Polyethylene (also known as polythene) is the simplest of the synthetic polymers and the most common among all plastic materials. Abbreviations are often used to call for example polyethylene through PE, as well as PS for polystyrene, PVC for polyvinyl chloride and PET for polyethylene terephthalate. Main macro-categories of PET material are Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) both characterized by a low melting point falling within a range between 110°C and 140°C [42]; in particular it was observed that HDPE reduces considerably the value of the no-recoverable deformations of a bitumen when it is used as a modifier binder like common SBS. Other research studies [43] proved, comparing HDPE and LDPE, that LDPE returns higher rutting resistance than previous one as a percentage of 4% by the total weight of bitumen. They also verified through a Multi Stress Creep and Recovery test (AASHTO TP 70) under 0.1 and 3.2 kPa as stress levels at test temperatures of 70°C and 76°C that rise low recovery deformations (around 5% over the loss deformation).

Khan et al. [44] investigated the effects of LDPE, HDPE and Crumb Rubber (CR) to a neat PG 64-10 bitumen; they observed in general how the rutting and cracking resistance increased. Dry and clean LDPE, HDPE and CR (all three materials in powder form with a size between 0.15 mm and 0.75 mm) were used each one as bitumen modifier in light of 2%, 4%, 8% and 10% by the total weight of the bitumen. The blends were prepared mixing the LDPE, HDPE and CR with the neat bitumen using a laboratory mixer at 160°C for two hours. Complex shear modulus (G^*) and phase angle (δ) were measured through a Dynamic Shear Rheometer (DSR) to evaluate the rutting and cracking resistance; the results in comparison to the neat bitumen showed that adding 10% LDPE or 4% HDPE into the binder, δ reduces of 25% on average and G^* increases of 200% almost, while the addition of 10%

CR reduces δ of about 70% and increases of 900% the G*. So, the authors showed the addition of LDPE, HDPE, CR to neat binder improves the elastic behaviour of binder in order to extend the service life of pavements in terms of reduced susceptibility to rutting and cracking.

Shahane, & Bhosale [45] evaluated the rheological properties of a VG-30 bitumen modified through E-waste plastic powder (EPP), deriving from the recycling of electronic waste, passing through 300-μm sieve (EPPMB) using 2%, 2.5%, 4%, 5% and 6% by the total weight of the bitumen. Bitumen was modified by heating it until to reach the fluid consistency in a metal container at 160°C and then the required amount of EPP was added and mixed by using a 150RPM frequency at 175–180°C temperature for 40 minutes. Viscosity, penetration, softening point, ductility, rheological properties in terms of dynamic modulus and phase angle, were analysed through a DSR. The results showed that the rutting resistance of EPPMB evaluated in terms of G*/sinδ increases by 1.6 and 1.8 times that VG-30 bitumen at 60°C (4MPa) by adding 2% and 5% EPP respectively; in addition, it was found that as the temperatures increase storage modulus and loss modulus of EPPMB increases, and in particular in correspondence of 60°C, the 5% EPP gives 2.7 times higher storage modulus and 1.84 times more loss modulus than that of the VG-30 bitumen.

Nasr and Pakshir [46] investigated the potential benefits derived by combining PET and CR in the total measure of 15% (by the total weight of neat binder) into neat binder to achieve a reduction of the rutting and fatigue cracking compared to a 60/70 binder and an 85/100 binder. Rheological tests were performed using a dynamic shear rheometer (DSR) at the test temperatures of 58, 64, 70, 76 and 82°C at the frequency of 1.59Hz, Multiple stress creep recovery (MSCR) at 64°C under 0.1 and 3.2 kPa and linear amplitude sweep (LAS) under 2.5 and 5% of strain amplitude were carried out. PET plus CR was gradually added at 160°C together in the measure of 15% by the total weight of neat binder, mixing the whole blend at 190°C for two hours. The main findings showed that increasing the amount of PET in polymer composites the value of Jnr decreases under both stress levels when compared with both neat binders, in particular of 50% when the 60% CR is combined with 40%PET into each binder.

Amirkhanian [47] evaluated the utilization of PE in neat binder. Two base binders PG 62-22 of different source, and three percentages of polyethylene (PE) content such as 2%, 4%, and 6% by the total weight of neat binder were adopted to produce PE modified bitumen. To made the modified binder each PE content with each binder were blending at the temperature of 177°C for two hours. Rotational viscosimeter at 135°C, MSCR test, Failure temperature test (carried out testing the sample at a starting temperature and increased it to the next PG grade until the value of G*/sinδ results greater than the value required by AASHTO M320), were carried out to evaluate the rheological properties of the modified binders. The results showed that the modified binder by using 6% of PE content returned higher both viscosity values at 135°C and failure temperature in comparison with neat binder respectively of 670% and 34%; at the same time the non-recoverable creep compliance at 0.1kPa resulted 97% lower that the neat bitumen at 76°C.

Nouali et al. [48] investigated the effects induced by plastic bag waste (LDPE) with a size of 2-5mm into neat 50/70 penetration grade bitumen (WPmB). Neat bitumen modified through LDPE content varying from 0.5 to 1.5% by the total weight of the bitumen was blending at 170°C for 60 min. A variation in the penetration and softening temperature values for LDPE contents greater than 0.9% was observed, in particular a decrease in the penetration values of about 40% and an increase in the softening temperatures of about 23% when the 1.5% LDPE was added to neat bitumen.

Nizamuddin et al. [49] utilized recycled LDPE with a maximum nominal size of 600 μm at four different content of 3%, 6%, 9% and 12% by the total weight of the bitumen for modifying a neat bitumen C320. The modification occurred at 170°C blending LDPE particles with neat bitumen for 1.5h. Viscosity, Softening point, Frequency sweep and MSCR tests were investigated. The viscosity value at 135°C of neat bitumen was 0.62Pa·s, that increased up to 5.75Pa s adding 12% LDPE, at which the softening point increased up 177% compared to the neat bitumen, and the phase angle touched the lowest value of 54° implying that the elasticity of binder is increased. The modified binder showed higher resistance to the permanent deformations at high temperatures compared to neat bitumen in particular when the 12% LDPE is added to neat bitumen the non-recoverable creep compliance reduces of 99.9%.

In conclusion, the study aimed at the reuse of plastic in bituminous blends has shown that plastic when processed with bitumen at its melting temperature acts as a modifier of the bitumen itself, increasing in particular its resistance to the accumulation of permanent deformations.

4.3 Road pavement life cycle assessment

Nowadays, in order to quantify the potential impacts on the environment and human health related to production and laying of bituminous mixtures, starting from the resource's consumption and emissions, a structured, standardised and unbiased tool is LCA. The life cycle perspective gives an important contribution to identify and improve the environmental performances of a product with a specific attention for each phase of the life cycle; therefore, the LCA itself is a decision-making support system for the design of pavement solutions characterised by enhanced environmental sustainability. To achieve universally sustainable results of road infrastructure effort not only the mechanical response is enough but economic and environmental appropriates have to be assess [50]. The results of the analysis conducted for example by Nicuta [51] showed that adopting RAP up to 75% into a hot bituminous blend help CO_2 emissions of 40% compared to HMA.

Moretti et al. [52] highlighted how there can be significant differences between two mixtures of bituminous mixtures produced in two different plants, and how these differences may not be appreciated if we only consider CO_2 emissions into the atmosphere since it could present unacceptable environmental burdens.

Xiao et al. [53] stated that a reduction of energy consumption, GHG emissions and production costs can be reached when aged binder derives from RAP equal to 30% on the weight of dry aggregates.

Auteliano et al. [54] investigated the behaviour of a binary asphalt/waste mixture in terms of hydrocarbon aerosols, vapours and gases is emitted in the atmosphere during the asphalt heating process with reference to various stages of road pavement construction. The analysis had confirmed that the temperature represents the more effective factor in the generation of airborne substances; in particular, the introduction of wax in the mixture shows a decrease in the temperature of mixing and laying of around 30°C and above all a reduction of asphalt emissions especially at temperatures below or close to the waxes melting point of 110°C.

Balaguera et al. [55] focused on the application of LCA in road construction as a tool to quantify the potential impacts derived from the use of traditional and alternative materials. The research showed that the most common materials found were recycled asphalt (concrete and bitumen), fly ash, and polymer. In addition, the environmental impact categories more commonly assessed were energy consumption and Global worming potential (GWP). It has been found that the most representative advantage of the materials analyzed is that they reduce the environmental impact by avoiding disposal in landfill.

Turk et al. [56] investigated by means of LCA two alternative road pavement rehabilitation techniques, a hypothetically defined comparable traditional approach and an actually used cold-in-place-recycling approach, both of which enable a comparable extension of road service life of about 20 years. The scenarios differ in terms of the processes involved in the performance of earthworks, whereas asphalt placing (i.e. placing of the asphalt base and wearing courses) takes place in exactly the same way, so it can be assumed that the same equipment and construction techniques are used for these works. Recycling can reduce environmental impacts by around 15-18% with regard to Acidification potential (AP) and Abiotic Depletion of Fossil Fuels, as well as energy consumption. However, with regard to GWP, recycling does not show any benefit. The “worst case” cold-in-place-recycling approach would occur in the case of the use of Portland cement with a relatively high clinker content.

Farina et al. [57] focused on LCA of different types of road paving technologies based on the use of bituminous mixtures containing recycled materials such as crumb rubber from end-of-life tires and RAP. Analyses were carried out by considering different scenarios, which stem from the combination of production, construction and maintenance operations, and by comparing them with a reference case involving use of standard paving materials. Results show that use of wearing courses containing asphalt rubber produced by means of the wet technology can lead to significant benefits in terms of energy saving, environmental impact, human health, preservation of ecosystems and minimization of resource depletion. The above mentioned benefits are only slightly increased by employing RAP in partial substitution of virgin aggregates and are guaranteed only if mixtures are properly designed and laid, with the corresponding possibility of reducing surface course thickness and maintenance frequency.

Li et al. [58] analyzed the contribution of each process in the transportation project life cycle based on an environmental impact assessment (EIA) model. The empirical results show that the construction phase has the highest environmental impact (62.7%) in the fast track transportation project life cycle, followed by the demolition (35.8%) and maintenance phases (1.7%).

In conclusion, the studies through LCA have demonstrated that the introduction of alternative materials and/or the application of new technology at low temperatures for pavement layers improve the environmental performances compared to traditional one.

4.4 Literature gap

Through the analysis of the literature in the road sector, it was possible to identify some missing aspects both from a material and technological point of view.

First of all, among the many alternative materials that have been investigated by researchers as substitutes for raw materials that are to be preserved in nature, it has been found that the reuse of jet grouting has not yet been investigated either for a study of hot bituminous mixtures or for cold bituminous mixtures.

Through the cold bituminous mixtures investigation it was assumed that at 28th day of curing time the complete maturation takes place and in particular the maximum stiffness of the mixtures is achieved, but the questions that arise are the following: 1) Are the performances reached at 28th day equal than those of a traditional hot mix? 2) Is there the possibility of introducing a material that allows to reduce the curing times to achieve the same mechanical performance of a traditional hot bituminous mixture?

Investigations on the reuse of alternative materials for bitumen blends, in particular for the reuse of plastic materials, have highlighted with the increase in mechanical performance the modification effect of the bitumen due to the introduction of plastic waste. Also in this case, questions arise: a) Is it right to think about increasing the bitumen blending temperatures to ensure the increase in mechanical performance through the modification effect? 2) Is there the possibility of introducing a quantity of plastic waste such as to obtain the same performance of a modified bitumen, blending the bitumen at its traditional temperatures considering the plastic as a filler and not a bitumen mdifier? 3) With a view to the introduction of HMA, is it possible to reduce the amount of bitumen whose benefits derive from the introduction of the interaction of plastic with bitumen?

The LCAs conducted to date have been based on data deriving from scientific literature studies, from the application of calculation software and not specific to the analyzed context. To date, a study is lacking whose attention is focused on the specific case, analyzing the real components of the process and in particular the specifications of the site under analysis.

5 The bituminous mixture

The bituminous mixture are composite materials obtained by mixing aggregates, bituminous binder, filler and any additives. The most common field of use of bituminous mixture is by far that of flexible or semi-rigid pavements, where the mixtures have different characteristics in relation to the layer of pavement they are intended for (base, binder and wearing course), this in terms of composition, volumetric characteristics and mechanical properties.

5.1 Composition

The main aspects related to the composition concern the granulometric mixture of aggregates and the binder dosage.

The aggregates mixture must comply with appropriate dimensional limits in order to fit within a particle fused grain, defined on the basis of an optimal distribution curve and predefined tolerances. In the traditional materials, reference is generally made to Fuller's formulation, according to which the maximum density curve of the aggregates is obtained from the following Equation 1:

$$P = 100\left(\frac{d}{D}\right)^{n} \tag{1}$$

where:

- P is the percentage of passing corresponding to dimension d
- D is the maximum size of the aggregate
- n is a constant.

In the formulation for bituminous mixtures the FHWA (Federal Highway Administration) suggests a value of n equal to 0.45, while the maximum size of the aggregate increases for the base layers (which corresponds to a coarser assortment) and values gradually decreasing for the higher ones, characterized by a finer assortment. In the SUPERPAVE system, the granulometric limits are indicated by the control points and the sand restriction zone. The control points were obtained experimentally with respect to the maximum density line and established as a function of the maximum and minimum nominal size.

The filler constitutes a particular category of aggregate since, due to its dimensional characteristics, it not only affects the granulometry of a mixture but also directly interacts with the other components (binder). The mineral fraction passing through the 0.063mm sieve is defined as filler. It can come from the finest part of the aggregates or it can be made up of rock dust, preferably limestone, cement, hydrated lime, hydraulic lime, asphalt dust, fly ash. The filler is added to the aggregate mixture to correct the granulometric curve in its lower part and/or to fill the intergranular voids left free by the larger elements. In the case of bituminous mixtures, it also mixes with the bitumen to form the so-called bituminous mastic, whose rheological properties have a considerable effect on those of the overall mixtures.

Furthermore, the particle size also influences the second parameter, that is the bitumen content, generally expressed as a percentage value with respect to the weight of the aggregates, although in the most recent European regulations reference is made to the total mass of the mixture (EN 13108-1). The optimal quantity must be such as to cover the overall surface of all the particles with a binding film of adequate thickness; each type of aggregate is characterized by its own specific surface which, in principle, increases as its average size decreases. The determination of the effective dosage is done through the mix design procedure.

5.2 Volumetric characteristics

Most of the performance properties of bituminous mixtures are directly influenced by their internal conformation, which can be expressed in terms of volumetric and weight ratios between the different component phases: solid (aggregates), semi-solid or binder (bitumen) and gaseous (air). Referring to Figure 5.1, the structure of the mixture is given by the grouping of spheroidal particles, in which the smaller elements progressively occupy the spaces left free by the larger ones. Each stone element is covered by the bond: the latter partially penetrates inside the surface porosity permeable to water (and so-called absorbed bitumen) while the remaining portion forms a thin covering film (effective bitumen). The final voids of the mixture are given by the intergranular volume occupied by the air.

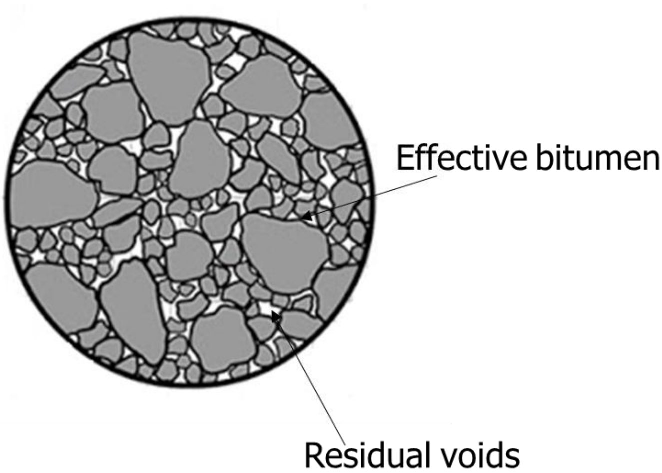


Figure 5.1 Internal composition of a bituminous mixture

Considering a generic portion of mixture in the compacted state of volume V and mass M, this can ideally be decomposed according to the diagram of Figure 5.2, associating to each component phase the corresponding volume and mass values. It should be noted that the actual volume of the aggregate (indicated with VG) partially overlaps with the quantity VBA, which represents the part of absorbed bitumen.

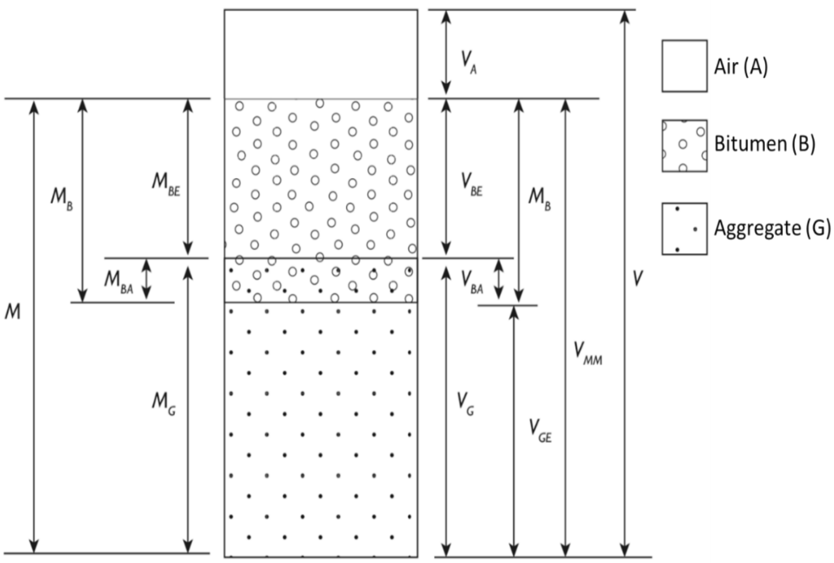


Figure 5.2 Relation between weight and volume inside the bituminous mixture

5.2.1 Density

The most common measurement procedure to evaluate the density (MV) consists in subjecting a sample (packaged in the laboratory or extracted from the pavement by coring) to three different determinations by evaluating respectively the mass in air after drying (MD), the mass in water under saturation conditions (MW), the mass in air under saturated dry surface conditions (MSSD). We have:

$$MV = \frac{M_D}{M_{SSD} - M_W} \cdot \rho_{w,T} \tag{2}$$

where $\rho_{w,T}$ is the density of water at the test temperature T, defined by the following Equation 3 [59]:

$$\rho_{w,T} = 1.00016584 - 0.000793 \cdot T - 0.00000529 \cdot T^2 \tag{3}$$

5.2.2 Maximum theoretical density

The maximum theoretical density (MMVT) is the limit value of the density in a condition of zero voids, defined as:

$$\mathrm{MMVT} = \frac{\mathrm{M}}{\mathrm{V_{MM}}} = \frac{\mathrm{M}}{\mathrm{V_G} + \mathrm{V_{BE}}} \tag{4}$$

which represents an intrinsic quantity of the mixture, independent of the compaction level to which it is applied, is determined with the pycnometer method on a sample in the dissolved state; the calculation formula is as follows:

$$\mathrm{MMVT} = \frac{\mathrm{M_D}}{(\mathrm{M_D} + \mathrm{M_{Pw}}) - \mathrm{M_{PGW}}} \cdot \rho_{\mathrm{w,T}} \tag{5}$$

where MD is the mass of the sample in air, $\mathrm{M_{Pw}}$ is the mass of the pycnometer filled with water (value known from the calibration curve), $\mathrm{M_{PGW}}$ is the mass of the pycnometer containing the sample and filled with water, $\rho_{\mathrm{w,T}}$ is the density of water at the temperature at which is being measured.

5.2.3 Percentage of voids

In general, for a generic mixture of the traditional type it is possible to identify an optimal void range within which it manifests a mechanical response that reconciles two opposite behaviors: an excessive increase in porosity, in fact, makes the mixture less durable than the action of water is subject to a faster fatigue breaking process, while in the opposite case a tendency to accumulate plastic deformations can be determined, which reduces the resistance towards rutting.

The percentage of voids (v) is determined starting from the previous quantities with the Equation 6:

$$v = 100 \cdot \left(1 - \frac{MV}{MMVT}\right) \tag{6}$$

5.2.4 Binder content

The binder content (P_B) is expressed in terms of weight percentages and, as previously mentioned, it can refer both to the mass of the aggregates and to the total mass of the mixture as shown by the Equation 7.

$$P_B = 100 \frac{M_B}{M_G} \tag{7}$$

5.3 Mechanical properties

The mechanical characterization of bituminous mixtures concerns the measurement and analysis of fundamental properties such as stiffness and resistance to the main mechanisms of failure and degradation. Although in common calculation models reference is made to the hypothesis of linear elasticity, the bituminous mixtures exhibit a much more complex behavior, given by the combination of elastic, viscous and plastic components. The evaluation of the mechanical response parameters, therefore, to be used for the optimal size of the layers of the pavement, in the mix design or even for control purposes, must take place by imposing load and temperature conditions that are representative of the service ones and linked to the actual performance on site.

5.3.1 Indirect tensile strength

The indirect tensile configuration is used for classical failure tests, obtaining a corresponding mechanical parameter called indirect tensile strength (ITS). This type of test involves the use of cylindrical specimens loaded along the entire thickness with a vertical force that develops normal compression stresses in the horizontal diametrical plane and normal tensile stresses in the vertical one.

The specimens are positioned between two strips while a piston applies a compressive load along a coaxial vertical diameter plane. With a polar coordinate system, it is possible to calculate the energy at any point but in particular we are interested in the maximum or the center of the specimen. The break occurs through a crack that runs diametrically to the specimen along the same direction of application of the load; this is a consequence of the tensile stresses generated in it that exceed the characteristic limit value of the material (EN 12697-23).

Having said P the maximum load and known the dimensions of the sample (diameter d and height t), the resistance ITS is obtained from the formula (in the hypothesis of homogeneous and isotropic material):

$$ITS = \sigma_t = \frac{2 \cdot P}{\pi \cdot d \cdot t} \tag{8}$$

This test can be used for different purposes, depending on the conditions in which it is performed. At low temperatures it allows to characterize the bituminous mixtures with regard to cracking of thermal origin and to derive the tensile strength parameters to be included in the analysis models (thermal cracking analysis). At higher temperatures (25°C) it is instead used to assess the susceptibility to water of bituminous mixtures or for control purposes (in the mix design and in the execution phase).

5.3.2 Stiffness

The characterization of the mixtures needs an additional parameter to represent the mechanical response of the material. The bituminous mixtures have a viscoelastic/viscoplastic behavior and everything depends on the time of application of the load and on the operating temperature.

The quantity that links the stresses and strains measured under dynamic conditions is the complex modulus E*.

The complex modulus E* is defined as the ratio between the sinusoidal stress with pulsation ω applied to the material $\sigma(t) = \sigma_0 \sin(\omega t)$ and the sinusoidal strain $\varepsilon(t) = \varepsilon_0 \sin(\omega t - \varphi(\omega, \theta))$ resulting from this (see Figure 5.3).

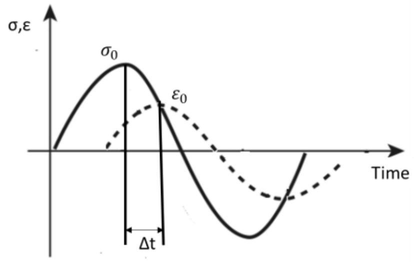


Figure 5.3 Stress-strain relation of a bituminous mixture

In complex notation:

$$\sigma(t) = Im(\sigma^*) \qquad \text{with} \quad \sigma^* = \sigma_0 e^{\omega t} \tag{9}$$

$$\varepsilon(t) = Im(\varepsilon^*) \qquad \text{with} \quad \varepsilon^* = \varepsilon_0 e^{i(\omega t - \varphi)} \tag{10}$$

$$E^*(\omega, \vartheta) = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} e^{i\varphi} \tag{11}$$

It can be noted that the definition of the complex modulus allows us to extend the laws valid for linear elastic materials to linear viscoelastic materials in the frequency domain.

$$E = \frac{\sigma(t)}{\varepsilon(t)} \tag{12}$$

The norm of the complex modulus also called stiffness modulus is equal to:

$$|E^*| = \left(\frac{\sigma_0}{\varepsilon_0}\right) \tag{13}$$

The complex modulus is therefore defined by its norm and its phase angle:

$$E^* = |E^*| \cdot e^{i\varphi} \tag{14}$$

But in the same way also from its real part E_1 and its imaginary part E_2:

$$E^* = E_1 + iE_2 \tag{15}$$

To characterize the stiffness of bituminous mixtures the dynamic modulus test is performed according to EN 12697-26- Annex C under a load with a haversine waveform. This method measures the resilient stiffness of bituminous mixtures using an indirect tensile test. The method is applicable to cylindrical specimens of various diameters and thickness, manufactured in the laboratory or cored from a road layer. In Figure 5.4 is reported an example of test equipment.

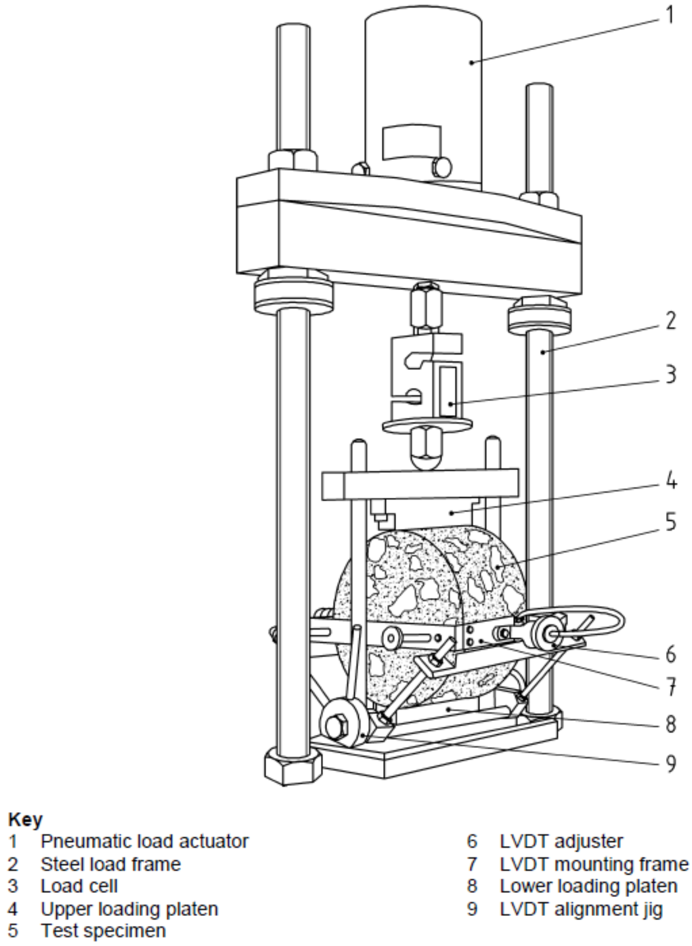


Figure 5.4 Stiffness equipment by EN 12697-26

The measured stiffness modulus is determined using the following Equation 16:

$$E = \frac{F \cdot (\nu + 0.27)}{(z \cdot h)} \tag{16}$$

where

- E is the measured stiffness modulus, MPa
- F is the peak value of the applied vertical load, N
- z is the amplitude of the horizontal deformation obtained during the load cycle, mm
- h is the mean thickness of the specimen, mm
- ν is the Poisson’s ratio, equals 0.35

5.3.3 Rutting

The rut is a deterioration characterized by the formation of ruts or longitudinal depressions (punching of the pavement) on the road surface accompanied by lifting on the sides. What is formed by the repeated passage of vehicles is a progressive thickening under the layer and a reflux at the sides. Here are the so-called ruts. The main cause is the continuous passage of vehicles and therefore traffic. At a temperature of 40°C we no longer speak of damage accumulation but of accumulation of permanent, non-recoverable viscous-plastic deformations. In this case the stone skeleton is dominant even if it is affected by bitumen type very much. To be able to counter this effect, a low bitumen content must be obtained.

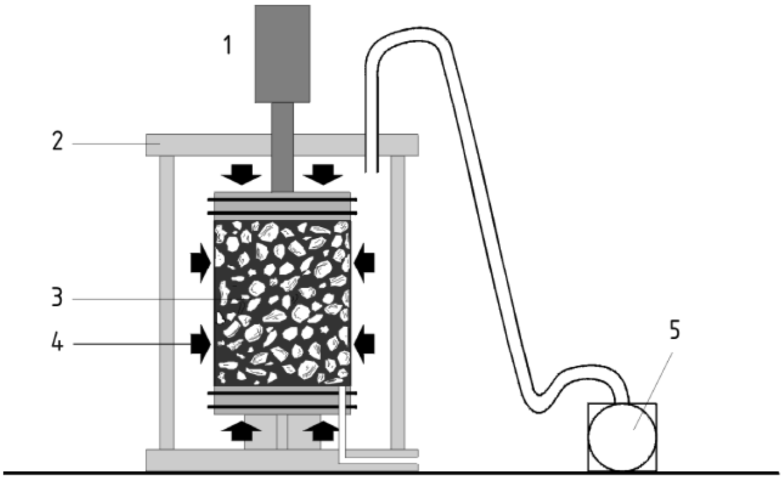
The rutting study is carried out following two approaches based respectively on the use of continuous regime tests (creep) and simulation tests.

In the creep tests, a cylindrical specimen is loaded in an axial configuration with a given vertical normal tension kept constant for a certain time and the corresponding vertical deformations undergone are measured. The relationship between deformation and tension defines the deformability (creep compliance) (see Equation 17):

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} \tag{17}$$

For the purposes of the rheological characterization of the material, in addition to the response in the creep phase, it is also interesting to analyze its behavior in the release phase (recovery), ie after the removal of the vertical pressure. In this case, a shorter load application time is adopted, followed by a sufficiently prolonged rest period in order to allow the complete recovery of the deferred deformation.

A variant of the creep tests is represented by the RLA (Repeated Load Axial) tests, so-called dynamic creep tests, based on the succession of loading-unloading cycles (creep-recovery) with confinement each with a predefined duration (EN 12697-25). In Figure 5.5 is reported a schematic representation of a triaxial cyclic compression test device with pressure cell.



Key

1 Actuator for dynamic pressure
2 Pressure cell
3 Specimen
4 Confining pressure
5 Compressor

Figure 5.5 Triaxial compression test equipment by EN 12697-25

The test is performed at the temperatures above 40°C with a haversinusoidal pressure $\sigma_a(t)$ calculated according the following Equation 18:

$$\sigma_C + \sigma_a(t) = \sigma_C + \sigma_V \cdot (1 + \sin(2\pi \cdot f \cdot t)) \tag{18}$$

where

- σ_C is the confining stress (all around the specimen), kPa
- $\sigma_a(t)$ is the cyclic axial pressure as a function of time, kPa
- σ_V is the amplitude of the haversinusoidal pressure, kPa
- f is the frequency, Hz
- t is the time

5.4 Cold bituminous mixtures

Since road maintenance involves the removal of damaged layers and the accumulation of the resulting milled material, the cold recycling technique has become an increasingly used alternative in the redevelopment of road pavements as it minimizes the economic and environmental burdens by producing materials of high performance characteristics. Recycling carried out with cold techniques allows in fact to obtain a considerable series of advantages [7]:

- limited exploitation of environmental resources due to the reduction in the mining of aggregates
- greater profitability, being guaranteed the same duration as paving with virgin materials
- energy saving as it is not necessary to heat the aggregates and, in the case of on-site recycling, to transport the material to and from the site
- reduction of emissions into the atmosphere of fumes, dusts and gases produced by the fuel burned in heating and transport.

A wide range of aggregates (natural or recycled) can be used in cold recycling, not only large quantities of bituminous mixture milled material (up to 100% of the mass of stone aggregates), but also any granular material of the old road foundations as well as recycled materials from the construction sector. Cold recycling can be carried out on site using stabilizing machines, or in the plant, fixed or mobile, to be positioned near the construction site.

5.4.1 Cold in place recycling

Cold in place recycling can involve layers of different materials and thicknesses. In deep renovations, after removing the thickness corresponding to the layer of the new hot bituminous mixture, the crushing, mixing and stabilization of the underlying bonded layers and a part of the unbound layers of the old pavement are carried out. In surface interventions, only the layers bonded to bitumen or part of them can be recovered, for much smaller depths. Compared to that in the plant, it avoids the handling and storage of the material recovered from the pavements to be redeveloped. This determines important advantages of different nature:

- a reduced duration of the intervention thanks to the elimination of some intermediate stages of processing and the high productivity of modern recyclers
- a lower risk of accidents due to the shorter exposure time, the fewer vehicles involved and thanks to the elimination of many movements within the construction site and the road network involved
- a lower construction cost
- less inconvenience for users.

5.4.2 The legislative framework on the reclaimed asphalt pavement (RAP)

The first step that concern the reemployment of RAP is to follow the general technical provide by the Environmental Ministerial Decree of 5 February 1998 for the recovery of material from non-hazardous waste.
In the Annex 1 of the decree are reported specific descriptions of the waste under exam, in particular for the RAP as follows:

- **Type**: bituminous mixture, CER code [170302].
- **Origin**: road surface scarification by cold milling.
- **Characteristics of the waste**: solid waste consisting of bitumen and aggregates.
- **Recovery activities**:
    a) hot and cold production of "virgin" bituminous conglomerate [R5];
    b) construction of embankments and road foundations (recovery is subject to the execution of the transfer test on the waste as is according to the method in annex 3 to this decree) [R5].
    c) production of material for road construction and industrial yards by preventive selection (grinding, rindling, separation of unwanted fractions, possible mixing with virgin inert material) with eluate compliant with the release test according to the method in annex 3 to this decree [R5]
- Characteristics of the raw materials and/or products obtained:
    a) bituminous conglomerate in the forms usually marketed
    b) construction materials in the forms usually marketed.

The technical specification **UNI/TS 11688** defines the qualification and use criteria of the recovery bituminous mixtures derived from the removal of existing pavements (so-called reclaimed asphalt pavement, RAP).
The technical specification has the purpose of characterizing the RAP in order to encourage its reuse in the same production chain, in compliance with the requirements on environmental protection, ensuring the technical performance of the products. In particular the standard requires that the bituminous mixture coming from the maintenance activities of flexible pavement, through a removal process is reused in the same construction chain as a material constituting other products or as a material reused directly, possibly subjected to normal industrial practices aimed exclusively at improving the geometric characteristics. To a minimum extent, the recovery bituminous mixture can

also come from the production process of the bituminous mixture and from the process of installation as waste or scrap.

The bituminous mixture can be reused directly or subjected to normal mechanical processes, where necessary, which modify its dimensional characteristics while leaving the physical and chemical characteristics unaltered.

The RAP can therefore be used as it is or subjected to subsequent processing to obtain granulate.

The applicable technologies are mainly two: milling and scarifying.

For the purposes of the Technical Specification, the use of recovery RAP in hot and cold bituminous mixtures, for in situ process, or as a component of recycled aggregates is considered.

Regardless of the purpose of use, the technical characteristics of the RAP deposited in the heap are determined by the producer, who must distinguish the heaps by homogeneous characteristics.

The procedures for determining the technical characteristics are defined in **EN 13108-8**, to which reference is already made for the correct characterization of the RAP, as required by the product standards of HMA.

An important role is played by the producer, who defines the responsibility, the authority and the interrelation between all the personnel assigned to the management, execution and control of the activities, including any activities outsourced.

The authority must be applied for:

a) Carry out checks in the various stages of production;
b) Initiate actions to prevent the occurrence of non-compliance;
c) Identify, record and intervene in the event of any deviations from the expected requirements.

In the case of outsourced activities, the manufacturer establishes an appropriate control method, maintaining general responsibility for the entire process.

The control of documents and data must include all documentation and data deemed important according to the requirements of the standard.

The production control of the RAP includes the following requirements:

a) Procedures for the identification and control of incoming lots and related heaps
b) Procedures to ensure that the material is identified and accumulated in uniquely defined areas
c) Production procedures aimed at ensuring compliance with the requirements defined by the manufacturer in the case of processed recovery bituminous conglomerate
d) Procedures to ensure that the material taken from the heaps is not altered in such a way as to compromise its characteristics

e) Procedures aimed at guaranteeing the functioning of the equipment and means used, including the execution of maintenance activities.

Proceedings must be defined and documented. Any anomalies found on the production control implemented are analyzed by the person in charge who, based on the severity of the anomaly, takes the appropriate corrective actions.
The producer of the recovery bituminous mixture is required to draw up and keep for 10 years the technical data sheets of origin and identification of the single incoming lots, as well as any additional documentation. The manufacturer takes all the necessary measures to maintain the characteristics of the materials at all stages, from entry into the plant to use or its delivery to third parties.
The measures are aimed at preventing:

- Contamination of the recovery bituminous conglomerate with foreign substances or materials
- The mixing of recovery bituminous conglomerates with non-homogeneous characteristics.

The storage areas must be clean and free of impurities, also separated with solid elements, fixed or mobile, to ensure the integrity of the heaps. Each area is distinguished by adequate signs relating to the type of material in storage.
The construction site machinery used for handling the materials are kept in conditions of efficiency and cleanliness, to avoid contamination and potential mixing.

The European standard **EN 13108-8** specifies the requirements for the classification and description of the recovery bituminous mixture constituting the bituminous mixtures, favouring their enhancement and extension of the useful life cycle. It aims to define the management methods of the recovery bituminous mixture in order to encourage its correct use in road construction and ensure the technical performance of the products obtained.

Reclaimed asphalt shall be designated by the abbreviation RA, preceded by the asphalt particle size designation U and followed by the aggregate size designation d/D mm, where d and D are respectively the lower and upper sieve sizes.

5.4.3 The study of the mixture

The mix design of the blends includes the following phases [59]:

a) determination of the granulometric composition of the mixture of aggregates
b) determination of the water content
c) determination of the type of binder (depending on the "prevalent" intended use)

d) determination of the dosage of the binder

a) The granulometric composition of the aggregate's mixtures: In the study of the mixture, the samples of the aggregates (milled bituminous mixture and any part of the underlying foundation) for the study of the mixture must be taken on site, immediately after a passage of the stabilizing machine (pulvimixer) without the laying of the binders. We operate in this way to take into due account the action of the mixing rotor which tends to shell the lumps of the milled product, especially those of larger size. At the plant, samples of the various particle size fractions obtained from the rindling of the RAP are taken and the percentages of use are identified (as for hot bituminous mixtures). The particle size analysis must be performed wet. Small or large lumps are considered as single granules and do not significantly affect the workability and performance of the final mix. For this reason, it has little interest, other than to ascertain the entity of the lumps, to perform the particle size analysis on the aggregates extracted from the milled bituminous mixture. Very often, especially in on-site mixing, it is necessary to integrate the recycled aggregates with virgin material. The correction of the granulometric curve sometimes concerns the coarse fraction, when the milled material comes from the demolition of surface layers (binder and wearing course), almost always the fine fraction and the filler which, although present in abundance in the original bituminous mixture, are scarce in the milled material because remain embedded in the bitumen. The lack of large aggregates does not significantly affect the characteristics of the final mixture as opposed to what happens with the lack of fine which strongly penalizes all the mechanical characteristics.

b) The water content: Water is a fundamental component of the mixture and must be properly dosed to facilitate compaction. It is normally already present in the wet grout and can be added to it before mixing. The total calculation must take into account that contained in the bituminous emulsion. For the determination of the optimal water content, samples are initially prepared by removing the coarser elements from the aggregates (held in a 20 mm sieve) by adding a fixed dosage of cement (2% by weight with respect to the aggregates) and different water contents, generally between 3 and 8%.

c) The type of binder: The binders that can be used are:

– over-stabilized emulsion of normal bitumen
– over-stabilized emulsion of modified bitumen
– foamed bitumen
– Portland cement.

The choice of binders and their dosage vary in relation to the type of mixture to be obtained, the availability and local uses and its prevalent distinct destination in the following three types of materials that can be used in the maintenance and construction of road pavements:

1. Cold mixes generally intended for the base layer
2. Stabilized mix with cement and bitumen for foundation layers
3. Mixed with cement portland.

Stabilization with cement and bitumen (in the form of foam or emulsion) allows to obtain a less rigid and more durable layer, intermediate between the cement mixture and the hot bituminous mixture, tending to combine the qualities of the two binders (cement and bitumen) in order to obtain the strength and lift properties typical of cemented mixes without compromising the fatigue performance. By acting on the bitumen and cement dosage, it is possible to control the stiffness of the mixture and the susceptibility to temperature, orienting its rheological behavior towards that of the cemented mixture or bituminous mixture. Emulsion and bitumen foam bind differently to the lithic skeleton due to the consistency of the binder which conditions its dispersion within the mixture. The foamed bitumen tends to incorporate the fine fraction forming a bituminous mortar which gives rise to punctual bonds with the coarse fraction. When the mixture of aggregates lacks the fine part, the foamed bitumen does not disperse adequately and tends to form the so-called “veins” (agglomerations of fine material rich in bitumen).

A strong lack of fines produces many large veins that act as lubricated sliding surfaces within the mixture, thus reducing its strength and stability. The bituminous emulsion is able to guarantee a greater dispersion and a more widespread coating on both the fine and coarse fractions. With foamed bitumen or emulsion it is possible to obtain mixtures which, in the long term, have very similar mechanical and performance characteristics. However, it has been observed that with the bituminous emulsion longer curing times are required and therefore lower characteristics in the short term. If the bitumen content (foam or emulsion) is low, the larger grains are not completely coated and the cement can stick to uncovered surfaces, creating rigid and brittle bonds. Under these conditions, as the cement content increases, the module tends to grow. When there is the right amount of bitumen and a good balance between the two components, there are no large variations in stiffness as the cement content increases. In conditions of abundance of bitumen, the structure is more deformable and flexible while the stiffness decreases. In these conditions the cement assumes the main function of filler and its increase increases the viscosity of the bitumen and, all other conditions being equal, makes it recover stiff. Compared to foamed bitumen, the use of emulsion offers some advantages both from a technical point of view and from a safety on site. In fact, it does not require heating of the binder, avoiding risks for the workers and greater flexibility in the management of waiting times before mixing; furthermore, with foamed bitumen, any considerably low temperature of the bitumen (below 160°C), whatever the cause, at any time, involves the rejection of the binder and therefore the return of the tanker (even partially used) to the place of loading. The over-stabilized emulsion, thanks to the very long breaking times, also allows you to manage the levelling and compacting phases with a greater time margin without compromising the success of the treatment. For the production of cold mixtures for base layers, both in the plant and on site, a modified bituminous emulsion is used and not necessarily the cement which in this case does not have a binding function. The stone aggregates consist almost entirely of recycled bituminous mixture, except for a small integration of virgin material (maximum 15-20%) for the possible correction of the granulometric curve. The use of modified bituminous emulsion and the generally higher dosage, compared to that of the stabilizations seen above, allow to obtain performance characteristics similar to those of traditional hot packaged bituminous mixtures. In the cement mix, the milled bituminous mixture must in any case be integrated with first use and / or recycled aggregates not coated with bitumen, both to carry out the granulometric correction and to guarantee the required mechanical performance. The presence of milled material produces a weakening of the mechanical characteristics for the same dosage of cement.

e) The dosage of the binder: In cold recycling, the bitumen present in the recovered aggregate does not seem to particularly affect the properties of the final binder and, therefore, its rheological characterization is not carried out. In this sense, the recovery mixture is considered only as a stone aggregate. To define the dosage of the binders, samples with different dosages of cement and foamed bitumen, or bituminous emulsion (normal over-stabilized or modified bitumen) are then prepared with the same compaction procedure and with the optimum water content. After a maturation period of 72 hours at 40°C, the indirect tensile strength and the loss of strength are determined after soaking for 1 hour (both mechanical tests and immersion in water are carried out at 25°C). The requirements are a strength greater than 0.35 MPa and a strength loss of less than 70%. Generally, the indirect tensile stiffness modulus (ITSM) at 20°C is then determined.

6 The bituminous mastics

To complete the understanding of the behavior of bituminous mixtures, it must be remembered that they contain mineral particles, made up of filler, which are included within the bitumen films, altering their mechanical properties. It follows that the schematization of the composition of a bituminous mixture closest to reality is that refers to a mastic, consisting of bitumen and filler, which binds the coarse aggregates and sand together, influencing the stress-deformation and breaking properties of the composite material.

The filler constitutes a particular category of aggregate since, due to its dimensional characteristics, it not only affects the particle size of a mixture but also directly interacts with the other components (binder). On bases of percentage passing by mass definite in EN 13043 (see Table 6.1) the mineral fraction is defined as filler. It can come from the finest part of the aggregates or it can consist of aggregate dust, preferably limestone, cement, hydrated lime, hydraulic lime, recycled asphalt and fly ash. The filler is added to the aggregate mixture to correct the granulometric curve in its lower part and/or to fill the intergranular voids left free by the larger elements. In the case of bituminous mixtures, it also mixes with the bitumen to form the so-called bituminous mastic, whose rheological properties have a considerable effect on those of the overall mixtures.

Table 6.1 Grading requirements for filler definition

Sieve size	Percentage passing by mass	
mm	Overall range for individual results	Producer's maximum declared grading range 1)
2	100	-
0.125	85 to 100	10
0.063	70 to 100	10

1) Declared grading range on the basis of the last 20 values (see prEn FPC). 90% of the results declared shall be within this range, but all the results shall be within the overall grading range

The theoretical source on which the rheological tests are based, is the concept of viscoelasticity. The study of rheological properties plays a fundamental role to understand the performance of binders and bituminous mastics; a binder that under the application of a load shows high deformations could generate rutting phenomena in the mixture, on the contrary a very stiff bitumen could give the pavement greater sensitivity to fatigue.

The analysis of the rheological behaviour of bituminous mastics is carried out using a Dynamic Shear Rheometer (DSR) which operates in an oscillatory regime to applying the most common test as the Viscosity test, the Frequency Sweep (FS) test that allows to evaluate the Shear modulus (G*), the Storage modulus (G'), the Loss modulus (G'') and Phase angle (δ), and the Multiple Stress Creep and Recovery (MSCR) to assess the Non recoverable creep compliance (J_{nr}) and Total creep compliance (J_{tot}).

6.1 Viscosity

A generic material, if subjected to a constant shear stress "τ" reveals a deformation "γ" variable in time. Its viscosity "η" (also called dynamic viscosity) is defined by the following Equation 19:

$$\eta = \frac{\tau}{d\gamma/dt} \tag{19}$$

where $d\gamma/dt$ is the value of the strain gradient and represents the flow velocity.

Like the other properties, the viscosity of bitumen varies considerably with its thermal state. Above a certain value of the temperature T, the link between tension and strain gradient as reported by Equation 19 is linear and corresponds to the Newtonian hypotheses, with η constant and independent of the two variables τ and $d\gamma$.

Under these conditions, the variation of viscosity as a function of T can be described by the Arrhenius law, as follows:

$$\eta = A \cdot e^{-\frac{B}{T}} \tag{20}$$

where A and B are constant that depend on the materials.

The condition of fluidity represents the necessary prerequisite for proceeding with the mixing of the bitumen with the aggregates during the production of the bituminous mixture. In fact, partial coverage must be guaranteed, which could affect the binding action. The optimal mixing temperature therefore corresponds to a predefined viscosity value which is a typical quantity that distinguishes each binder and which must be determined in its performance characterization phase.

As the temperature decreases, in addition to an increase in the absolute value of viscosity, there is also a progressive transition towards a non-linearity regime, where n is no longer constant but depends on the applied tension or deformation gradient.
Below a certain threshold, then, the material is no longer able to flow (at least under ordinary conditions) and its response can be associated with that of a visco-elastic solid. among the different types of non-Newtonian behavior that can be found (see Figure 6.1), bitumen generally falls into the category of pseudo-plastic materials. In this case the law of dependence of the deformation gradient can be expressed by means of the Cross model, as follows [59]:

$$\frac{\eta-\eta_0}{\eta-\eta_\infty} = \left(k\frac{d\gamma}{dt}\right)^m \tag{21}$$

where:

- η_0 represents a limit value of viscosity corresponding to a deformation gradient tending to zero and called zero shear viscosity
- η_∞ corresponds to the limit value of viscosity for high flow velocities
- k is a time-dependent experimental parameter
- m is a dimensionless constant

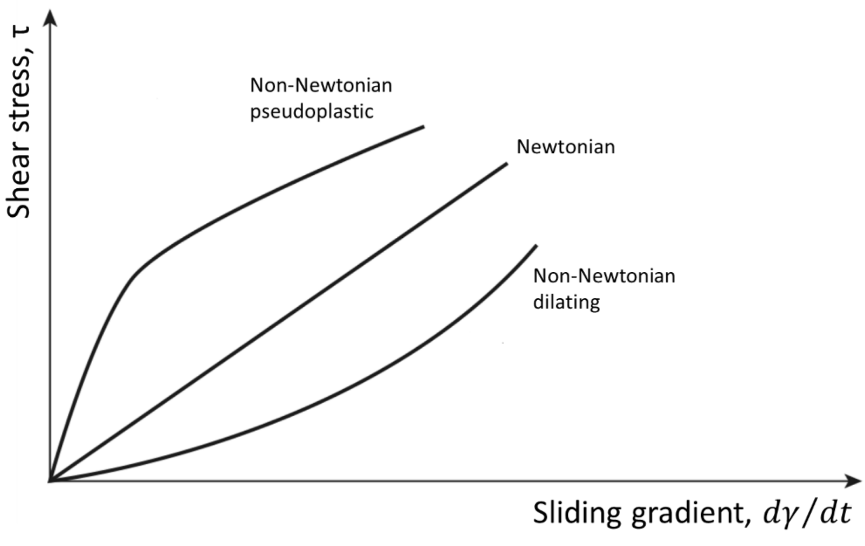


Figure 6.1 Newtonian and non-Newtonian behaviour

The EN 13702 specifies a method for determining the dynamic viscosity of a bituminous binder over a range of temperatures by means of a cone and plate viscometer.
In the standard are reported the shear rates suggested in function of different test temperatures as follows:

- For test temperature of (60.0±0.5)°C it is suggested to adopted a shear rate of $5x10^{-2}s^{-1}$
- For test temperature of (100.0±0.5)°C it is suggested to adopted a shear rate of $5x10s^{-1}$
- For test temperature of (150.0±0.5)°C it is suggested to adopted a shear rate of $5x10^{2}s^{-1}$

6.2 Shear modulus and phase angle

In the oscillatory regime, the rheological properties of the material subject to cyclic stresses are analysed, a situation that simulates better the effects related to traffic. The forcing generally varies with a sinusoidal law expressed by the Equation 22 characterized by a pulsation ω and an amplitude τ_0:

$$\tau(t) = \tau_0 \sin(\omega t) \tag{22}$$

The corresponding response is also of the sinusoidal type as expressed by the Equation 23

$$\gamma(t) = \gamma_0 \sin(\omega t + \delta) \tag{23}$$

but out of phase with respect to the forcing by a quantity δ, called phase angle. This parameter expresses a measure of the degree of elasticity of the bituminous mastic and varies, by definition, in the interval [0-π / 2]. The lower end of the interval corresponds to a response in phase with the forcing and is therefore associated with the hypothesis of an elastic solid. Conversely, the upper extreme corresponds to a phase opposition response with respect to the forcing, which can be associated with the hypothesis of viscous fluid.

The operating principle of the DSR provides, under controlled temperature conditions, that a stressing torque T variable over time is applied to a sample of material having axial symmetry, according to a predefined law; correspondingly, the angular rotations Θ undergone by the sample itself are measured. The determination of the properties of the material (|G*|, G’, G", δ) takes place using a relationship that links the torque to the relative angular velocity or rotation and tracing from these to the tangential stresses and strains τ and γ (see Figure 6.2).

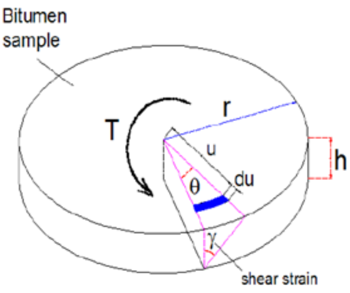


Figure 6.2 Schematic representation of bitumen sample for evaluating G*and δ

The complex shear modulus G* is calculated as follows:

$$G^* = \frac{\tau_{max}}{\gamma_{max}} \tag{24}$$

where :

- τ_{max} is the maximum value of the shear stress calculated according to Equation 25

$$\tau_{max} = \frac{T \cdot r}{I} \tag{25}$$

where:

- T is the maximum torque applied
- $I = \int_0^r u^2 dA$ =Moment of inertia

where

- u is the speed of the torque
- r is the radius of the specimen (either 12.5 or 4 mm)

$$\gamma = \frac{u}{h}\theta \rightarrow \gamma_{max} = \frac{r}{h}\theta \tag{26}$$

where

- γ is the shear strain
- h is the specimen height (either 1 or 2 mm)
- γ_{max} is the maximum value of the shear strain
- θ is the rotation angle

The parameters G* and δ are linked according to the following Equation 27:

$$G^*(\omega) = G' + iG'' = G^* \cos\delta + iG^* \sin\delta \tag{27}$$

For very high temperatures and very low frequencies (viscous limit), the Equation 24 is reduced to:

$$G^* \sin\frac{\pi}{2} = G^* = G'' \tag{28}$$

and the following relation also holds:

$$G^* = \eta^* \cdot \omega \tag{29}$$

that is the symbol η* indicates the so-called complex viscosity.

For very low temperatures and very high frequencies (elastic limit), the phase angle approximates the value 0 and the relationship is valid:

$$G^* \cos(0) = G^* = G' \tag{30}$$

for which the complex modulus assumes the meaning of a real elastic modulus.

6.2.1 Frequency sweep test

The common test adopted to evaluate the stiffness of bituminous mastics and binder is the Frequency sweep (FS) test, carried out according to EN 14770.
Frequency sweeps generally help the purpose of describing the time-dependent behavior of a sample in the non-destructive deformation range.
A DSR with an internal temperature control system with plate-plate geometries through diameters from 8 mm to 25 mm and gap settings from 0,5 mm to 2,0 mm is adopted operating in two ways:

a) Controlled strain (or controlled shear deformation CSD)
b) Controlled shear stress (CSS)

The precondition is that the selected shear-strain or shear-stress amplitude is within the LVE region. For a given geometry, determination of the linear region on the all-selected temperature ranges shall consist, at least, of carrying out strain (or stress) sweep at the lowest temperature and at the highest frequency, strain (or stress) sweep at the highest temperature and at the lowest frequency, in order to select the adequate strain level.

The principle of the FS test is to apply a known oscillatory shear stress to the temperature-controlled test geometry, in which the bituminous test specimen is held. The binder's strain response to the stress is measured. Alternatively, a known oscillatory shear strain is applied to the test specimen and the resulting shear stress is measured. The final results are adopted to design the Master Curve, the Cole-Cole diagram and the Black diagram.

6.2.2 The master curves

A single rheometer operated at a single temperature can usually provide data only over a range of three or four decades of frequency or time, and this inadequate to track viscoelastic behavior from high-frequency end of the plateau zone into the low-frequency terminal zone. By obtaining data at several temperatures, time-temperature superposition can be used to generate a “master curve” showing the behavior at a “reference temperature” that covers many decades of time or frequency. A material to which this technique is applicable is said to be “thermorheologically simple”. In Figure 6.3 is reported a master curve example where the Complex modulus is in function of the reduced frequency. The properties of the material actually disregard the type of stress and in fact it is possible to pass in an approximate manner from one and the other quantity by associating the values obtained at time t with those corresponding to the pulsation ω (and vice versa) according to the relationship:

$$t = \frac{1}{f} = \frac{2\pi}{\omega} \tag{31}$$

In both cases the master curve has concavity shape downward facing and bounded by a bilateral.
The horizontal asymptote, also called glassy, defines the elastic limit condition reached for low values of the load application time and high values of the frequency, the oblique asymptote (inclined 45° in the bi-logarithmic scale) defines the limit condition of viscous flow and is achieved for high load application times and low frequency values. The rheological index, R, identifies the shape of the curves while the cross over point its horizontal position in the plane.
It is evident that the limit states of behavior of the material can be reached both by varying the temperature (all other conditions being equal) and time (or frequency), the same rule can be applied to any other intermediate visco-elastic stage as a correspondence can always be established between these two parameters, according to the time-temperature equivalence principle.

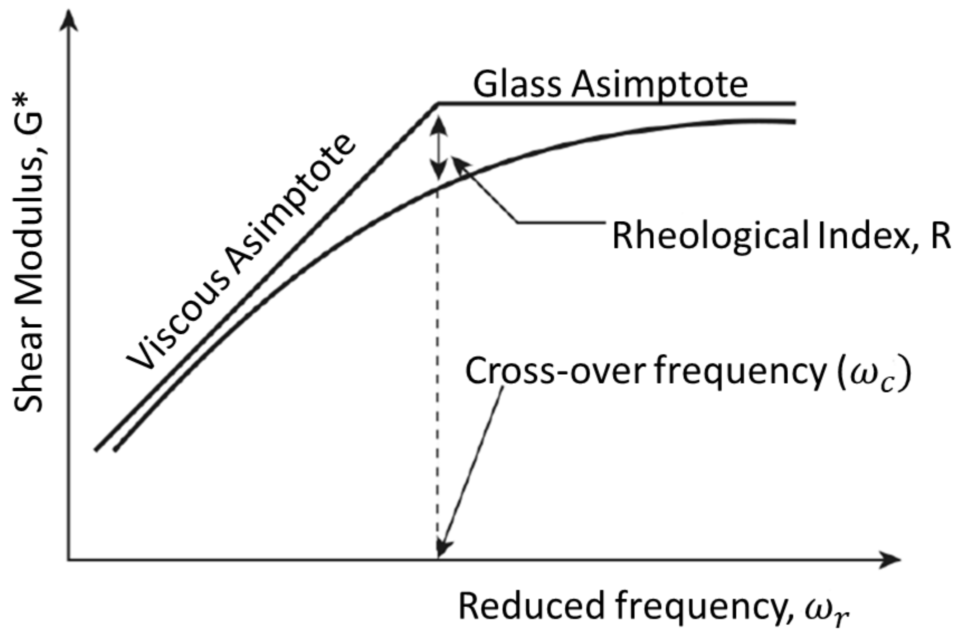


Figure 6.3 Master curve

From an operational point of view, this occurs through the use of appropriate shift factors in accordance with the following formula, which constitutes the analytical definition of the principle itself:

$$\omega_r = \omega_s \cdot a(T) \text{ from which } \log(\omega_r) = log(\omega_s) + loga(T) \tag{32}$$

where:

- ω_s is the frequency corresponding to a certain value of the complex modulus at the temperature T
- ω_r is the reduced frequency, that is the frequency value which gives the same value of G* at a reference temperature T_0
- $a(T)$ is the shift factor, a function of the temperature $\left(G^*(\omega_s, T) = G^*(\omega_r, T_0)\right)$.

The function a (T) is dependent on the nature of the material and must be evaluated on an experimental basis; in most cases one can refer to an Equation proposed by WIilliams-Landel-Ferry from which it takes its name as the WLF law [59]:

$$log\frac{a(T)}{a(T_0)} = \frac{-C_1 \cdot (T - T_0)}{C_2 + T - T_0} \tag{33}$$

where $C_1$and C_2 are characteristic constants depending on the nature of the material.

The application of the superposition principle is functional to the construction of the master curves itself, which must necessarily take place by combining different types and test conditions. In fact, it is not possible to carry out an experiment, for obvious technological reasons, which allows to measure the entire viscoelastic field with a single determination. The graphical representation relating to the application of the method is shown in Figure 6.4; as it can see, the material is analyzed in a range of frequencies limited to different temperatures and the experimental data relating to each temperature are subsequently brought back, by horizontal translation, at a single reference temperature T_0. It follows that, once the master curve is defined at the reference temperature and the translation function a (T) is known, it is possible to fully describe the viscoelastic response of the material.

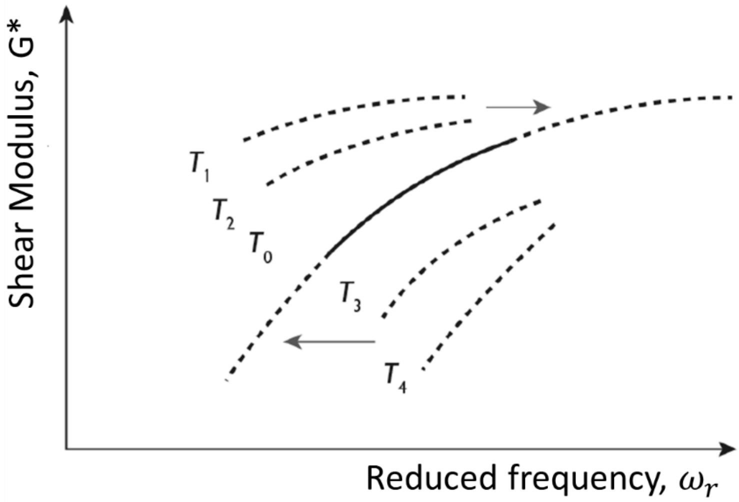


Figure 6.4 Time-temperature superposition principle

6.2.3 The black diagram

Black diagram is a representation of raw rheological data (shear modulus and phase angle) regardless of any shifting occurring when developing master curves. In fact, the latter procedure can be only applied to thermo-rheological simple materials (hence complying with the time-temperature superposition principle). Black diagram is developed using the phase angle and complex shear modulus of the binder without any manipulation of the rheological data. Black diagrams have many advantages; i.e., finding inconsistencies in the rheological data, distinguishing between the thermo-rheological simple and complex materials, compliance of DSR geometries and confirming polymer modifications [60].

In the diagram each pair (G*-δ) is representative of a frequency and a temperature (see Figure 6.5).

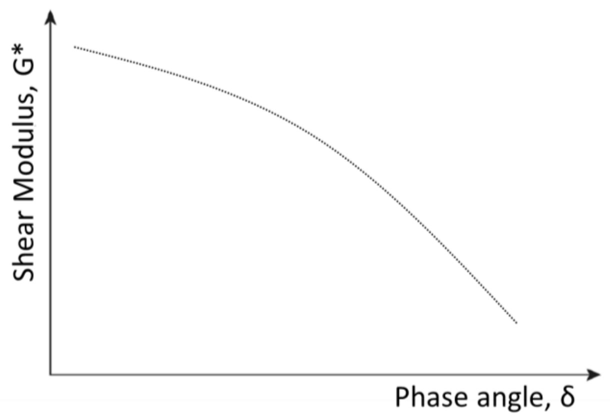


Figure 6.5 Black diagram

6.2.4 The Cole-Cole diagram

The Cole-Cole diagram is a way to show a graphical description of the viscous and elastic part of the material's stiffness under study. It illustrates the contribution of elastic (storage modulus) and viscous (loss modulus) components that contribute to the overall stiffness of the material. A Cole-Cole diagram is typically plotted between the storage and loss modulus (see Figure 6.6).

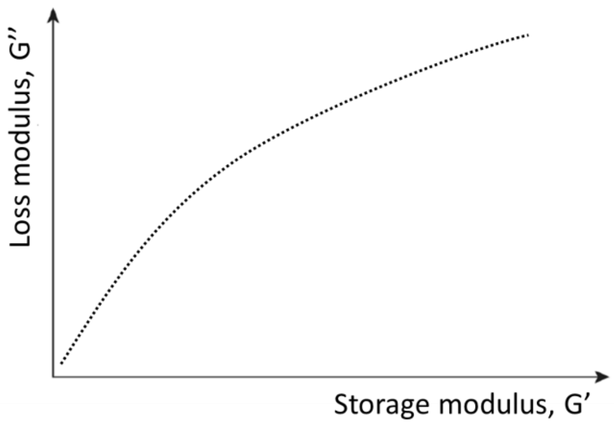


Figure 6.6 Cole-Cole diagram

6.3 Permanent deformation

Bitumen for high load application rates and low temperatures behaves like an elastic body, while it assumes the mechanical properties of the viscous fluid for low load application rates and high temperatures. The binder, in intermediate operating conditions to the previous ones, exhibits a viscoelastic behavior. During the application of force, the bituminous blends therefore develop an instant elastic response followed by an increasing deformation over time. After the removal of the load, the blend returns the elastic components instantaneous and delayed, maintaining an irreversible residual deformation, so called permanent deformation. This permanent deformation, accumulated in the material under the action of a cyclic load, produces the phenomenon of rutting (see Figure 6.7).

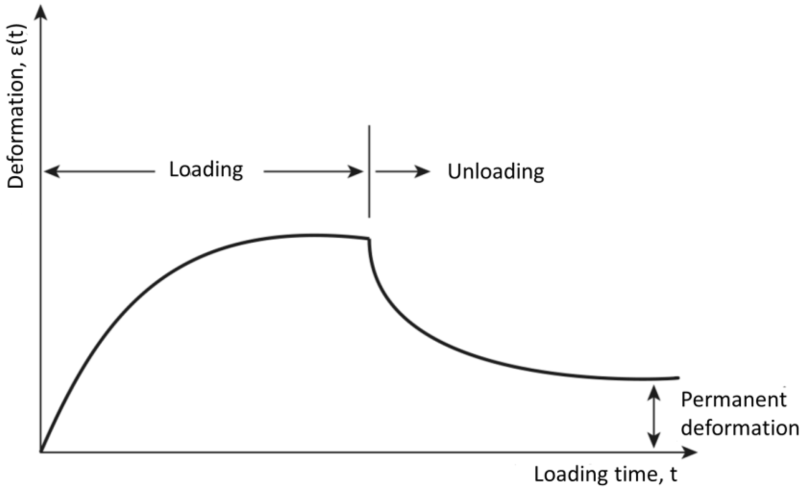


Figure 6.7 Typical trend of a Loading ime-Deformation relation

6.3.1 Multiple stress creep and recovery test

The Multiple stress creep and recovery test (MSCR) is used to determine the presence of elastic response in bitumen and bituminous binders. The MSCR uses the well-established creep and recovery test concept to evaluate the binder's potential for permanent deformation. Using the DSR, a one-second creep load is applied to the asphalt binder sample. After the 1 second load is removed, the sample is allowed to recover for 9 seconds. The test starts with the application of a low stress, 0.1kPa for 10 creep and recovery cycles then the stress is increased to 3.2 kPa and repeated for an additional 10 cycles.

A 25 mm plate-plate DSR geometry with a 1 mm gap is adopted to carry out an MSCR test; two samples are tested for each bituminous mastic and binder at each test temperature.

An MSCR test made it possible to perform an initial assessment of the non-recoverable creep compliance J_{nr} for each mastic; in addition, J_{tot}, the total creep compliance at the end of the creep phase calculated immediately before load removal was studied for a complete comparison of the materials (see Figure 6.8). The average of non-recoverable creep compliance and the average total creep compliance are used to carried out comparative analysis.

The average non-recoverable creep compliance is calculated at 0.1kPa using Equation 34, while that at 3.2kPa is obtained using Equation 36.

$$J_{nr0.1kPa} = \frac{1}{10}\sum_{N=1}^{10}(J_{nr0.1kPa}^{N}) \;\; (kPa^{-1}) \tag{34}$$

where

- $J_{nr0.1kPa}^{N}$ is the non-recoverable creep compliance at the N-th cycle with 0.1 kPa creep stress, as follows:

$$J_{nr0.1kPa}^{N} = \varepsilon_{10}^{N}/_{0.1} \;\; (kPa^{-1}) \tag{35}$$

where

- ε_{10}^{N} is the strain value at the end of recovery phase (after 10 secs) of each cycle

$$J_{nr3.2kPa} = \frac{1}{10}\sum_{N=1}^{10}(J_{nr3.2kPa}^{N}) \;\; (kPa^{-1}) \tag{36}$$

where

- $J_{nr3.2kPa}^{N}$ is the non-recoverable creep compliance at the N-th cycle with 3.2 kPa creep stress, as follows:

$$J_{nr3.2kPa}^{N} = \varepsilon_{10}^{N}/_{3.2} \;\; (kPa^{-1}) \tag{37}$$

The average total creep compliance is calculated at 0.1kPa using Equation 38, while that at 3.2kPa was obtained from Equation 40.

$$J_{tot0.1kPa} = \frac{1}{10}\sum_{N=1}^{10}(J_{tot0.1kPa}^{N}) \;\; (kPa^{-1}) \tag{38}$$

where

- $J^N_{tot0.1kPa}$ is the total creep compliance at the N-th cycle with 0.1 kPa creep stress, as follows:

$$J^N_{tot0.1kPa} = {\varepsilon^N_1}/{0.1} \quad (kPa^{-1}) \tag{39}$$

  where

  - ε^N_1 is the strain value at the end of the creep phase (after 1 sec) of each cycle

$$J_{tot3.2kPa} = \frac{1}{10}\sum_{N=1}^{10}(J^N_{tot3.2kPa}) \ \ (kPa^{-1}) \tag{40}$$

where

- $J^N_{tot3.2kPa}$ is the total creep compliance at the N-th cycle with 3.2 kPa creep stress, as follows:

$$J^N_{tot3.2kPa} = {\varepsilon^N_1}/{3.2} \quad (kPa^{-1}) \tag{41}$$

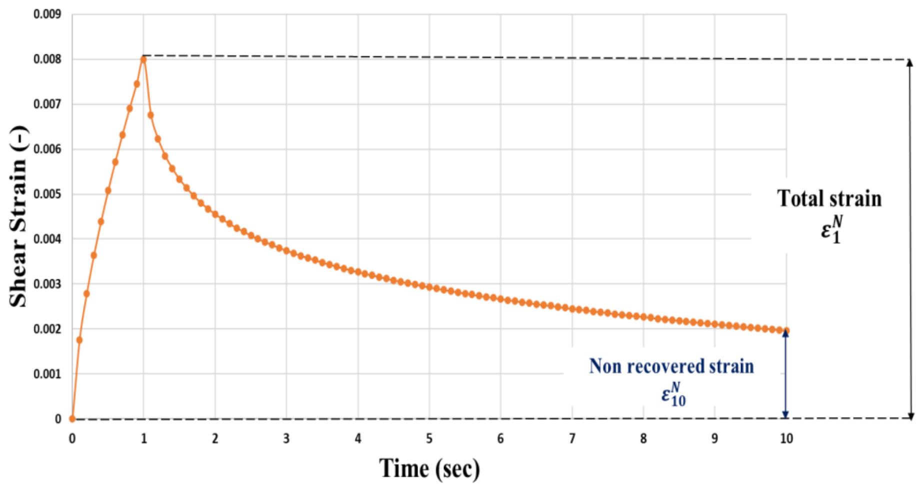


Figure 6.8 MSCR output for 1 cycle of creep and recovery

7 Experimental investigations

This chapter will describe the experimental laboratory investigation to assess the possibility of introducing jet grouting and plastic waste into bituminous blends. In particular, a first part will cover the study of bituminous mastics made up of jet grouting waste both hot and cold and the study of hot bituminous mastics made up of plastics waste, while a second part will cover the study of bituminous mixtures with jet grouting waste.

7.1 Study of the bituminous mastics made up of jet grouting waste

Following the main results available in scientific literature on Cold Bituminous Mixtures (CBM) and mastics, the experimental study presented in this section aims to bridge a gap in the laboratory protocol for mixing the cold bituminous mastics and to appreciate the main differences in relation to hot bituminous mastics.

Different mastics were prepared based on a filler-to-bitumen weight ratio of 0.3, 0.4 and 0.5. The fillers adopted were of the limestone (LF) and jet grouting waste (JW) types, while neat bitumen 50/70 (B50/70) was adopted for hot mastics, and bituminous emulsion (BE) made up of 60% neat bitumen and 40% water was used for the cold ones; mixing was carried out without adding cement traying to substitute it with JW in the cold bituminous mixture production, since the JW is also a mixture made up of cement. The experimental program is reported in Figure 7.1.

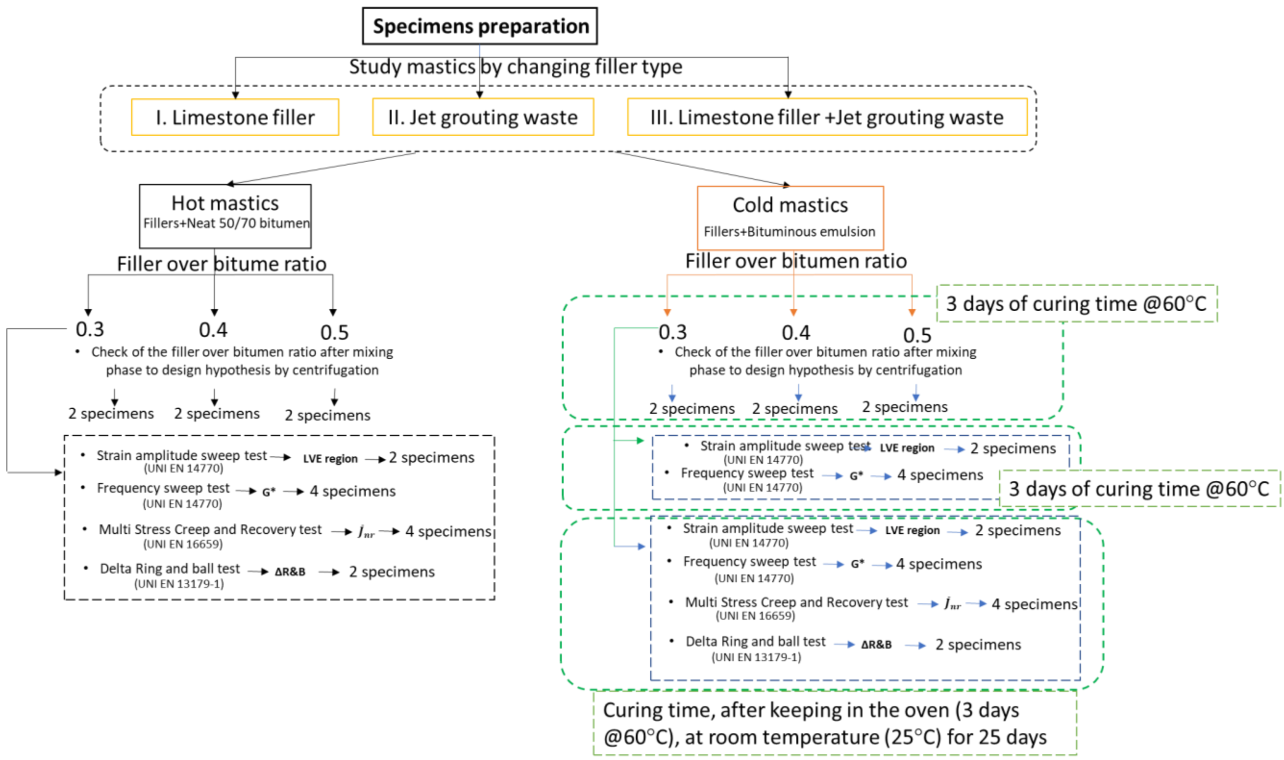


Figure 7.1 Experimental program of the study of the bituminous mastics made up of jet grouting waste

7.1.1 Materials

Binder

Hot and cold mastics were prepared adopting for the hot-process a neat bitumen 50/70 produced by an oil refinery in southern Italy, while for the cold process a bituminous emulsion mixture of 60% neat bitumen 50/70 and 40% water.

The main properties of the bitumen and bituminous emulsion are shown in Table 7.2.

Jet grouting waste

Jet grouting waste, before moving to the design of a bituminous blends, was subject to a grinding process by a jaw mill for its introduction into the binder; every 30 minutes, until three hours, the material was removed from the jaw mill, dried and a grading curve was plotted to verify that no variation in terms of grading curve existed. It was found that after two hours almost, no variation is arised. Figure 7.2 shows JW before and after grinding process. On bases of percentage passing by mass defined in EN 13043, JW graded resulted not completely a filler (see Table 7.2).

Table 7.1 Binder properties: a) Neat bitumen 50/70, b) Bituminous emulsion 60/40, and c) Bitumen Contained in bituminous emulsion.

a)

Properties	Unit	Standard	Value
Penetration at 25°C	dmm	EN 1426	64
Softening point (R&B)	°C	EN 1427	46
Dynamic viscosity at 150°C			0.25
Dynamic viscosity at 135°C	Pa s	EN 13702	0.413
Dynamic viscosity at 60°C			3.220
Fraass	°C	EN 12593	-9

b)

Characteristics	Unit	Standard	Value
Water content	%	EN 1428	40
pH value	-	EN 12850	4.2
Settling tendency at 7 days	%	EN 12847	5.8

c)

Properties	Unit	Standard	Value
Penetration at 25°C	dmm	EN 1426	62
Softening point (R&B)	°C	EN 1427	47

Figure 7.2 Jet grouting waste before and after grinding process

Table 7.2 Main properties of JW: a) EN 13043 requirements, b) Grading curve, c) Volumetric characteristics

a)

Sieve size	Percentage passing by mass	
mm	Overall range for individual results	Producer's maximum declared grading range 1)
2	100	-
0.125	85 to 100	10
0.063	70 to 100	10

1) Declared grading range on the basis of the last 20 values (see prEn FPC). 90% of the results declared shall be within this range, but all the results shall be within the overall grading range

b)

Sieve size [mm]	Retaining [%]	Passing [%]
6.3	0	100
4	1.13	98.87
2	**0.57**	**98.3**
1	4.14	94.16
0.5	15.62	78.54
0.25	18.8	59.74
0.125	**14.7**	**45.04**
0.075	7.8	37.24
0.063	**2.52**	**34.72**

A leaching test was carried out at the end of the JW grinding process; specimens were prepared in compliance with UNI 10802:2013. Each specimen was dried to minimize losses due to adhesion to the surfaces of the equipment, and it was mixed and reduced in quantities of less than 50g. Part of the sample was subjected to mineralization using chemical agents assisted by a microwave source in accordance with EPA 3052 1996 for chemical element evaluation.

The analysis was performed by taking at least three measures, whose average values are shown in Table 7.3, highlighting the presence of Calcium (7.35%), Silicium (18.5%) and Magnesium (1.3%).

The leaching test was conducted at room temperature (20 ± 5° C according to EN 12457-2) by examining the other parts of the JW sample: a) metals were sought in the eluate using plasma optical emission spectrometry applying the method prescribed in EN ISO 11885 (2009); b) the dissolved solids were established as specified in EN 15216; c) the COD (Chemical Oxygen Demand) was established in terms of an aliquot of eluate using the APAT CNR IRSA 5130 Man. 29/03 method (see Figure 7.3).

C.O.D. preparation and tritation atomic absorption agitation device

Figure 7.3 C.O.D. preparation and tritation. APAT CNR IRSA 5130 Man. 29/03 and agitation for leaching test

Leaching test results (see Figure 7.4) demonstrate how JW can be re-used according to the Ministerial Decree of 5/02/1998 "Identification of non-hazardous waste subject to simplified recovery procedures under Articles 31 and 33 of Legislative Decree no. 22 of 5 February 1997", as its chemical elements components do not exceed the limits mentioned in the above Ministerial Decree.

Table 7.3 Chemical composition of JW

Elements	Result
Ca	7.035%
Fe	1.330%
Si	18.515%
Mn	0.475%
As	0.002%
Be	0.001%
Co	0.001%
Cr	0.002%
Hg	0.001%
Ni	0.002%
V	0.007%
Others	72.620%

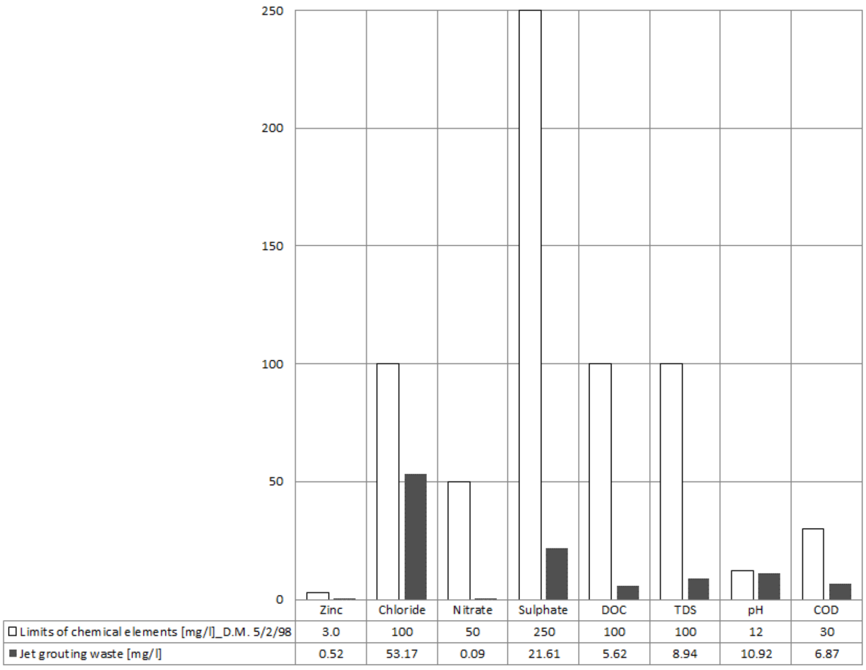
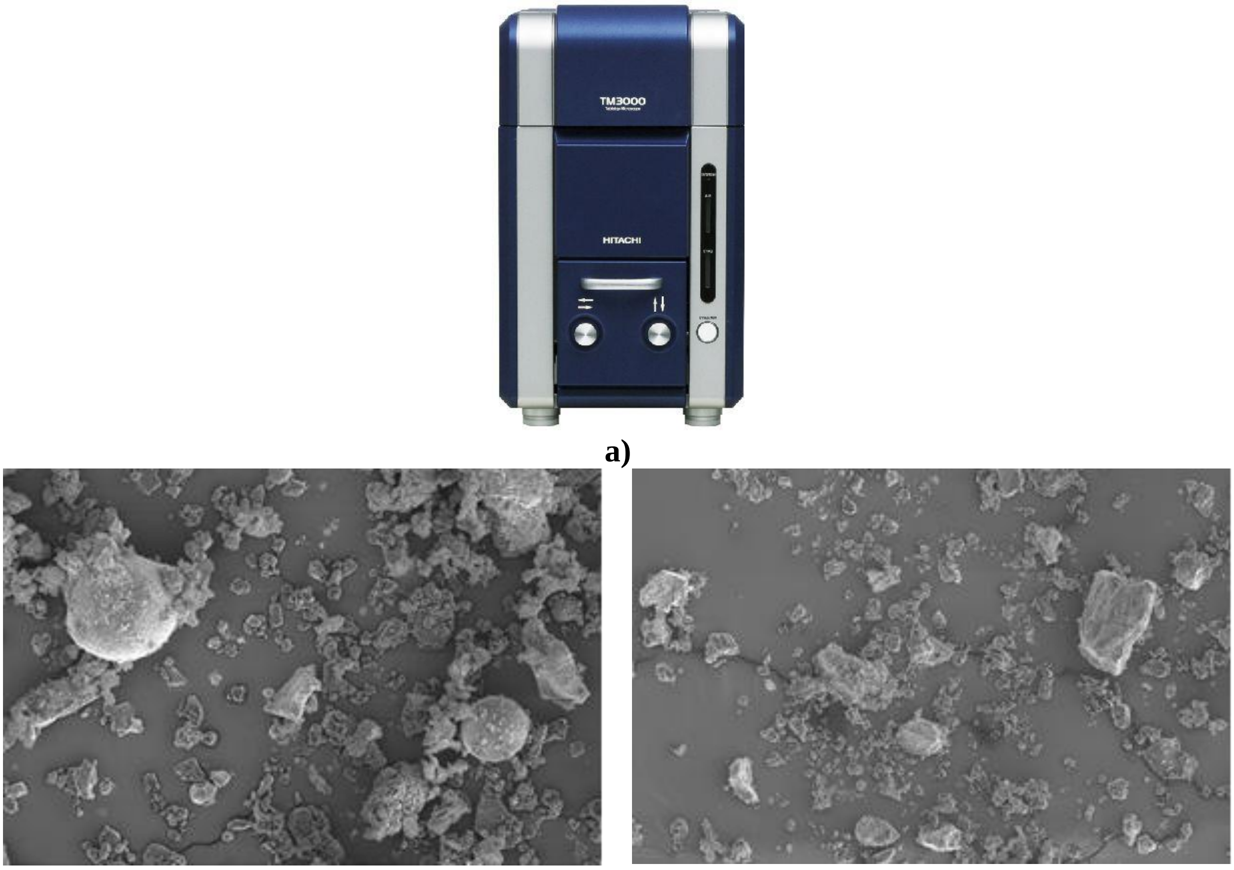


Figure 7.4 Leaching test results for grinded JW

Comparing JW and LF through SEM characterization

The morphology of the two materials was investigated by a Scanning Electron Microscopy (SEM) to observe the microstructure and the geometric shapes of the particles. Each specimen has been observed by a Hitachi TM3000 microscope (see Figure 7.5a).

The observed LF (see Figure 7.5b) is composed of coarse particles, with a diameter that is clearly visible at low magnification and in detail: lithic fragments with smooth and rough jagged edges, with a size between 10 and 76 µm; spherical particles between 3 and 55 µm in size; aggregates of variable size apparently cemented together; the JW (see Figure 7.5c) is composed of very coarse lithic fragments with a smooth and rough surface, with rounded and rough edges, with a diameter between 2.7 and 56.1 µm. There are also very fine particles that aggregate with each other, ranging in size from nanometric levels up to about 10 µm.



a)

b) c)

Figure 7.5 SEM analysis: a) Hitachi TM3000 microscope, b) LF microstructure and c) JW microstructure

LF and JW volumetric analysis

LF and JW were adopted in bituminous mastics production as a total passing through a 0.063 mm sieve. The main volumetric properties as specific gravity and Rigden voids were analysed (see Figure 7.6). The results reported in Table 7.4 show that the Specific gravity of LF is lower than JW and the Ridgen voids of JW are 24% higher than LF; this circumstance obviously will affect the final stiffness of the mastics due to the bitumen fixed in the interparticle voids and a part of bitumen that will remain free.

Figure 7.6 Rigden voids equipment

Table 7.4 LF and JW main volumetric propreties

Filler	Specific gravity [g/cm^3]	Rigden voids [%]
LF	2.737	41.440
JW	2.687	51.360

7.1.2 Bituminous mastics preparation

The mastics were prepared adopting two different laboratory protocol procedures for hot and cold mastics.

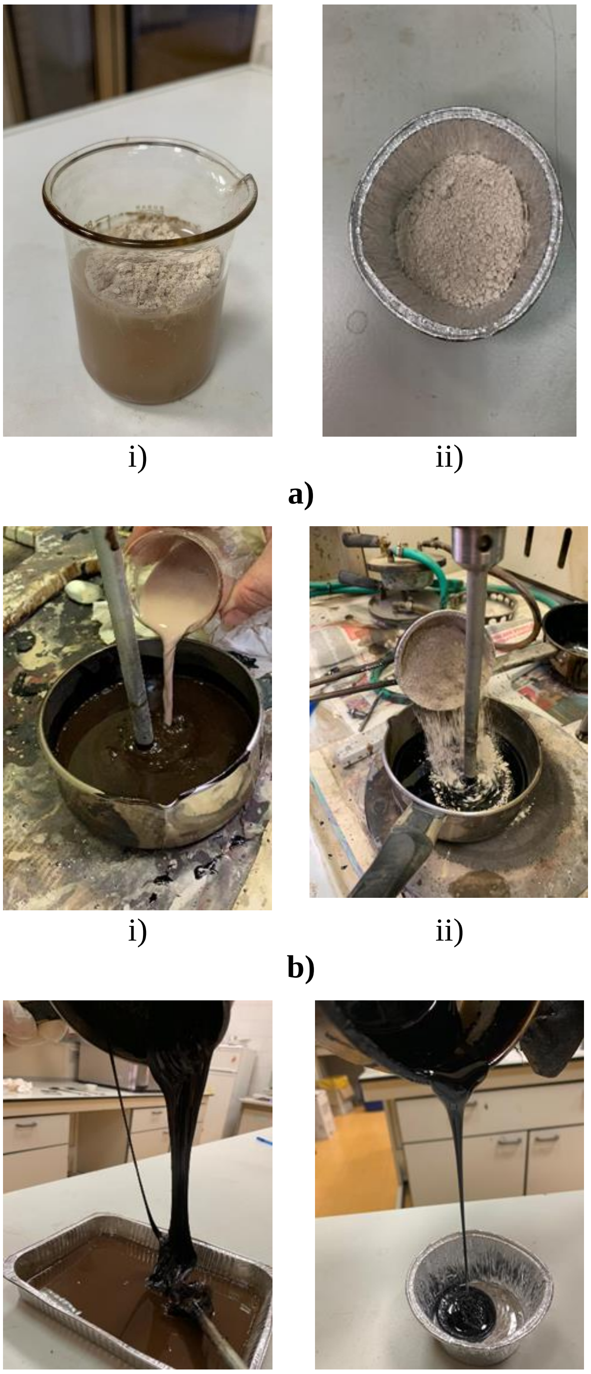
For the hot mastics, suitable mixing temperatures were chosen according to AASHTO T316 using rotational viscosimetry. An RW 20 DZMn mechanical mixer was used to mix filler and binder at the traditional temperature of 150 °C used for the HMA mixture.

The mixing process was performed carefully to obtain homogenous matrices: a stainless-steel beaker was used, cleaned, and kept in an oven at test temperature with the asphalt binder. The beaker was put on a hot plate to maintain a constant mixing temperature; a mixer running at 500 rpm was then used. An amount of filler pre-heated to 150°C, in compliance with the three filler-to-bitumen study ratios (0.3, 0.4 and 0.5), was gradually added to the beaker while stirring; the mixing process lasted for at least 30 minutes, until a homogenous binder-filler mastic was obtained (see Figure 7.7).

In the case of cold mastics (see Figure 7.7), the bituminous emulsion and filler were put into two different boxes and heated in an oven to 60°C according to the technical workability specification of the bituminous emulsion, until homogenous conditioning was reached.

The mixing process was different from that adopted for the hot mastics. An initial water content hypothesis was assumed for a suitable mastic workability level in compliance with EN 1744-1; consequently, a filler-to-water content per mass of 0.5 (f/W=0.5) was used for all three study filler-to-extracted bitumen (0.3; 0.4; 0.5) ratios. Table 7.5 shows the minimum quantity of water for each mastic, guaranteed by varying the filler type and according to the three above-mentioned ratios.

For only the cold mastics containing LF or JW filler, the bituminous emulsion broke up within 15 minutes after adding filler with water (see amount of mastic mixing per 100gr of study sample in Table 7.5). The 15 minutes were long enough to allow the separation of the bituminous emulsion into water and bitumen.



i) ii)

a)

i) ii)

b)

i) ii)

c)

Figure 7.7 Mastic preparation using jet grouting waste: a) Filler preparation: i) cold mastic, and ii) hot mastic, b) Adding filler to the binder: i) cold mastic and ii) hot mastic, and c) final mastic: i) cold mastic and ii) hot mastic

On the other hand, for mastics made from LF plus JW filler added to EB previously mixed with a suitable amount of water to obtain workability, the EB broke up at the close of the 24th hour.

The water remaining from the separation of the water and bitumen was removed, and the cold mastic obtained was subsequently subjected to a 72h conditioning process in the oven at 60°C until the remaining water was fully expelled.

A comparison of bitumen produced from bituminous emulsion after conditioning in the oven for 72h at 60°C and aged bitumen made from bituminous emulsion using a Rolling Thin Film Oven (RTFO) procedure (see Figure 7.7a) has shown that the values of the latter, in terms of Softening point and penetration grade at 25°C, are not comparable to the previous one as they are higher (see Table 7.6); the conditioning process was therefore such that it did not cause aging of the bitumen contained in the cold mastics.

After the conditioning process, the actual filler content for each of the 18 mastics was checked.

Ten grams of mastic were poured into a glass test tubes, and a suitable quantity of "Perchloroethylene" was added to submerge the mastic; the sample was stirred for ten minutes. Centrifugation was performed on four samples at the same time to verify the repeatability of the results achieved; the four samples (mastic plus perchloroethylene) reached the same weight. In fact, before inserting the four glass test tubes into the centrifuge, the correct balance of sample quantities (mastic plus solvent) was checked to avoid imbalance during centrifugation. Centrifugation lasted 30 minutes at a speed of 6,000 revolutions/minute. At the end of the centrifuge process, the solvent was removed using filter paper to help retain filler particles. To remove all quantities of solvent, the filter papers and each glass test tubes were put in an oven heated to above the boiling temperature of the solvent for a maximum of around one hour to reach a constant weight. The amount of residual filler, and, therefore, its ratio to bitumen is expressed in the following Equation 41.

$$f/b = \frac{P_2 - P_3}{P_3 - P_1} \tag{41}$$

where:

- f/b is the actual ratio of the mastic being tested
- P_1 is the weight of the glass test tubes, in grams
- P_2 is the weight of the glass test tubes plus the quantity of mastic before centrifuge, in grams
- P_3 is the weight of the glass test tubes with the residual amount of filler after the curing process, in grams

Table 7.5 Amount of mastic mixing materials per 100gr of study sample.

Type	Filler-to-bitumen ratio (%)	Label	Materials [gr]				
			LF	JW	Water f/W= 0.5 (Added+Contained in BE)	B50/70	BE (60%bitumen+40%water)
Hot mastics	0.3	$LH_{0.3}$	30	-	-	70	-
		$JH_{0.3}$	-	30	-	70	-
		$LJH_{0.3}$	15	15	-	70	-
	0.4	$LH_{0.4}$	40	-	-	60	-
		$JH_{0.4}$	-	40	-	60	-
		$LJH_{0.4}$	20	20	-	60	-
	0.5	$LH_{0.5}$	50	-	-	50	-
		$JH_{0.5}$	-	50	-	50	-
		$LJH_{0.5}$	25	25	-	50	-
Cold mastics	0.3	$LC_{0.3}$	30	-	60 (13.2Added+46.8Contained in BE)	-	117 (70.2bitumen+46.8water)
		$JC_{0.3}$	-	30	60 (13.2Added+46.8Contained in BE)	-	117 (70.2bitumen+46.8water)
		$LJC_{0.3}$	15	15	60 (13.2Added+46.8Contained in BE)	-	117 (70.2bitumen+46.8water)
	0.4	$LC_{0.4}$	40	-	80 (40Added+40Contained in BE)	-	100 (60bitumen+40water)
		$JC_{0.4}$	-	40	80 (40Added+40Contained in BE)	-	100 (60bitumen+40water)
		$LJC_{0.4}$	20	20	80 (40Added+40Contained in BE)	-	100 (60bitumen+40water)
	0.5	$LC_{0.5}$	50		100 (66.8Added+33.2Contained in BE)	-	83 (49.8bitumen+33.2water)
		$JC_{0.5}$		50	100 (66.8Added+33.2Contained in BE)	-	83 (49.8bitumen+33.2water)
		$LJC_{0.5}$	25	25	100 (66.8Added+33.2Contained in BE)	-	83 (49.8bitumen+33.2water)

Bitumen from EB properties after aging and curing

Table 7.6

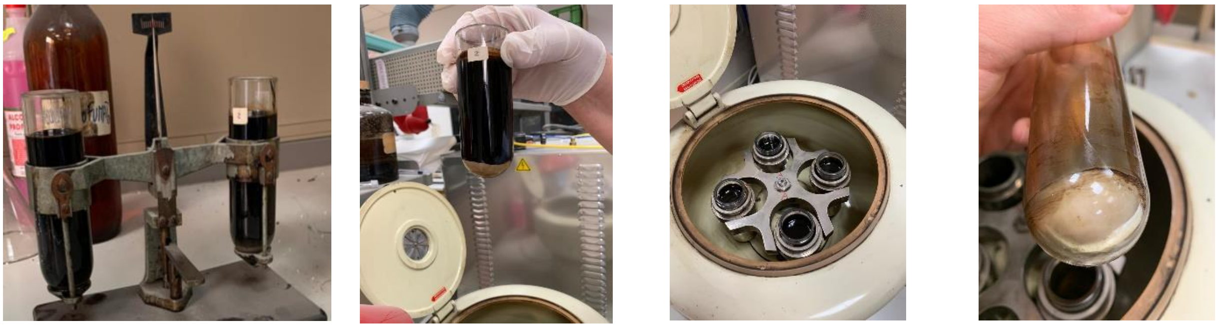
Properties	Unit	Standard	Aged Bitumen from EB60/40	Bitumen from EB60/40 after 72h at 60°C
Penetration at 25°C	dmm	EN 1426	40	60
Softening point (R&B)	°C	EN 1427	54.5	49

a) b)

Figure 7.8 La.Stra device:a) RTFOT and b) DSR

The results in Table 7.7 show that in the case of hot mastics, the amount of filler obtained following the above-mentioned procedure is the same as that adopted in the first phase of mastic preparation, and no change in the filler-to-bitumen ratio was observed before and after centrifugation.

On the other hand, a loss of filler was observed when cold mastic was prepared with filler-to-bitumen ratios of 0.4 and 0.5 after centrifugation for all the filler types adopted here (see Figure 7.9). Consequently, the ratios of 0.4 and 0.5 were not investigated further as the mixture is chemically unstable and produces insufficient adhesion for the solution proposed here. Consequently, only a filler-to-bitumen ratio of 0.3 was examined further, as it satisfies the test proposed here due to the component materials adopted and will therefore be simply labelled LC (LF added to EB), JC (JW added to EB) and LJC (LF plus JW added to EB) in the rest of the work.



a) b) c) d)

Figure 7.9 Checking filler content: a) calibration of the glass test tubes, b) specimen ready for the centrifuge, c) centrifuge equipment, and d) residual filler

Table 7.7 Filler-to-bitumen ratio results.

f/b	Weight	Hot mastics*					
		LH		JH		LJH	
		Specimen 1	Specimen 2	Specimen 1	Specimen 2	Specimen 1	Specimen 2
0.3	P1	112.230	115.880	135.970	126.160	112.200	115.830
	P2	122.260	126.000	145.990	136.190	122.200	125.860
	P3	114.480	118.105	138.279	128.469	114.450	118.121
	f/b	**0.289**	**0.282**	**0.299**	**0.299**	**0.290**	**0.296**
0.4	P1	112.210	115.830	135.930	126.120	112.200	115.880
	P2	122.210	226.780	145.930	137.120	122.900	125.880
	P3	115.036	147.530	138.739	129.183	115.259	118.726
	f/b	**0.394**	**0.400**	**0.391**	**0.386**	**0.400**	**0.398**
0.5	P1	112.230	115.860	135.910	126.150	112.180	115.860
	P2	122.430	125.960	145.910	136.350	122.580	125.860
	P3	115.627	119.163	139.243	129.486	115.627	119.153
	f/b	**0.499**	**0.486**	**0.500**	**0.486**	**0.496**	**0.491**
		Cold mastics					
f/b	Weight	LC		JC		LJC	
		Specimen 1	Specimen 2	Specimen 1	Specimen 2	Specimen 1	Specimen 2
0.3	P1	136.000	126.120	112.220	115.880	135.990	126.150
	P2	146.100	136.120	122.230	125.900	146.100	136.140
	P3	138.331	128.412	114.520	118.000	138.302	128.455
	f/b	**0.300**	**0.297**	**0.298**	**0.268**	**0.296**	**0.300**
0.4	P1	135.980	126.160	112.210	115.870	135.960	126.110
	P2	146.680	136.260	122.210	125.990	146.160	136.130
	P3	138.584	128.754	114.719	118.332	138.490	128.497
	f/b	**0.322**	**0.346**	**0.335**	**0.322**	**0.330**	**0.313**
0.5	P1	135.000	126.110	112.230	115.880	135.970	126.130
	P2	145.100	136.110	122.390	126.150	146.330	136.330
	P3	137.613	128.753	114.845	118.371	138.710	128.620
	f/b	**0.349**	**0.359**	**0.347**	**0.320**	**0.360**	**0.323**

*LH=hot mastics with LF, JH=hot mastics with JW, LJH=hot mastics with JW plus LF

7.1.3 Frequency sweep test results

G* was taken as the rheological benchmark used to characterize and compare the nine mastics prepared by adopting a filler-to-bitumen ratio of 0.3. Test temperatures were between 10°C and 60°C with an increment of 10°C and a test frequency range from 0.1 to 10 Hz across the 19 obtained measures. Strain amplitude sweep (SAS) tests were performed first with the aim of identifying the LVE limit and defining a suitable range of strain level for hot and cold mastics with all filler types.

The SAS tests were performed at 10°C using 8 mm parallel-plate-geometry and a 2 mm gap, applying a constant frequency of 10 rad/s (1.59Hz). A unique strain level of 0.05% was adopted as the LVE limit for all mastics in order to simplify the testing procedure. This value was selected on the basis of the LVE limit identified for the LH mastic, although the other mastics had higher LVE limits [38][61][62][63].

Figure 7.10 shows the master curves for the three hot mastics (1: hot mastics made with LF filler added to B50/70, 2: hot mastics with JW filler added to B50/70, and 3: hot mastics with LF plus JW added to B50/70). It may be noted that adding the filler to the three hot mastics increases stiffness when compared to B50/70. In greater detail, LH returns the lowest G* values for all test temperatures and frequencies investigated compared to JH and LJH; on the other hand, at a test temperature of 10°C, JH behaves in a similar way to LH. It should also be noted that the highest G* values were observed for LJH; specifically, at a low-test temperature, there were no great differences between LH and JH, with behaviour very close to that of B50/70. Otherwise, at high temperatures, LJH gave higher G* performance than LH and B50/70, albeit quite close to that of JH. The phase angle behaviour of mastics follows the base bitumen trend; neither filler changes the viscoelastic response of the bitumen, giving a completely viscous response at high temperatures and an elastic approach at low temperatures.

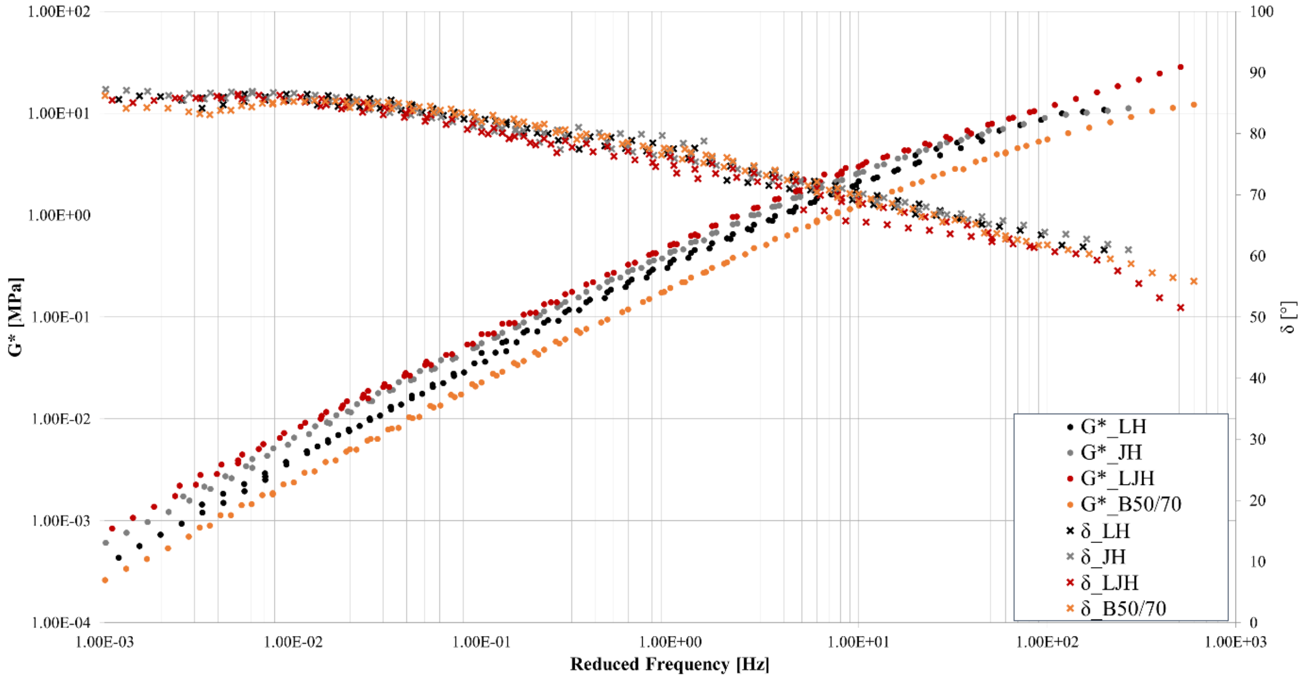


Figure 7.10 Master curve for hot mastics and neat bitumen 50/70

Before moving on to assess the cold mastics from the point of view of G* and δ, an assessment of the behaviour of B50/70 in terms of G* and δ and the bitumen extracted from the bituminous emulsion was carried out. Figure 7.11 shows the master curve results for the two bitumens, with no variation when moving from high to low test temperatures.

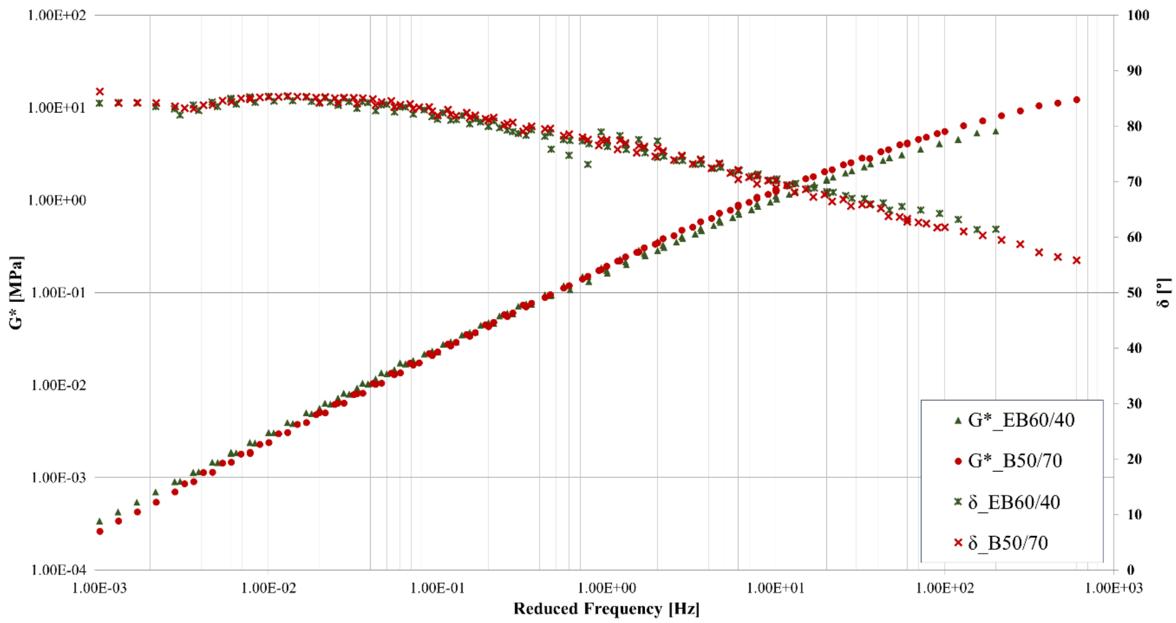


Figure 7.11 Master Curve of Bitumen and Bitumen Contained in emulsion

Three cold study mastics (LC, JC and LJC) were prepared following the procedures shown in section 7.1.2 and kept in an oven for 3 days at 60°C until a constant weight was reached. On the third day, no variation in weight had occurred, so after this period, three specimens of the cold mastics were tested for G* with a range of frequencies between 0.01 and 10 Hz, at temperatures of 10, 20, 30, 40, 50, and 60°C. An 8 mm plate with a 2 mm gap was used below 30°C, and above this temperature a 25 mm plate and a 1 mm gap were used.

The master curves for the cold mastics are shown in Figure 7.12. What is immediately evident is the remarkable difference between the cold mastics after 3 days of curing time and the EB60/40 at low temperatures, where the former (LC, JC and LJC) show lower G* values compared to EB60/40; on the other hand, JC reaches performance at temperatures up to 40°C and seems to produce the same behaviour as EB60/40. In comparison with the other two cold mastics at 10°C, the LC shows a dramatic fall in G*. In terms of phase angle, it is possible to observe a lower δ value at high temperatures for LC than for EB60/40, with slightly elastic behaviour, which is the opposite of what happens at low temperatures, where the δ value for JC is higher than for EB60/40.

In particular, it can be observed that the trend of the phase angle at low temperatures for JC is the opposite of the trend for G* modulus; in this case the behaviour of JC, unlike the other mastics, approaches that of a pseudoplastic material, which may mean that a mastic mix using only JW as a filler cannot increase the stiffness of bitumen after 3 days.

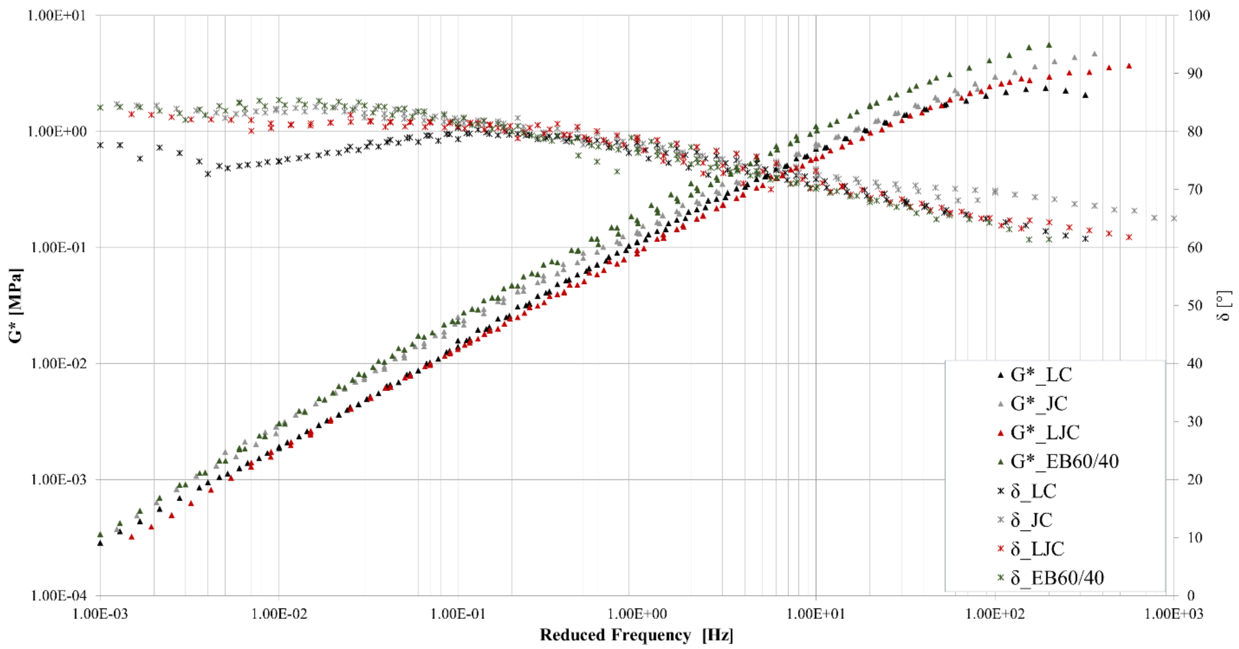


Figure 7.12: The master curves of the cold mastics after 3 days of curing time in an oven heated to 60°C and EB60/40

Since many studies carried out on CBM have demonstrated that maximum mechanical performance in terms of ITS and/or Stiffness can be achieved on the 28th day of curing time [33]; cold mastics that had been kept for 3 days at 60°C were subsequently kept at room temperature for 25 days (for a total of 28 days' curing time), and then subjected to G* evaluation (labelled LC28d (LF added to EB after 28 days of curing time), JC28d (JW added to EB after 28days of curing time), and LJC28d (LF plus JW added to EB after 28days of curing time).

The results of the FS test in terms of master curves are reported in Figure 7.13. Unlike the previous results for all cold mastics, G* always resulted higher than EB60/40, highlighting the stiffening effects of the fillers in the bitumen. In particular, it can be noted that, although JC28d G* is higher than EB60/40 at low temperatures (10-20-30°C), JC28d is comparable to LC28d; on the other hand, at high temperatures (40-50-60°C), it displays worse behaviour with a reduction in G*. JW filler added to the bitumen without LF, JC28d G* is lower than the remaining mastics. On the contrary, when JW is added to bitumen with LF, the G* value increases at all temperatures and for all frequency ranges (see LJC28d).

The phase angle behaviour of mastics follows the bituminous emulsion trend; in particular the LC28d δ values at higher temperatures resulted lower for all the mastics and the bituminous emulsion, while the JC28d shows greater elasticity than the others at low temperatures. Furthermore, greater viscosity was observed when both LF and JW was added to bituminous emulsion.
Therefore, cold interaction between LF filler with bitumen favours the best mechanical performance of all the prepared mastics, including the hot ones (see Figure 7.13).

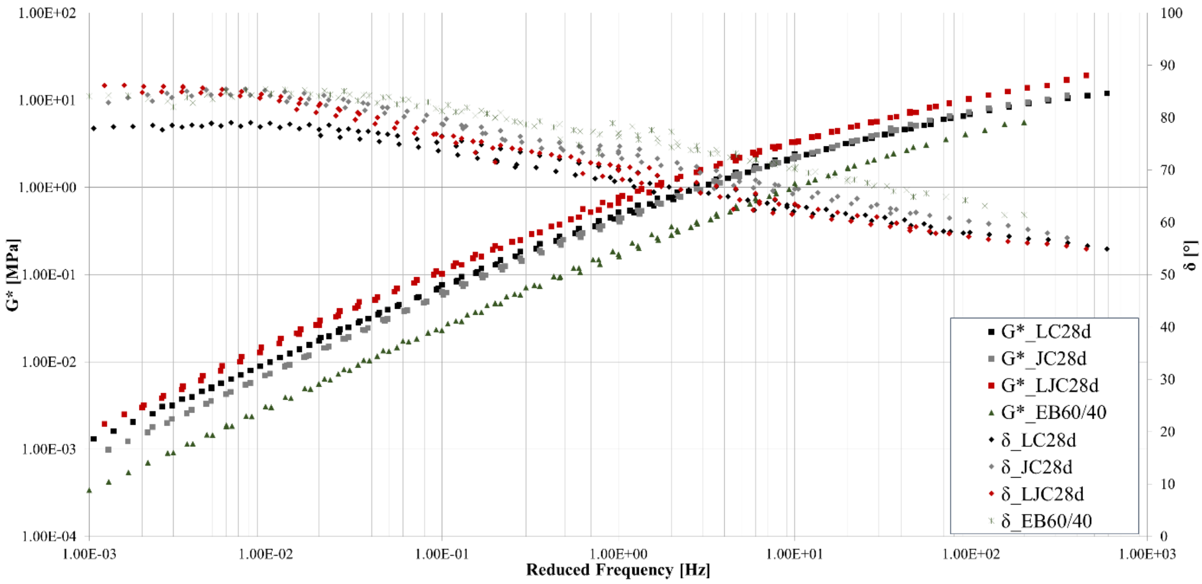


Figure 7.13: Master curves of the cold mastics subsequent to curing time, after being kept in the oven for three days at 60°C and at room temperature (25°C) for 25 days

On the basis of the results achieved so far, focusing only on the mastics that returned better performance during comparison when hot and cold procedures were used, it can be observed in Figure 7.14 that three main regions can be identified taking into account G* values: 1) for region I (test temperatures >30°C), it may be observed that LJC28d shows higher performance in terms of G* than LJH; 2) for region II (test temperatures from 20°C to 10°C) LJC28d shows the same performance in relation to G* as LJH; and 3) for region III (test temperatures<10°C), LJC28d displays poorer performance than LJH, which, on the other hand, has a higher G*.

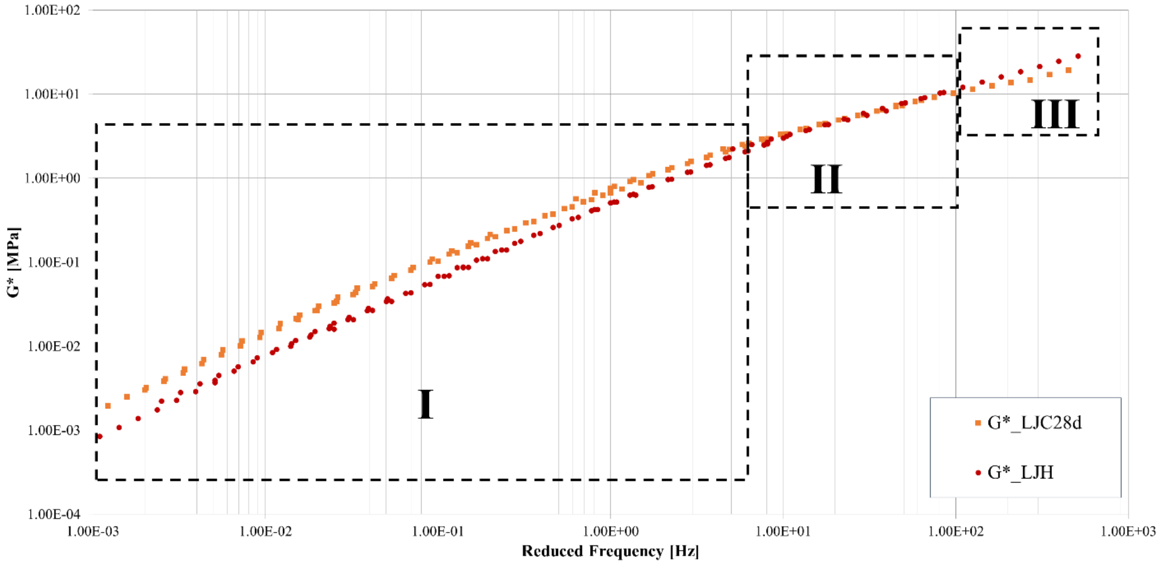


Figure 7.14: Master curves comparison between LJC28d and LJH

7.1.4 MSCR test results

The passage of traffic loads generates stress within the pavement causing accumulated strain in the mixture. The rutting resistance of cold bituminous mixtures, like those of a traditional HMA, is due to a) the interlocking of the aggregates and their form, and b) the stiffening effect of the mastic [64]. In the research presented here, mastic response to permanent deformation was estimated using the MSCR test. As the results shown in the previous sections demonstrated that best performance of cold mastics can be achieved at the end of the 28th day of curing time, the MSCR test was carried out using the above-mentioned mastics and the hot mastics (LH, JH an LJH) as control systems to measure the performance of the cold ones. .

Table 7.8 shows the $\bar{J}_{nr}$, values for each of the six mastics (LH, JH, LJH, LC28d, JC28d and LJC28d) at temperature of 40°C and 60°C and 0.1kPa and 3.2kPa stress levels.

As expected, $\bar{J}_{nr}$, increases as the temperature rises both for binders (B50/70 and EB60/40) and mastics. This is due to lower viscosity during the bituminous phase at higher temperatures, which results in higher permanent strain in the material under stress.

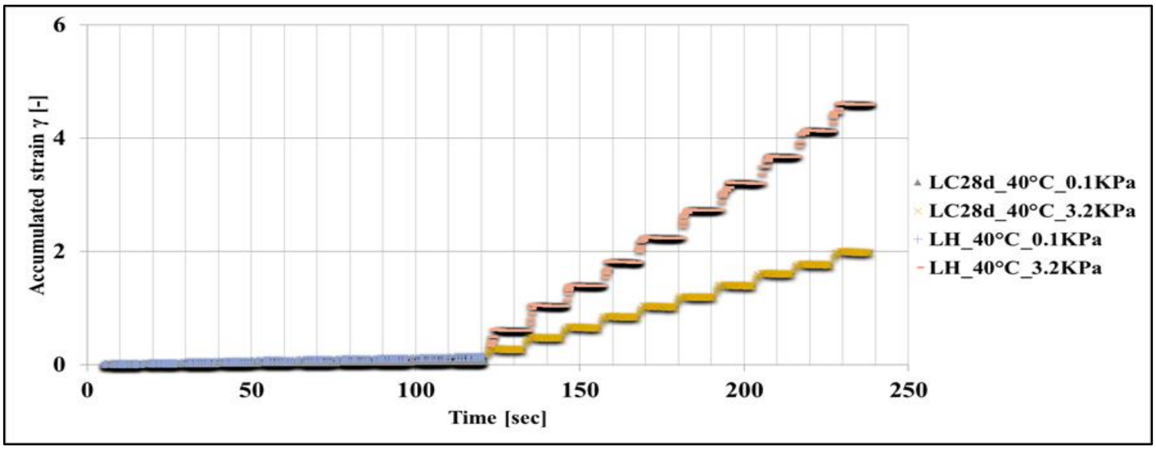
First of all, from a comparison between hot and cold mastics at the same test temperatures and load levels, all the cold mastics show a reduction of $\bar{J}_{nr}$; in particular, at 40°C and at 3.2kPa stress level, a greater reduction was observed, comparing the cold mastics with the corresponding hot mastics, for LJC28d, associated with a 68% $\bar{J}_{nr}$ reduction compared with LJH; a reduction of 57% was observed moving from LH to LC28d, and a 21% $\bar{J}_{nr}$ reduction when moving from JH to JC28d.

The experimental data highlight the contribution of adding alternative fillers to the bitumen and the bitumen derived from bituminous emulsion. The presence of JW improves the resistance of bitumen to permanent deformations, especially when added together with LF to bituminous binder. In fact, at temperatures of 40°C and 60°C, when JW is added to B50/70 for hot packaging, the $\bar{J}_{nr}$ values decrease by 38% and 21% respectively compared with LH; as for the cold mastics, LJC28d returned the highest reduction compared with the remaining cold mastics. In particular, LJC28d is characterized by a 74% $\bar{J}_{nr}$ reduction at a 40°C test temperature and 52% $\bar{J}_{nr}$ at a 60°C test temperature compared to LH.

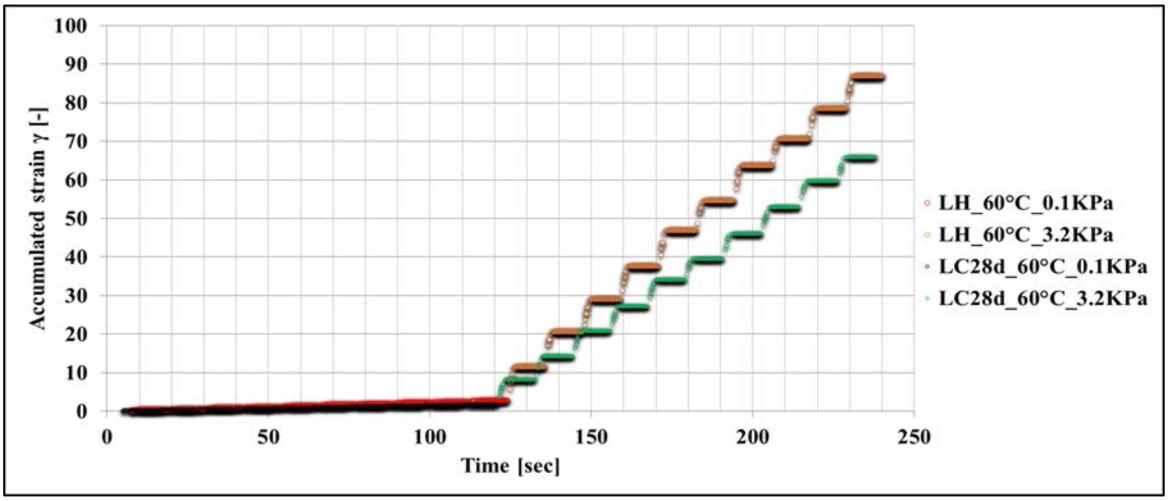
Figure 7.15 shows the differences between hot and cold bituminous mastics in terms of accumulated strain during 10 creep and recovery cycles; when adding LF and JW to bitumen Contained in bituminous emulsion (LJC28d), the stiffening effect reaches its highest value both at 40°C and 60°C. This confirms the results obtained previously for $\bar{J}_{nr}$.

Table 7.8 $\bar{J}_{nr}$ value of hot and cold mastics

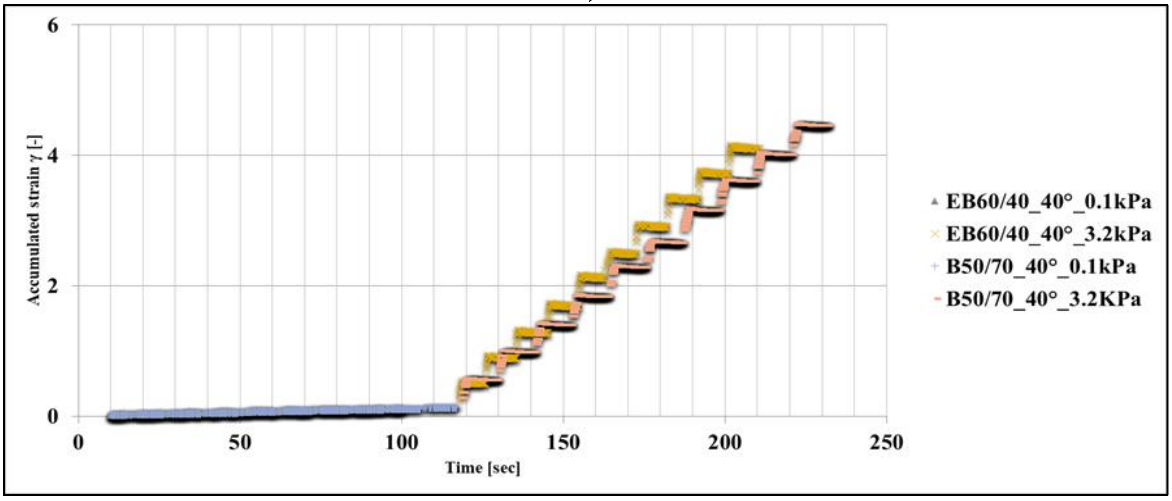
ID	Specimens	Test Temperatures			
		40°C		60°C	
		Jnr_0.1 kPa	Jnr_3.2 kPa	Jnr_0.1 kPa	Jnr_3.2 kPa
1	B50/70	0.128	0.139	4.149	4.321
2	EB60/40	0.112	0.128	3.387	3.829
3	JH	0.083	0.091	2.312	2.503
4	JC28d	0.053	0.062	2.059	2.211
5	LH	0.137	0.143	3.002	3.054
6	LC28d	0.051	0.072	1.767	2.394
7	LJH	0.104	0.108	2.745	2.753
8	LJC28d	0.036	0.052	1.360	1.529



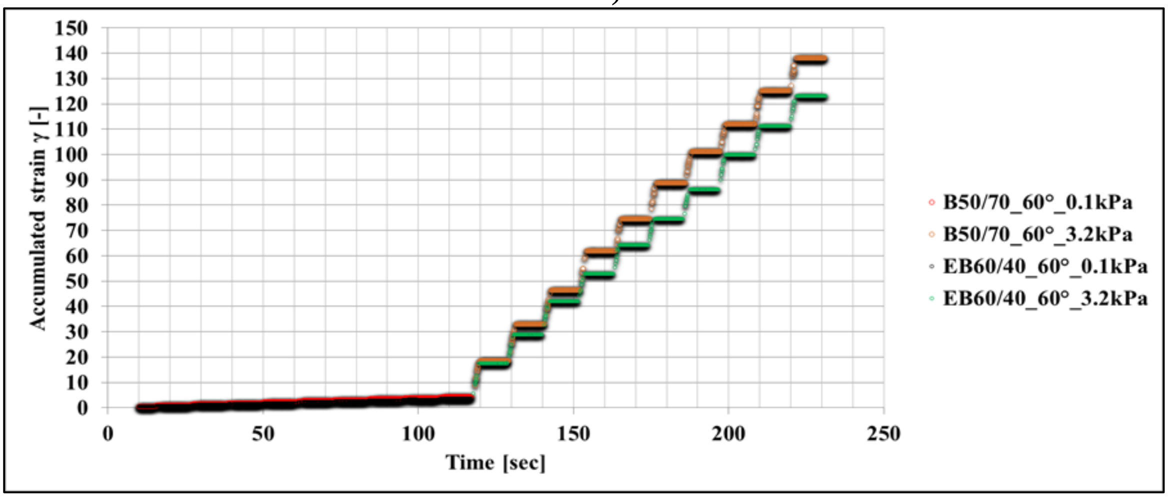
a)


Accumulated strain γ [-]
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
Time [sec]
LH_60°C_0.1KPa
LH_60°C_3.2KPa
LC28d_60°C_0.1KPa
LC28d_60°C_3.2KPa

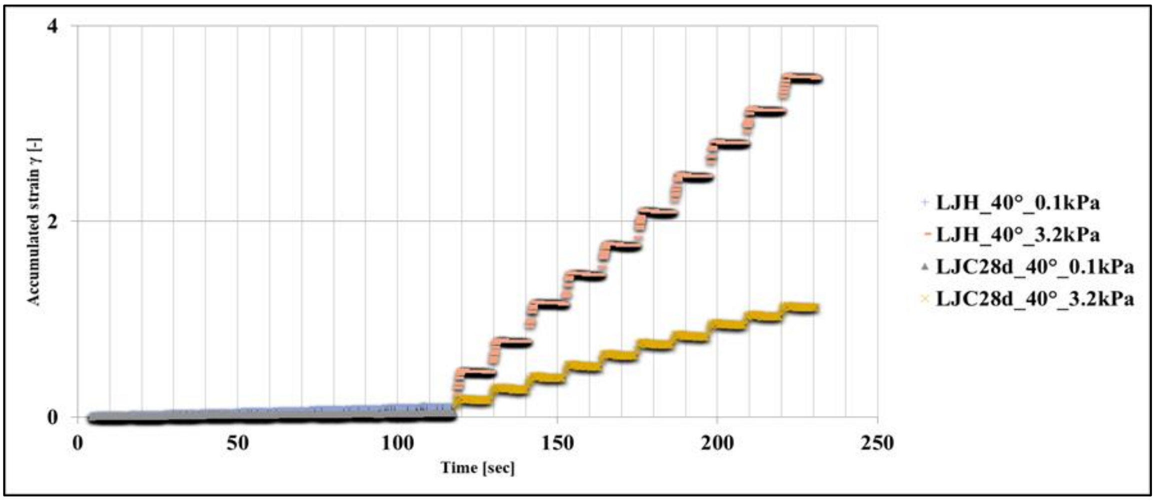
b)


Accumulated strain γ [-]
6
4
2
0
0
50
100
150
200
250
Time [sec]
EB60/40_40°_0.1kPa
EB60/40_40°_3.2kPa
B50/70_40°_0.1kPa
B50/70_40°_3.2KPa

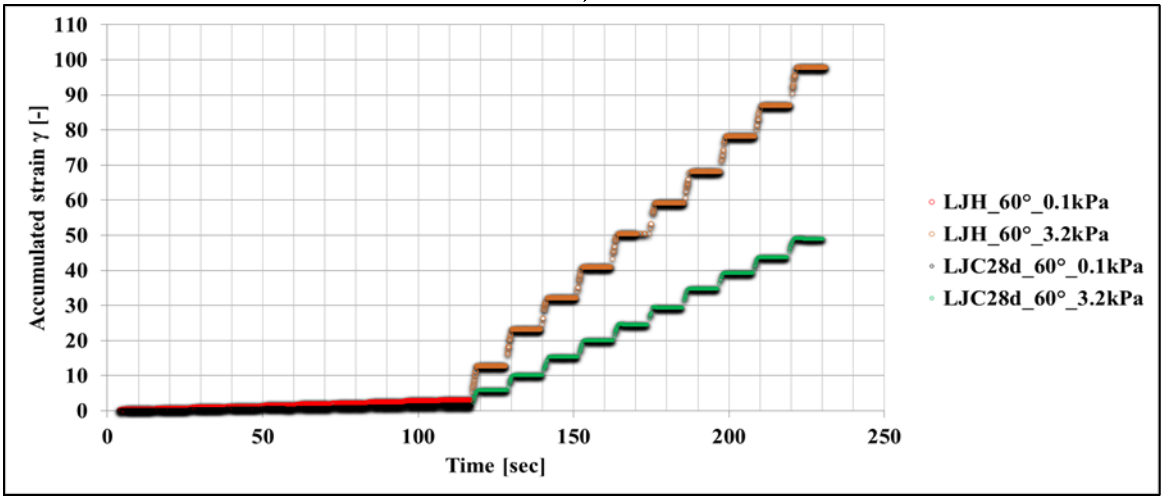
c)


Accumulated strain γ [-]
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
Time [sec]
B50/70_60°_0.1kPa
B50/70_60°_3.2kPa
EB60/40_60°_0.1kPa
EB60/40_60°_3.2kPa

d)



e)



f)

Figure 7.15: Accumulated strain results at the end of every 10 creep-recovery cycles of hot and cold bituminous mastics: a) LH vs LC28d (I at 40°C and II at 60°C), b) JH vs JC28d (I at 40°C and II at 60°C), and c) LJH vs LJC28d (I at 40°C and II at 60°C).

The ability of each mastic to recover from deformation at the end of the creep phase was evaluated in terms of J_{nr}/J_{TOT}.

If the material is unable to recover from any deformation, and the strain measured at the end of the creep phase remains the same at the end of the recovery phase, the J_{nr}/J_{TOT}. will be 1. On the contrary, if the material is totally elastic and able to recover from all the accumulated deformation, the J_{nr}/J_{TOT} will be 0 [65].

The results, in terms of J_{nr}/J_{TOT} expressed as percentages, are reported in Figure 7.16 but only at a test temperature of 60°C and 3.2kPa, as the results shown in Table 7.9 highlighted the most critical situations under these conditions.

Table 7.9 shows that more than 30% of elastic deformation is recovered by LJC28d, and positive performance was also observed for LC28d, which regains more than 25% of the deformation, while

JC28d returns less than 25% of elastic deformation. These results match previously achieved results in terms of G*. Hot mastics have poorer performance in terms of recovery from elastic deformation when compared with cold mastics, and in all cases less than the hot mastics. JH shows the best performance (recovery of elastic deformation less than 15%). This circumstance also confirms the results previously achieved in terms of G* for the cold mastics.

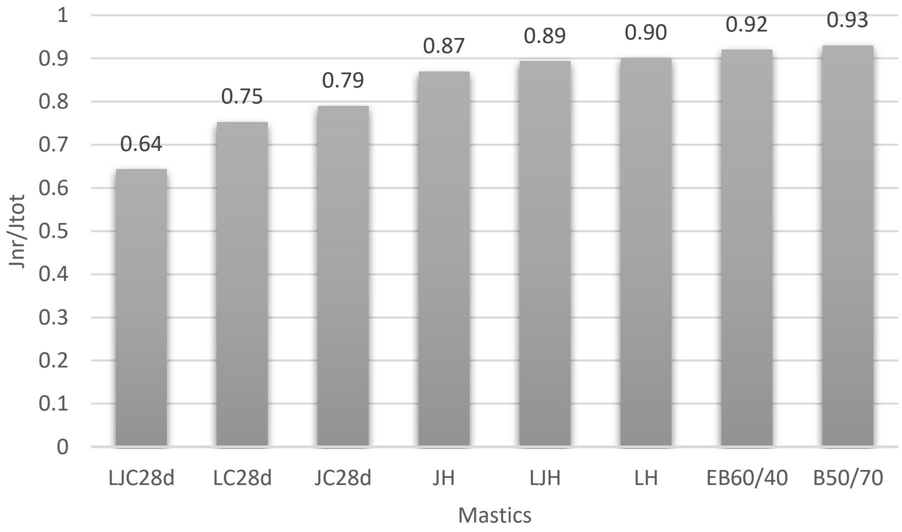


Figure 7.16: J_{nr}/J_{TOT} results under 3.2kPa and 60°C

In order to further evaluate the stiffening effect of the JW when added to hot and cold bituminous mastics, a ratio between the $\bar{J}_{nr}$ of mastics containing JW with LF (as results for G* and J_{nr}/J_{TOT} demonstrated how these mastics achieved the best performance) and the $\bar{J}_{nr}$ for mastics containing only LF, defined $J_{nr_{ratio}}$, was calculated from results in Table 7.8.

The results in Table 7.9 show that JW filler improves mastic stiffening during both hot and cold mixing. In particular, under hot conditions, the increase in stiffening caused by the addition of JW changes with the temperature but is not affected by stress levels. Under hot conditions, JW filler helps to increase stiffening by almost 25% compared with LH mastic at a test temperature of 40°C. In the case of hot mixing, the stiffening effect decreases from 40°C to 60°C, making up only around 10% of a further increase in stiffness due to the presence of JW in the mastic.

The greatest benefits can be achieved when the mastics are prepared under cold conditions: JW increases stiffness, both at 40°C and 60°C. At 0.1 and 3.2 kPa, the increase is around 30% compared with cold mastic made up of limestone filler and bitumen.

Table 7.9: $J_{nr_{ratio}}$ results: a) LJH/LH and b) LJC28d/LJ28d

	Mastics	Temperature			
		40°C		60°C	
		$J_{nr_{ratio}}$_0.1 kPa	$J_{nr_{ratio}}$_3.2 kPa	$J_{nr_{ratio}}$_0.1 kPa	$J_{nr_{ratio}}$_3.2 kPa
a)	LJH	0.763	0.755	0.914	0.901
b)	LJC28d	0.706	0.694	0.770	0.639

7.2 Study of the bituminous mastics made up of plastic waste

The research presented in this section aims to provide a broad-based experimental-methodological approach to the reuse of plastic waste (PW) materials as an alternative filler in bituminous mastics through the study of their physical and mechanical properties (see Figure 7.17). One of the main objectives of the research was to prepare mastics able to meet or exceed the performance of a) traditional limestone mastics (three solutions made up of 10%, 15%, and 20% LF by the total weight of B50/70) and, on the other hand, b) high performance hard modified bitumen (PmB 10/40-70) adopted for this study.

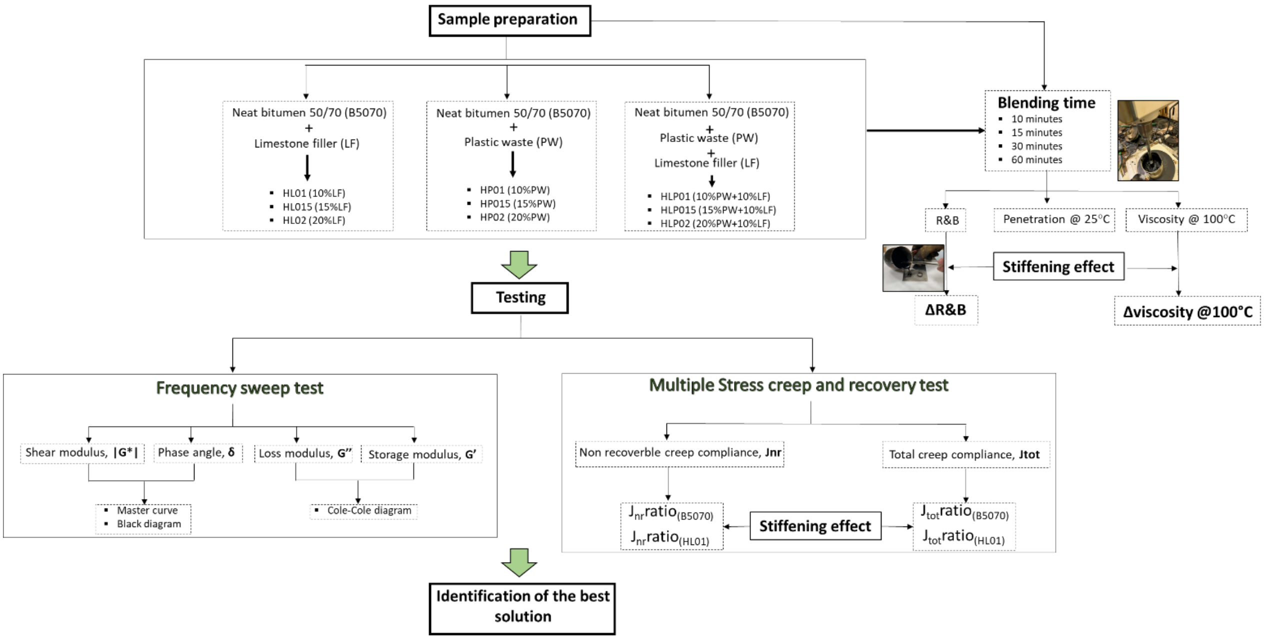


Figure 7.17 Experimental program of the study of the bituminous mastics made up of plastic waste

7.2.1 Materials

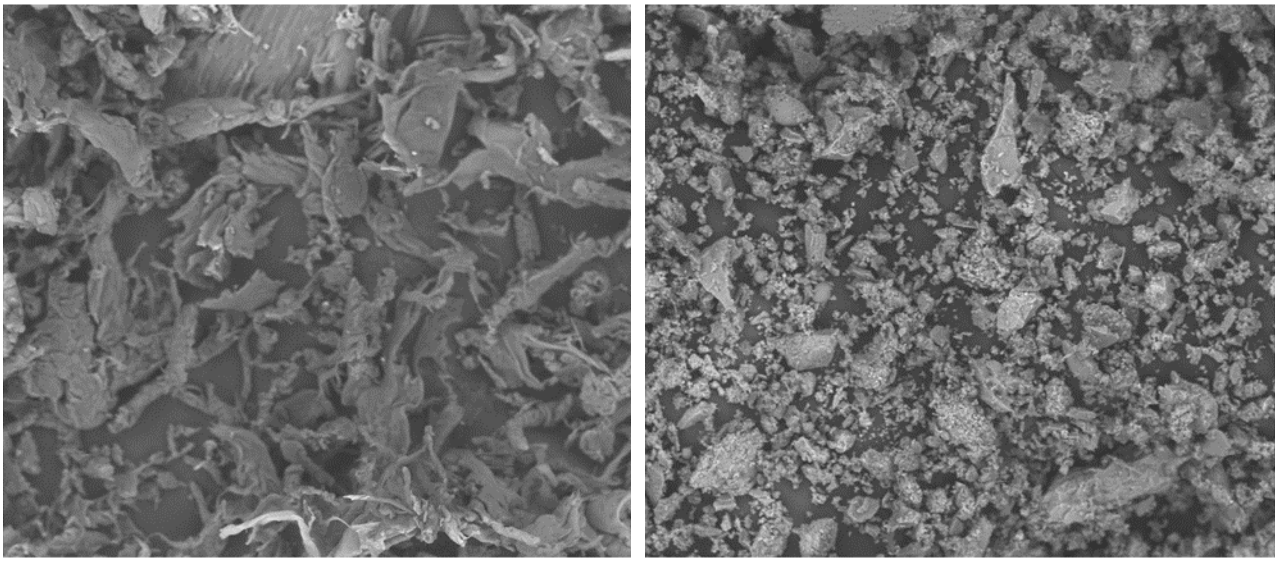
Plastic waste

The plastic waste material (PW) used here as an alternative filler in bituminous mastics (see Figure 7.18) is made up of PP, PET, HDPE and LDPE types; the result of the compound passes 100% at 2mm sieve size. PW derived from mechanical shredding of plastic bottles was subsequently washed in adequate facilities to remove any non-plastic residual, dried by centrifugation and by air stream ventilation, and finally sent to an extruder equipped with a perforated plate with a diameter of 2 mm.

Figure 7.18 PW filler

Comparing PW and LF through SEM characterization

Figure 7.19 shows the microstructure morphology of PW and LF fillers using Hitachi TM3000 Scanning Electron Microscopy (SEM) (see Figure 7.5a). Figure 7.19a shows a rough PW surface that appears as a strictly interconnected mesh of elongate elements more useful for the distribution of loads across the entire load-bearing section than an LF microstructure (see Figure 7.19b) made up of many circular elements separated from each other.



a) b)

Figure 7.19 SEM analysis: a)PW and b) LF

PW and LF volumetric analysis

Table 7.10 shows some of the main physical properties of PW and LF fillers, such as specific gravity, Rigden voids and specific surface area.

It can be observed in Table 7.10 that the mean value of the specific gravity of PW is 1.363 g cm^{-3}, lower than that associated with LF, due to the presence of different plastic types in the entire plastic matrix: it ranges from PP with a specific gravity of 0.9 g cm^{-3} to PET with 1.4 g cm^{-3}.

Table 7.10 also shows a mean PW Rigden void value 56% higher than that observed for LF; this condition will obviously affect the final stiffness of the mastics prepared using the above-mentioned fillers since it will be regulate the bitumen amount fixed in the interparticle voids and thus the amount of bitumen that will remain free. This implies that mastics made up of PW will be potentially stiffer than those made up of LF. Table 7.10 also shows a specific PW surface area 45% higher than LF: high surface area implies that PW filler particles can potentially adsorb more bitumen due to the greater interface surface between the granular particles and binder. This point fully fits with the value of the Ridgen voids.

Table 7.10 Main volumetric properties of the fillers used

Filler type	Specific gravity [g/cm^3] EN 1097-6	Ridgen voids [%] EN 1097-7	Specific surface area [cm^2/g] ISO 9277
LF	2.737	41.440	5480
PW	1.363	64.368	7930

Binders

Two types of binders were used for the purpose of the study: a) neat 50/70 bitumen (B50/70) from a refinery in Southern Italy, and b) a hard modified bitumen PmB 10/40-70 (HMB). The main properties of B50/70 are reported in previous Table 7.2a while the HMB properties are reported in Table 7.11.

Table 7.11 HMB properties

Properties	Unit	Standard	HMB
Penetration at 25°C	dmm	EN 1426	52
Softening point (R&B)	°C	EN 1427	87
Dynamic viscosity at 135°C			1.38
Dynamic viscosity at 100°C	Pa s	EN 13702	9.18
Dynamic viscosity at 60°C			1560

7.2.2 Bituminous mastics preparation

To prepare the mastics (see Figure 7.20), the filler over bitumen ratios have been carefully investigated, bringing together a) some scientific findings in the literature [66], and b) outcomes deriving from the laboratory research that pointed out a serious problem of workability by increasing the percentage of PW in mastics beyond 20% by the total weight of bitumen (see Figure 7.20c).

A total of nine mastics were prepared as follows:

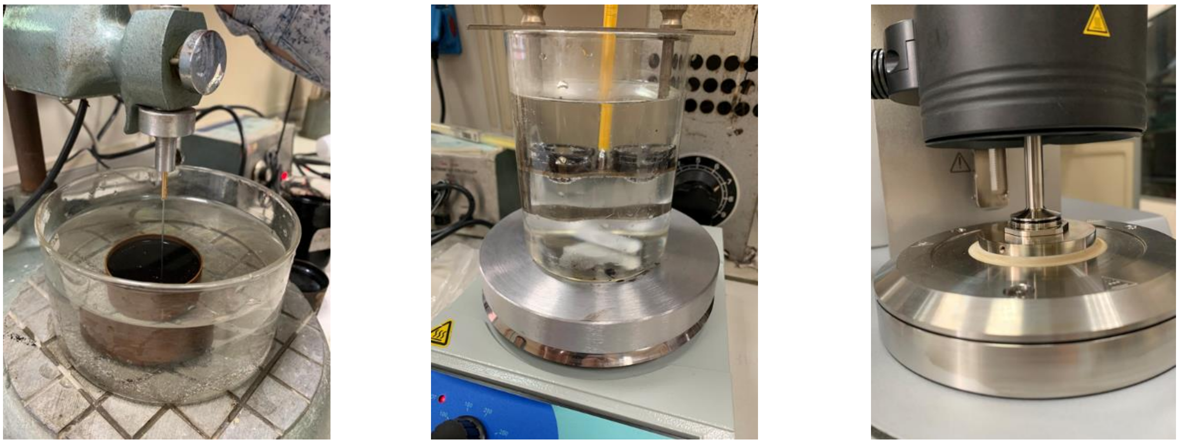
1) three mastics prepared by adding traditional limestone filler (LF) to neat 50/70 bitumen (B50/70); in particular three percentages (10%, 15%, 20%) of LF by the total weight of the bitumen were used, obtaining HL01 solution (filler-to-bitumen weight ratio (f/b) equal to 0.10), HL015 solution (f/b equal to 0.15), and HL02 solution (f/b equal to 0.20) respectively
2) three mastics prepared by adding plastic waste materials (PW) to B50/70; in particular three percentages (10%, 15%, 20%) of PW by the total weight of the bitumen were used, obtaining HP01 solution (f/b equal to 0.10), HP015 solution (f/b equal to 0.15), and HP02 solution (f/b equal to 0.20), keeping the weight of the mastic the same as the traditional one seen at point *1* above respectively
3) three mastics prepared by adding PW, a small percentage of LF and B50/70; in particular, 5% PW plus 5% LF, 10% PW plus 5% LF, and 15% PW plus 5% LF by the total weight of the bitumen obtaining, HLP01 solution (f/b equal to 0.10), HLP015 solution (f/b equal to 0.15) and HLP02 solution (f/b equal to 0.20) respectively.

Table 7.12 shows the amount of filler and bitumen adopted to make the mastics mentioned above, while Figure 7.20 shows the main steps for making mastics and for assessing some base properties such as penetration at 25°C, ring and ball temperature and dynamic viscosity at 100°C (see Figure 7.21), all of which together are taken as preliminary analyses for identifying the most appropriate blending time [67].

a) **b)** **c)**

Figure 7.20 Preparing bituminous mastics: a) mixing bitumen and filler, b) bituminous mastic specimen after completing the mixing phase and c) wrong mixing of PW and bitumen

To summarize the main steps for making mastics, first of all the bitumen was pre-heated in a metal container at 150°C for 1 hour and then poured into a steel container previously oven heated to 150°C. The filler was weighed and placed in an aluminium container before being gradually poured into the bitumen; the whole blend was mixed at 4500 rpm. Four samples were compared to define the optimal blending time of the mastics: 10, 15, 30 and 60 minutes mixing time. No substantial differences were found for any of the mastics by increasing mixing time in terms of R&B, penetration at 25°C or dynamic viscosity at 100°C. Thus, to save time and resources, a lapse of 10 minutes was selected to mix all the mastics for study. The results are shown in Table 7.12.



a) **b)** **d)**

Figure 7.21 Preliminary tests:a) Penetration, b) Ring and ball ancd c) Viscosity

Table 7.12 Main base properties of the mastics to be investigated after mixing for 10 minutes

Mastic type	Amount of LF	Amount of PW	Amount of B50/70	f/b	R&B EN 1427	Penetration at 25°C EN 1426	Dynamic Viscosity at 100°C EN 13702	ΔR&B EN 13179-1	Δviscosity at 100°C
	[gr]	[gr]	[gr]		[°C]	[dmm]	[Pa·s]	[°C]	[Pa·s]
HL01	15.00	-		0.10	47.60	65.00	4.13	1.60	0.03
HL015	22.50	-		0.15	48.00	65.00	4.17	2.00	0.07
HL02	30.00	-		0.20	48.80	64.00	4.31	2.80	0.21
HP01	-	15.00		0.10	55.20	49.00	8.83	9.20	4.73
HP015	-	22.50	150.00	0.15	61.10	N.A.	12.9	15.1	8.80
HP02	-	30.00		0.20	86.30	N.A.	15.62	40.3	11.52
HLP01	7.50	7.50		0.10	56.30	N.A.	9.50	10.30	5.40
HLP015	7.50	15.00		0.15	62.50	N.A.	13.88	16.50	9.78
HLP02	7.50	22.50		0.20	87.20	N.A.	18.76	41.20	14.66

Discussion of preliminary tests on the obtained bituminous mastics

Starting with a discussion of dynamic viscosity, Table 7.12 shows that none of the bituminous mastics with LF filler (HL01, HL015 and HL02) return relative small differences: the highest difference (3%) was observed by comparing HL015 with HL02. On the contrary, all the mastics containing PW as a filler showed a mean increase of 50% in terms of dynamic viscosity compared with previous mastics made up of LF. A slight increase in the dynamic viscosity was also observed when PW and LF were added together to the bitumen to make mastics: in particular, HLP01 showed an increase of 7.5% compared with HP01, while HLP015 showed an increase of 7.6% compared with HP015, and HLP02 20% more than HP02 (see Table 7.12 details on mastics). A rise in the total amount of filler in the mastic while keeping the amount of bitumen constant essentially increases dynamic viscosity.
Table 7.12 shows how increasing filler amount, R&B temperature also increases; in particular, it was observed an increase of 11% moving from HP01 to HP015, an increase of 41% from HP015 to HP02. Focusing on mastics made up adding together PW and LF as a filler, it was observed a) an increase of 11% from HLP01 to HLP015, and b) an increase of 39.52% from HLP015 to HLP02. A larger

amount of filler turns into more stiffness of the mastics; in particular comparing traditional limestone mastics with alternative mastics, it was observed how HL01 was 13.8% and 16.5% lower than HP01 and HLP01, respectively, HL015 was 21.4% and 23.2% lower than HP015 and HLP015, respectively, and HL02 was 43.5% and 44% lower than HP02 and HLP02.
With penetration at 25°C, Table 7.12 shows how the value for mastics with LF filler decreases by 4% compared with neat 50/70 bitumen, while for HP01 the value is 5.8% lower than HMB, which makes them comparable.

Table 7.12 shows two further parameters useful for investigating the stiffening effect of PW in mastics: a) ΔR&B as the difference between the R&B value for each of the nine bituminous mastics and the R&B value of B50/70, and b) Δviscosity at 100°C as the difference between the dynamic viscosity at 100°C for each of the nine bituminous mastics and the dynamic viscosity at 100°C of B50/70.
Table 7.12 shows that when increasing the Ridgen voids in the filler, the ΔR&B of the mastic containing it increases; it will be noted, for example, that HL01 was 82.6% lower than HP01 in terms of ΔR&B value, and HL015 was 86.75% lower than HP015, while HL02 was 93.05% lower than HP02. It is also observed that the ΔR&B increases as the amount of PW increases in the bituminous mastic; results showed that the ΔR&B value of HP015 is 64.13% higher than HP01, while the ΔR&B of HP02 is 167% higher than that of HP015. On the contrary, when mastics with PW filler (HP01, HP015 and HP02) and mastics with both LF and PW as filler (HLP01, HLP015 and HLP02) are compared, slight increases may be observed in terms of ΔR&B when the total filler amount is increased. In particular, when comparing HP01 with HLP01 a 1.99% ΔR&B increase was observed; a comparison of HP015 with HLP015 shows an increase of 2.29%, while comparing HP02 and HLP02 gives an increase of 1.04%. Therefore, the behaviour of mastics containing PW or PW+LF filler showed only slight differences when the specimens were under static load actions during laboratory tests, while the differences were greater when dynamic loads were applied.
In terms of Δviscosity at 100°C, no substantial differences were observed for mastics with LF filler (HL01, HL015 and HP02), but moving towards mastics with PW filler an increase of Δviscosity at 100°C was observed when the amount of filler was increased; in particular, there was an increase of 86% and 31% when comparing HP015 with HP01, and HP02 with HP015, respectively. Investigating mastics containing both PW and LF as filler, an increase of Δviscosity at 100°C compared with mastics containing only PW can be observed: respective increases of 14%, 11%, and 27% were observed when comparing HP01 with HLP01, HP015 with HLP015, and HP02 and HLP02.

7.2.3 Frequency sweep test results

The frequency sweep (FS) test (EN 14770) was carried out by using frequency values falling within a range from 0.1 to 10Hz (a total of 20 observations were made with a gap of 0.1 for frequencies from 0.1 to 1Hz, and a gap of 1Hz for frequencies from 1 to 10Hz, passing through 1.59Hz) at six test temperatures (0, 10, 20, 30, 40, and 50°C).

In compliance with EN 14770, before moving on to the FS test, a viscoelastic linear region (LVE) was identified setting out a number of three conditions as follows: a) strain sweep was evaluated under a "25 mm plate-plate geometry" configuration at 50°C and for a frequency of 0.1Hz; b) strain sweep was evaluated under an "8mm plate-plate geometry" configuration at 0°C and for a frequency of 10Hz; c) making sure it fell within the LVE region, it was verified that the difference between G' (storage modulus) and G'' (loss modulus) did not differ more than 5% from its initial value, chosen where the intercept of a regression line fitted the measured values.

The obtained results were explained through the master curves, the black diagrams and the Cole-Cole diagram as follow described.

Looking at the master curves in Figure 7.22, it can first be observed that two main issues emerge under 10°C: a) the HL02 solution (the mastic with the highest percentage of LF among all those prepared using LF as a filler, see Table 7.12) shows a slight increase in G* (3%) compared with B50/70, and HP02 shows an increase of no more than 6% compared to B50/70, and b) on the other, HL015 and HP015 mastics show the greatest differences in terms of G* than was observed for B50/70, with a mean increase of 46% and 44%, respectively.

Examination of the mastics with PW filler reveals a gradual increase in G* moving from 20°C to 50°C compared to B50/70; in particular, the HP01 solution shows an increase of 47% (20°C), 60% (30°C), 82% (40°C) and 99% (50°C), while HP015 shows an increase of 63% (20°C), 88% (30°C), 120% (40°C), and 181% (50°C), and HP02 an increase of 74% (20°C), 93% (30°C), 170% (40°C), and 223% (50°C).

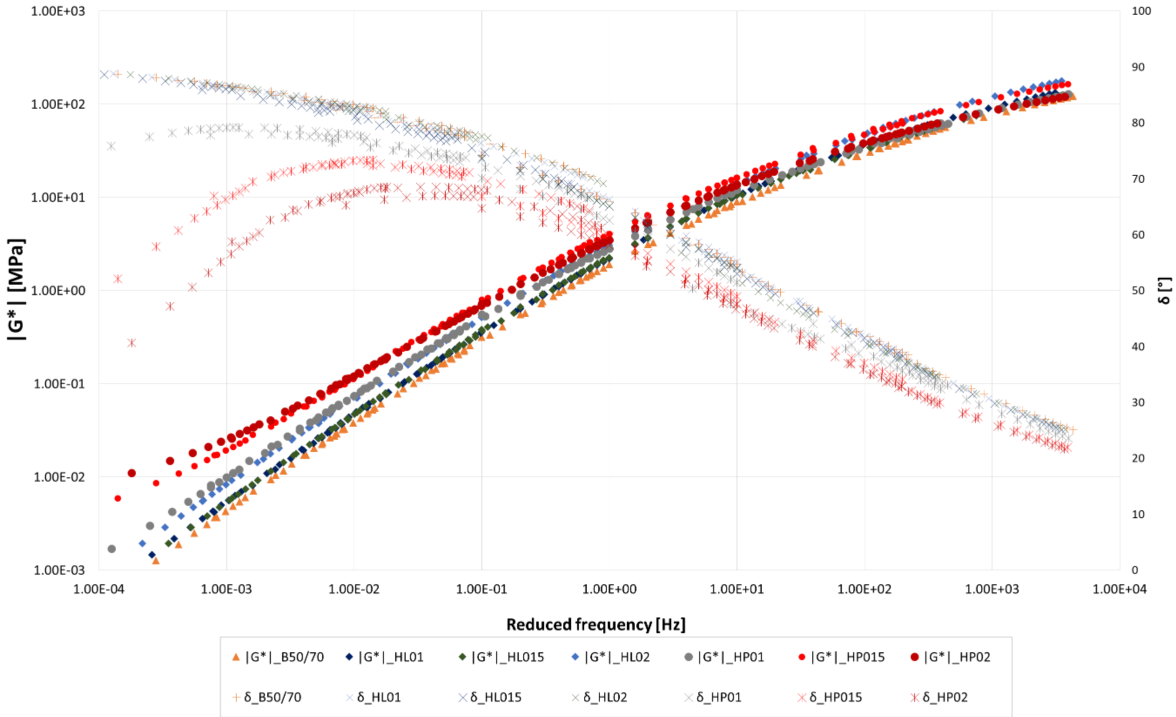


Figure 7.22 Comparing HL01, HL015, HL02, HP01, HP015, HP02, B50/70 solutions as master curves, showing phase angles

Moving on to the phase angle analysis, it can be observed that none of the mastics with LF (HL01, HL015 and HL02) differed substantially from B50/70. Further analysis of the results was thus necessary, which involved plotting the black diagrams and Cole-Cole diagrams. The B50/70 bitumen showed partial visco-elastic behaviour at low temperatures (0°C with minimum and maximum phase angles of 25.08° and 46.38°, respectively) and fully viscous behaviour at the highest temperature investigated (50°C), which is close to its softening point (see Table 7.12); a phase angle of 90° was observed at 50°C.

Mastics made up with plastic waste returned lower phase angle values than those observed for all limestone mastics (20% mean global decrease of the phase angle moving from mastics made up of LF to PW as a filler).

Looking in greater detail at the black diagram in Figure 7.23, two main zones can be identified to group the main performance of all investigated binders and mastics, on the basis of the locus of the points that mark potential reversal in the behaviour of the investigated material as follows: the upper (A) and lower zones (B) have been defined.

The range of the test temperatures belonging to zone A moves from 0°C to 30°C; within zone A, the HP01 and HP015 solutions return the best performance compared with the traditional limestone mastics (HL01, HL015 and HL02) because the values of the shear modulus assume a mean global increase of 30% compared with the limestone mastics, while the phase angles show a mean global reduction of 15% compared with limestone mastics.

Looking at zone B, the results refer to test temperatures of 40°C and 50°C. It can be noted that all the mastics made up with PW as a filler return a mean global phase angle reduction of 46% compared to all the prepared limestone mastics; specifically, the HP02 solution obtains good performance in terms of elastic behaviour, since by keeping a constant G* value, the corresponding phase angle value is 18% lower than HP01 and 12% compared to HP015. Dissimilarly, examining mastics made up with LF (HL01, HL015 and HL02) and B50/70, on the one hand, some of the corresponding results falling within zone A show that the shear modulus decreases by increasing the phase angle and the test temperatures from 0°C to 40°C, on the other, for zone B, the remaining results show how G* values continue to decrease by increasing the phase angle (total viscous behaviour): this is the exact opposite of what can be observed in the same B zone for mastics made from PW filler, as described above.

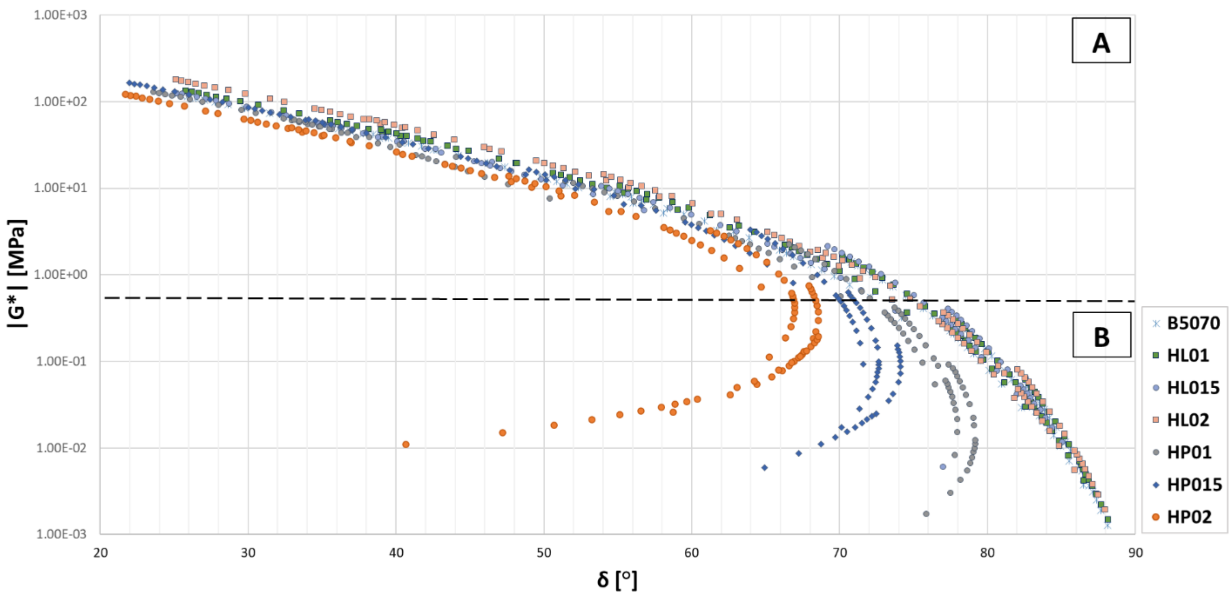


Figure 7.23 Black diagrams: comparing the performance of the HL01, HL015, HL02, HP01, HP015, HP02, B50/70 solutions

On the basis of the results achieved so far, it was decided to proceed with further investigation by comparing HP02 (that resulted to be the mastic solution with the highest performance) and modified bitumen (HMB) in order to identify the conditions under which the performance of the two solutions matched. Figure 7.24 shows the master curves and the phase angles of HMB and HP02. Looking for main similarities and differences, Figure 7.24 was divided into main four zones: A, B, C, D.

Zone A shows a first discrepancy between the HP02 and HMB solutions; if on the one hand the solutions have comparable shear modulus values by changing the reduced frequency, on the other there is a great difference in terms of phase angles, touching an average of 20% moving from HMB to HP02.

Zone B indicates comparable homogeneous behaviour for the two solutions in terms of both the shear modulus and the phase angle; on the one hand, it can be observed that at the beginning of the zone, HP02 shows a) a mean 30% increase in phase angle compared to HMB, b) a mean reduction in G* of around 16% compared to HMB, and c) on the other hand, the two solutions perfectly overlap from the middle to the end of the B zone.

Zone C shows other inconsistencies in the comparison of HP02 and HMB; in fact, while the HP02 solution G* values increase consistently compared with HMB from the beginning to the end of the zone, reaching the substantial difference of 57%, the phase angles, conversely, are on average always higher for HP02 than for HMB, reaching the biggest gap at the beginning of zone C (the phase angle of the HP02 solution is 30% higher than that observed for HMB) indicating viscous behaviour by the HP02 solution. The trend is consistent only at the end of zone C, where the phase angles of two solutions overlap.

Zone D shows uniform behaviour for the HP02 and HMB solutions, pointing out the elastic behaviour of HP02 that maintains higher shear modulus values than those observed for the HMB solution (HP02 reaches a 92% mean shear modulus increase compared to the HMB solution at the end of the zone), matched by 19% lower phase angle values.

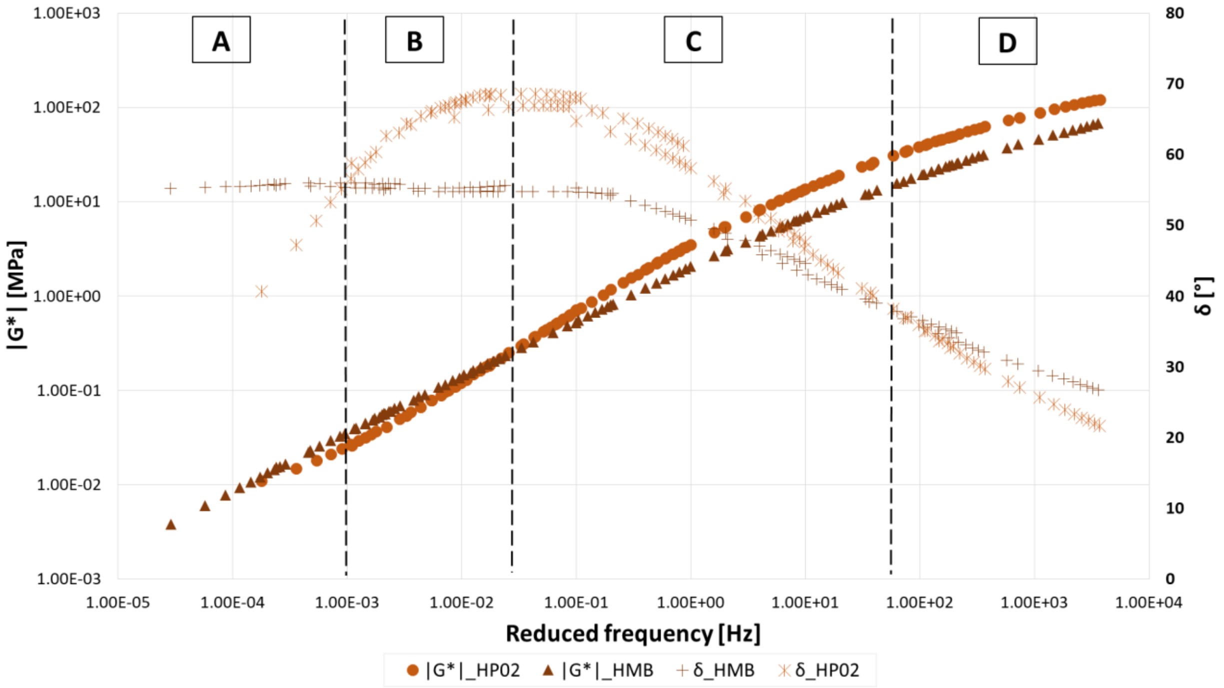
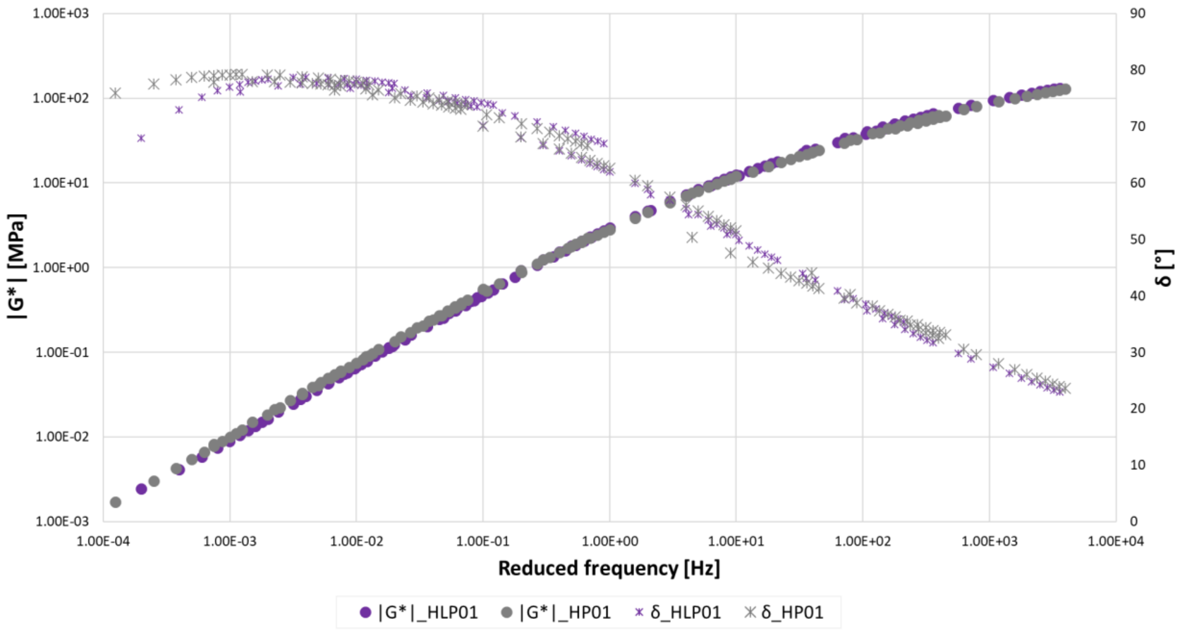
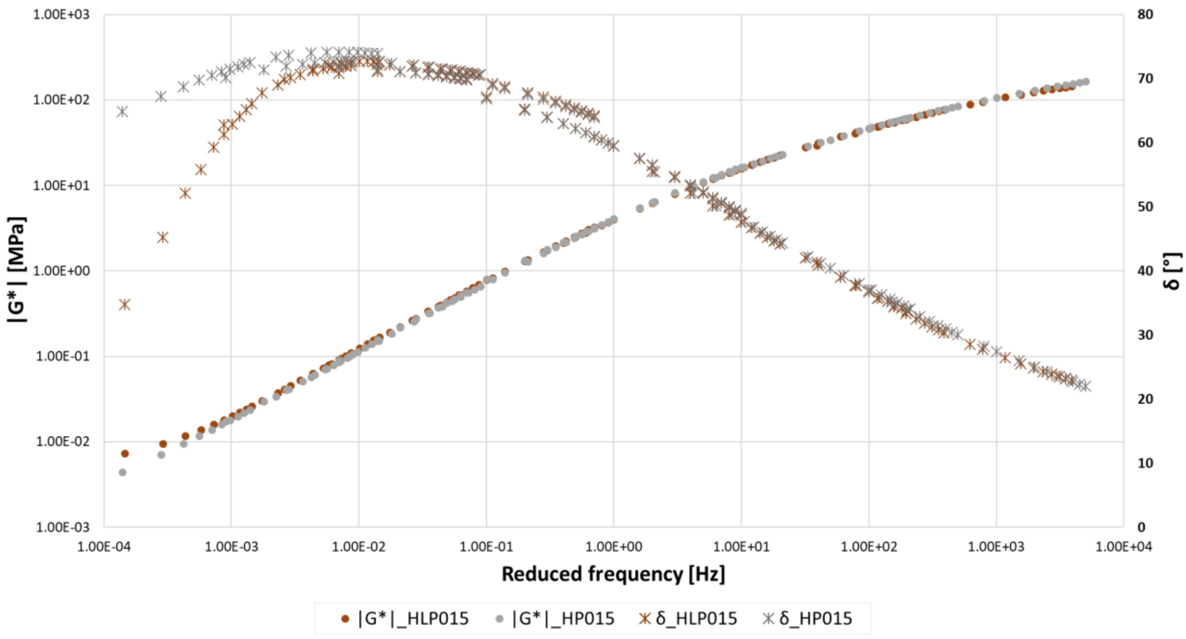


Figure 7.24 Comparing HP02 and HMB as master curves, showing phase angles

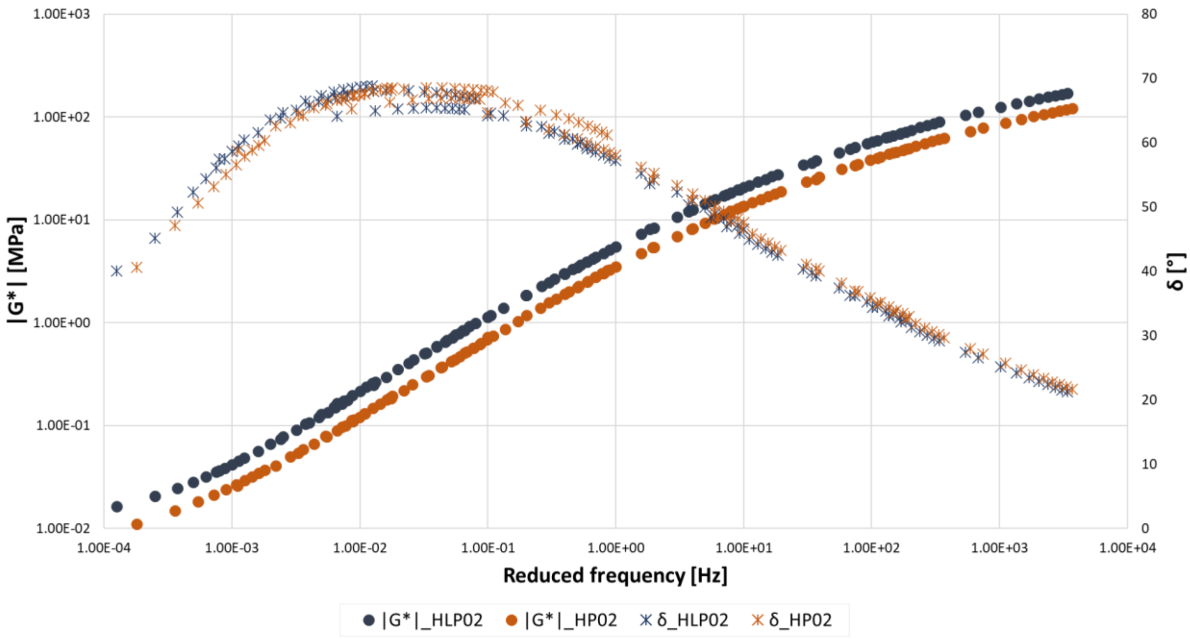
Figure 7.24 helps to demonstrate that HP02, considered to be the best solution so far before moving to an analysis of the black diagram, has insufficient abilities to match or exceed the high performance of HMB under all temperatures and frequencies. Thus, in order to support the reuse of plastic waste in bituminous mastics in a wide range of applications, it was decided to prepare three other new bituminous mastics, where a low portion of limestone filler was added to PW and neat 50/70 bitumen. Three additional mastics were made by adding 5% LF by the total weight of neat bitumen to 5%, 10%, and 15% PW by the total weight of the bitumen, obtaining the HLP01, HLP015 and HLP02 solutions respectively (the amounts of materials are shown in Table 7.12).
To bridge the gaps deriving from the results in Figures 38 and 40, three mains pairwise comparisons were carried out as shown in Figure 7.25.



a)



b)



c)

Figure 7.25 Comparing G* master curves and phase angles: a) HP01 vs HLP01, b) HP015 vs HLP015 and c) HP02 vs HLP02

Figure 7.25 contains the following information:

- Figure 7.25a shows HP01 vs HLP01; no significant differences exist in terms of the shear modulus and phase angles for the mentioned solutions. Slight differences exist in terms of the phase angle within a range frequency of 0.1-0.3 Hz, where HLP01 returns a mean reduction of 8% compared to HP01;

- Figure 7.25b shows HP015 vs HLP015; there are no significant differences in terms of the shear modulus and phase angles for the two mentioned solutions. Slight differences exist in terms of G* below 0.4Hz, where HLP015 shows a mean increase of 12% of the shear modulus compared to the other solution, and small differences exist in terms of the phase angle below 0.5Hz where HLP015 shows a mean reduction of 32% of the phase angle compared with the other solution;
- Figure 7.25c shows HP02 vs HLP02; significant differences exist in terms of the shear modulus that always appears on average 29% higher for HLP02 than for HP02, while no significant differences exist in terms of the phase angles between the two mentioned solutions (on average the difference is less than 2%).

To obtain more information on the two last solutions, a further study was made comparing HLP02 and HMB (see Figure 7.26); for simplicity, the area was divided into three main zones: A, B, C.

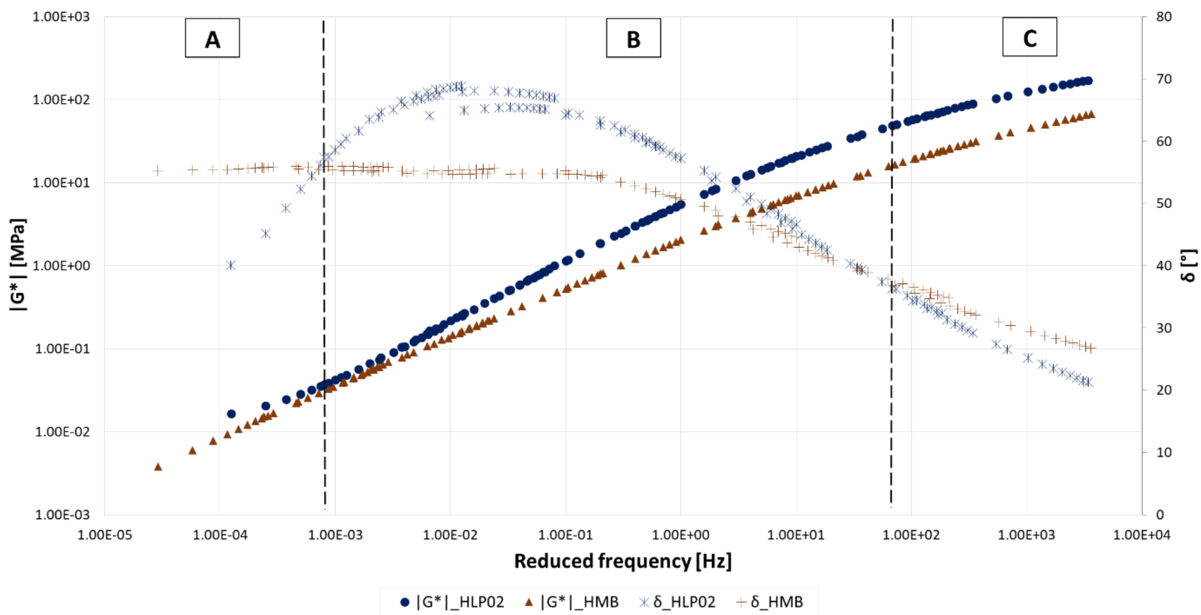


Figure 7.26 Comparing HLP02 vs HMB as master curves, showing phase angles

Zone A shows comparable shear modulus values for the two solutions even if, on average, HLP02 generally maintains higher shear modulus values than those observed for HMB, which matches HLP02 at the end of zone A. On the other hand, there is a great difference in terms of phase angles: HLP02 shows a mean reduction of 27.4% compared with HMB.

Zone B shows other inconsistencies when comparing HLP02 and HMB; in fact, on the one hand, the HLP02 G* value increases more than HMB from the beginning to the end section of B zone, where the highest difference is 182%. On the other hand, the HLP02 phase angles are always higher than

HMB, reaching the greatest gap at the start point of this zone (the HLP02 phase angle solution is 24% higher than that observed for HMB). This indicates viscous behaviour by the HLP02 solution in zone B. The trend only shows reliable behaviour at the end of zone B, where the phase angles of the two solutions overlap.

Zone C shows a comparable performance of HLP02 and HMB solutions, pointing out the elastic behaviour of the first former, which maintains higher shear modulus values than those observed for HMB (HLP02 maintains a constant gap of 170% compared to the HMB solution, starting from the end of the B zone); the HLP02 G* values meet the low values of the phase angles that attain their highest reduction compared with HMB, equalling 21% at the end of the zone.

To make a complete and exhaustive comparison, the next step focused on the comparison of the HP02, HLP01, HLP015, HLP02, and HMB solutions by plotting the black diagrams as shown in Figure 7.27.

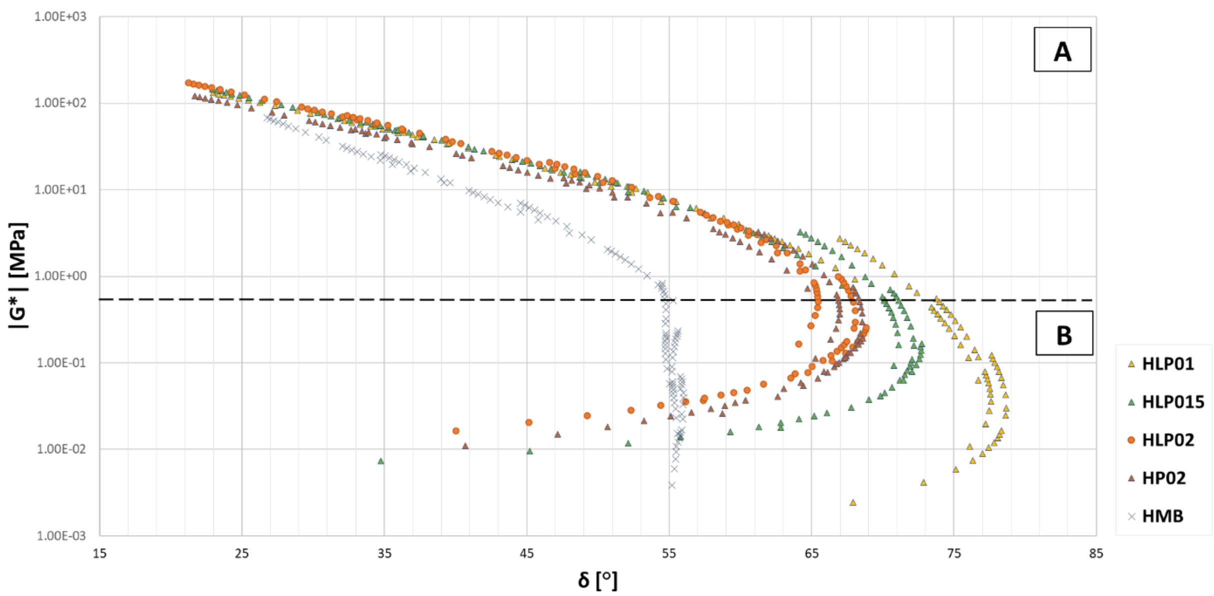


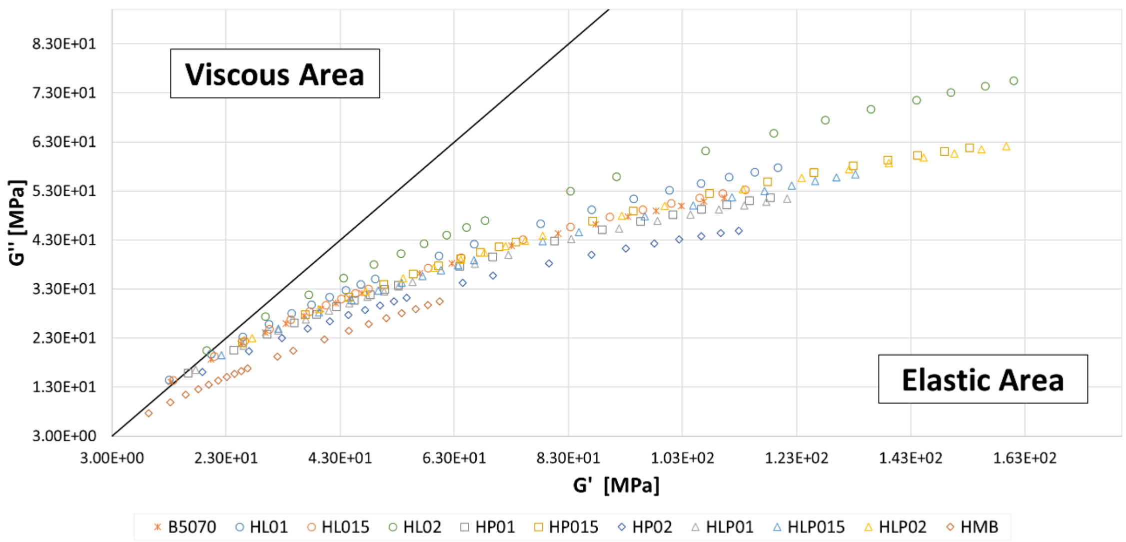
Figure 7.27 Comparing the HLP01, HLP015, HLP02, HP02, and HMB solutions by plotting the black diagrams

Looking into the black diagrams, two main areas can be identified to facilitate a description of the main behaviour of all the investigated materials: upper zone (A) and lower zone (B).

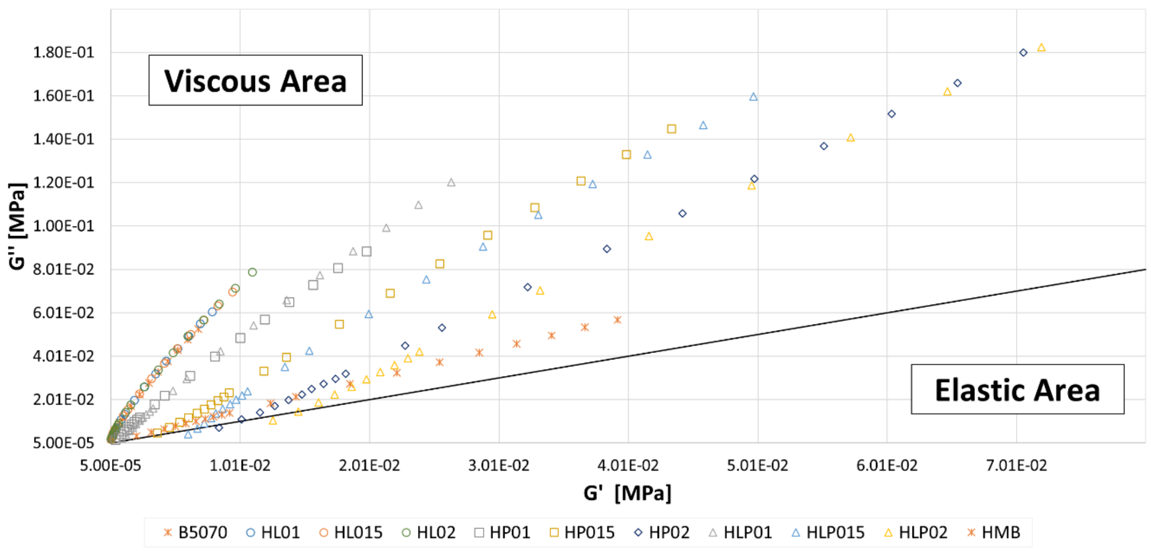
The range of test temperatures falling within zone A goes from 0°C to 30°C; within zone A, HLP02 shows the best performance compared with the HP02 and HMB solutions because, on average, the values of the shear modulus are around 15% higher than those observed for HP02 and around 42% higher than those observed for HMB; on the contrary, HMB shows an average of 7% lower phase angles than those observed for HLP02 and HP02, which are essentially equivalent.

Looking at zone B, the results refer to 40°C and 50°C test temperatures. It may be noted that the HLP02 solution has the best performance in terms of elastic behaviour since by maintaining a constant G* value, the corresponding phase angle values are on average 23% lower compared with the HP02 solution and 30% lower compared to HLP01. The HMB is not able to return phase angle values lower than those observed for HLP02, which fall to less than 55° (i.e. 30°). This finding helps to support the point that HLP02 as a whole gives the best performance compared with the remaining solutions investigated here.

A further careful investigation regarding the performance of the mastics and binders prepared here was carried out by plotting a Cole-Cole diagram (see Figure 7.28) where the x-axis indicates the storage modulus (G'), and the y-axis shows the loss modulus (G'') [68]. For all the investigated mastics (HL01, HL015, HL02, HP01, HP015, HP02, HLP01, HLP015 and HLP02), a Cole-Cole diagram for neat bitumen (B50/70) and modified bitumen (HMB) at test temperatures of 0°C (see Figure 7.28a) and 50°C (see Figure 7.28b) was drawn. Each diagram was divided into two main areas by the bisector of the I quadrant: a) the upper area defines the zone where materials show prevalently viscous behaviour; b) the lower area defines the zone where materials show prevalently elastic behaviour [69].



a)



b)

Figure 7.28 Comparing bituminous mastics and binders by plotting the Cole-Cole diagram: a) 0°C test temperature, b) 50°C test temperature

Figure 7.28a shows how all the investigated materials at 0°C fall within the elastic area; in particular, the bituminous mastics that showed more elastic behaviour are HP02 and HLP01 followed by HMB, which returns average G' values higher than G'' of 89%, 76% and 66%, respectively. Therefore, the results achieved above, confirmed by the Cole-Cole diagram at a low test temperature lead to the conclusion that 20% of PW by the total weight of bitumen added to B50/70 bitumen (the HP02 solution) helps make a mastic with a much better elastic performance than the modified bitumen (HMB). In addition, the performance improves even more when 5% LF is mixed with 15% PW by the total weight of bitumen and neat B50/70 bitumen (HLP02) (see Figure 7.28a).

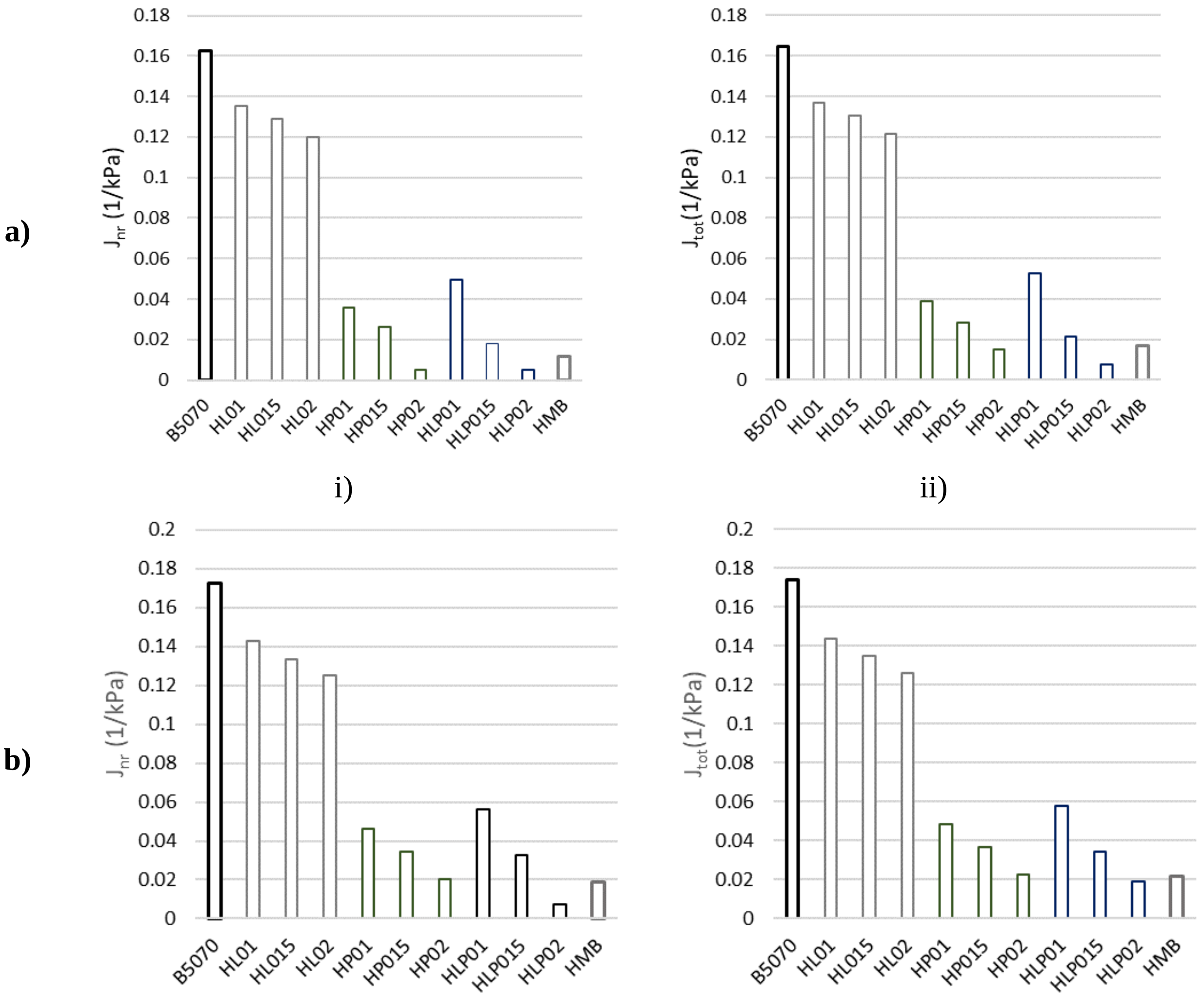
When the temperatures increase, the bitumen and bituminous mastics tend towards predominantly viscous behaviour: the G'' component is greater than G'. All the investigated materials accord with the previous condition-placing in the Cole-Cole diagram above the bisector in the viscous zone (see Figure 7.28b). Neat 50/70 bitumen returns lower G' values than G'' values (with a mean reduction of 92%). HP02, HLP02 and HMB show a prevalently elastic component. Modified bitumen (HMB), on the other hand, was found to have a higher G' to G'' ratio than HLP02 and HP02, which have the same reduction at around approximately 15% (see Figure 7.28b).

7.2.4 The multiple stress creep and recovery test results

An MSCR test was carried out using DSR. Following EN 16659, the value of 40°C was selected from the lowest temperature values suggested here, while a test temperature of 50°C was chosen in the light of the lowest value of the softening point achieved during the laboratory test (see Table 7.12).
Figure 7.29 shows the MSCR test outcomes. What first meets the eye is that, at all test temperatures and under two stress levels, the B50/70 binder gives mean J_{nr} and J_{tot} parameters higher than those associated with all the other solutions. Overall, it is noted that recoverable creep compliance improves starting with B50/70, which, as mentioned, gave the worst performance, in the following order: mastics made up with LF filler (averaging 30% more than B50/70), mastics made up with PW filler (averaging 84% more than B50/70), mastics made up adding both PW and LF as fillers (averaging 90% more than B50/70), and HMB (92% on average than B50/70). The results confirm the positive contribution of LF and/or PW filler when added to B50/70; specifically, the best performance is shown by mastics consisting of 20% PW by the total weight of the bitumen, and above all when 5% LF is added to 15% PW by the total weight of the bitumen.
On the whole, J_{nr} and J_{tot} appear to be thermo-dependent but not stress-dependent in all the solutions investigated. We should now examine performance of all the solutions at 40°C and 50°C, with 3.2kPa. It can be observed, first of all, in Figure 7.29a-ii that the mean J_{nr} and J_{tot} values at 40°C match each other, and this is true for all mastics made up from PW, both when it is used a) as a total filler (HP01, HP015, HP02 show a mean J_{nr} value of 0.0338 kPa^{-1} and a mean J_{tot} value of 0.0352 kPa^{-1}), and b) when it covers a part of the total amount of filler (HLP01, HLP015, HLP02 have a mean J_{nr} value of 0.0359 kPa^{-1} and a mean J_{tot} value of 0.0378 kPa^{-1}). So, the best performance at 40°C was reached by three main solutions such as HP02, HLP02, and HMB that more or less meet the same lowest average values for J_{nr} and J_{tot} equals 0.0213 and 0.0217 kPa^{-1} respectively. Upon comparison at 40°C, HL02 vs HP02, and HL02 vs HLP02 (HL02 gives the lowest value of loss deformations among all the remaining limestone mastics), a mean total reduction of 84% in terms of J_{nr}, and 82% in terms of J_{tot} can be observed. It is clear that J_{nr} and J_{tot} values do not differ significantly from each other at 40°C (8%); this means that the stiffness contribution brought by PW to the mastic gives good HP02 and HLP02 elastic behaviour even from the end of the loading phase as J_{nr} and J_{tot} are equal.
Moving on to Figure 7.2b-ii, it can be observed that the mean value of J_{nr} and J_{tot} at 50°C overlap each other, and this is true for all mastics made up of PW both when PW is used a) as a total amount of filler in the mastics (HP01, HP015, HP02 solutions, which show a mean J_{nr} value of 0.2278 kPa^{-1} and a mean J_{tot} value of 0.2243 kPa^{-1}), and b) when it covers a part of the total filler amount (HLP01, HLP015, HLP02 solutions that show a mean J_{nr} value of 0.2147 kPa^{-1} and J_{tot} mean value of 0.2082

kPa^{-1}); in particular, as happened at 40°C, both the first (HP) and second (HLP) mastic-making options show a mean decrease in J_{nr} and J_{tot} values of 73% and 72% respectively, in comparison with the whole dataset, that includes mastics prepared with LF filler (HL01, HL015 and HL02 show a mean J_{nr} value of 0.7913 kPa^{-1} and a mean J_{tot} value of 0.7922 kPa^{-1}). So, the best performance at 50°C was reached by HP02, HLP015, HLP02, and HMB, which approximately meet the same lowest average value as J_{nr} and J_{tot} equals 0.1456 kPa^{-1} and 0.1196 kPa^{-1} respectively. Comparing the four above-mentioned solutions with HL02, a mean reduction of 83% in terms of J_{nr} and J_{tot} can be observed, as at 40°C.

So, drawing some conclusions, HLP02 appears, in the light of the results achieved so far, to be the most suitable mastic solution, both in terms of J_{nr} and J_{tot} at 40°C and 50°C under 0.1kPa and 3.2kPa, and in terms of the mechanical characterization carried out in the previous sections, exceeding the performance of the limestone mastics and fitting very well the performance of the hard modified bitumen used here as top reference.



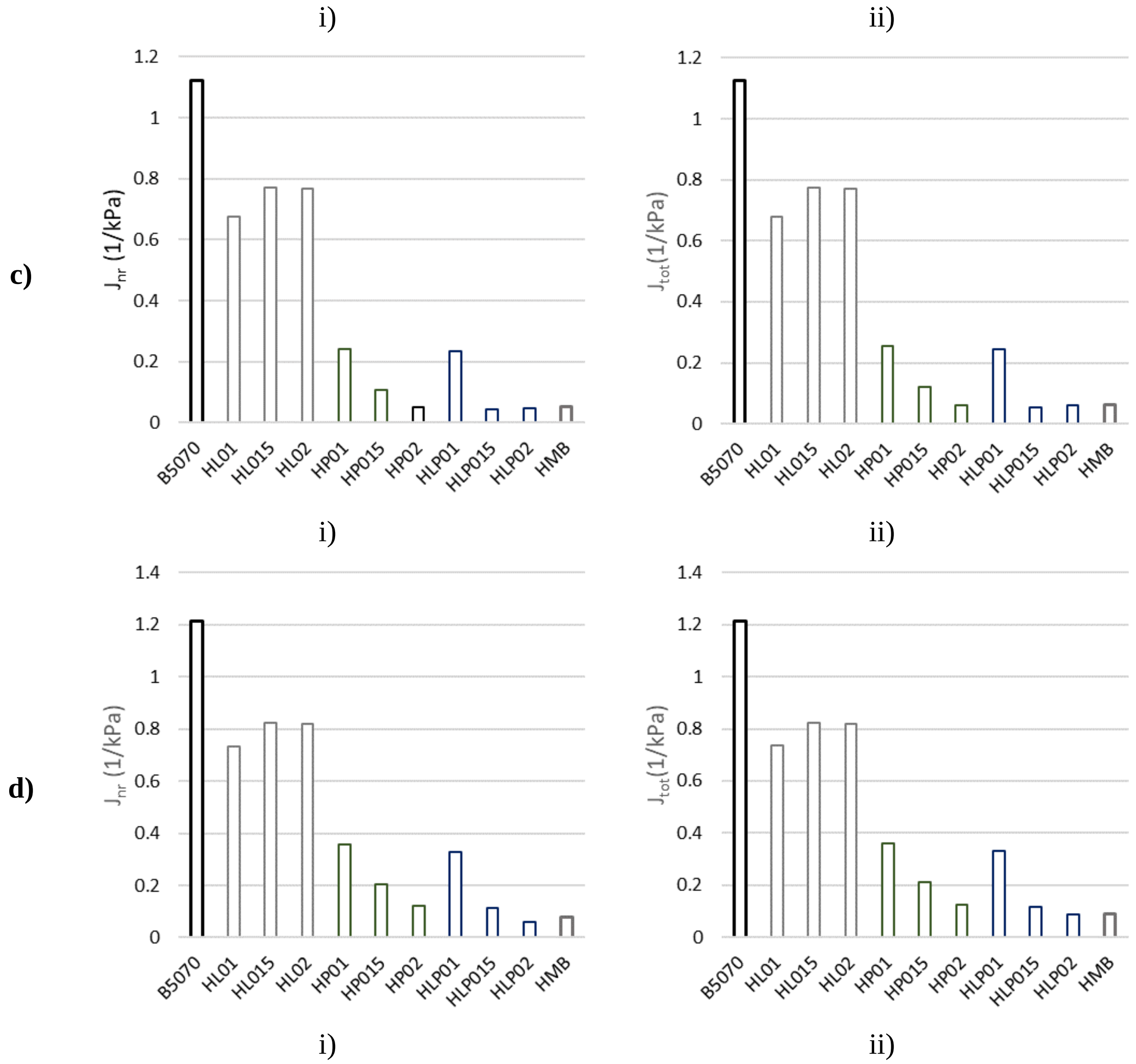


Figure 7.29 J_{nr} and J_{tot} results for all prepared samples: a) 40°C and 0.1kPa: i) J_{nr} and ii) J_{tot}; b) 40°C and 3.2kPa stress level: i) J_{nr} and ii) J_{tot};, c) 50°C and 0.1kPa: i) J_{nr} and ii) J_{tot};, d) 50°C and 3.2kPa: i) J_{nr} and ii) J_{tot};

Two further parameters have been calculated to compare all bituminous solutions (mastics and binders) under 0.1kPa and 3.2kPa, at 40°C and 50°C test temperatures in greater depth, as follows:

a) J_{nr}ratio$_{(B50/70)}$, the ratio between the J_{nr} value of each of the six mastics (HL01, HL015, HL02, HP01, HP015, HP02) and the J_{nr} of B50/70;

b) J_{tot}ratio$_{(B50/70)}$, the ratio between the J_{tot} value of each of the six mastics (HL01, HL015, HL02, HP01, HP015, HP02) and J_{tot} of B50/70.

By way of clarification, when the ratio at point *a* tends to 1, it means that the mastic shows a low recovery from deformation when compared to B50/70. When it is close to 0, it means that the mastic shows a high aptitude to recover deformation when compared to B50/70. When the ratio at point *b* tends to 1, it means that the mastic matches the deformation of B50/70 almost at the end of the creep phase. When it is close to 0, it means that the mastic, compared to B50/70, exhibits an excellent elastic recovery right from the end of the loading phase without waiting for the end of the unloading-rest time.

Table 7.13a summarizes the values of $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70)}$ for all six mentioned mastics, as follows:

a) $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70)}$ overlap, maintaining the test temperature constant at each of the six mastics (a difference less than 3% on average), without returning significant differences under two stress levels. In particular, if, on the one hand, for each of the three mastics with PW filler (HP01, HP015, HP02) no significant differences exist in terms of $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70),}$ not moving from 40 to 50°C (an increase of approximately 5%) or from a stress level of 0.1 to 3.2kPa (an average of approximately 4%), on the other, the mastics with LF filler (HL01, HL015, HL02) show large differences, whether they are analysed at 40 or 50°C (the values increase at an average of 20% from around 40 to 50°C) regardless of stress level.

b) Making a comparison between mastics made up with PW and mastics made up with LF, keeping the percentage of filler (HP01 vs HL01, HP015 vs HL015, HP02 vs HL02) constant, there is a total mean increase of $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70)}$ of around 83%. This means that, while, on the one hand, the limestone mastics naturally show an increase in stiffness compared with B50/70 (around 20%), on the other, their stiffness contribution is lower than that of mastics made up of PW, in any case with elastic deformation recovery at the end of the loading time not much greater than 20%.

c) It can therefore be said that mastics made with PW filler return low mean values of $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70}$ by increasing the filler amount: it starts with 0.23071 for HP01, passing through 0.10470 for HP015 until the lowest value calculated here, 0.03657, for the HP02 solution is reached.

   This behaviour occurs neither for the neat B50/70 binder nor for the three mastics with LF filler.

d) Then, it may be added that mastics made up with LF return a higher mean value for the $J_{nr}ratio_{(B50/70)}$ and $J_{tot}ratio_{(B50/70)}$ compared with the other mastics. The mean total value starts for HL01with 0.69289 at 40°C and 0.83839 at 50°C respectively, passing through 0.68472 at 40°C and 0.82166 at 50°C for HL015, reaching 0.61105 at 40°C and 0.72715 at 50°C for HL02.

   This means that limestone filler used for making HL01, HL015, HL02 solutions gives a stiffness effect when compared to binder, but the general ability of the corresponding mastic to recover elastic deformation at the end of the creep phase is weak compared to B50/70 (i.e. HL01 and

HL015 show a mean value of the recoverable deformation at the end of the creep phase of 31% at 40°C and 17% at 50°C, while HL02 returns 39% on average at 40°C and 27% at 50°C).

Table 7.13 J_{nr}ratio and J_{tot}ratio at 40 and 50°C test temperatures under 0.1 and 3.2kPa: a) mastics made up with PW and LF as a filler, b) mastics made up by adding both PW and LF as a filler

a)

Solution for comparison	$J_{nr}ratio_{(B50/70)}$ [-]				$J_{tot}ratio_{(B50/70)}$ [-]			
	40°C		50°C		40°C		50°C	
	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
HP01/B50/70	0.21390	0.22246	0.22673	0.23580	0.22530	0.23431	0.23882	0.24837
HP015/B50/70	0.09630	0.09919	0.10208	0.10514	0.10400	0.10712	0.11024	0.11355
HP02/B50/70	0.03550	0.03621	0.03728	0.03802	0.03515	0.03585	0.03690	0.03764
HL01/B50/70	0.67930	0.70647	0.82195	0.85483	0.72006	0.74886	0.87127	0.90612
HL015/B50/70	0.67460	0.69484	0.80952	0.83381	0.66111	0.68094	0.79333	0.81713
HL02/B50/70	0.60500	0.61710	0.71995	0.73435	0.62315	0.63561	0.74155	0.75638

b)

Solution to be compared	$J_{nr}ratio_{(HLP)}$ [-]				$J_{tot}ratio_{(HLP)}$ [-]			
	40°C		50°C		40°C		50°C	
	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
HLP015/HP01	0.3228	0.5973	0.5032	0.7037	0.3312	0.5423	0.5371	0.7116
HLP02/HP015	0.1971	0.5013	0.2543	0.5538	0.2032	0.4859	0.2765	0.5712

Further investigation, as shown in Table 7.13b, was carried out in order to prove, through the data analysis made here, whether a low percentage of limestone filler (5% by the total weight of the fixed bitumen wax) may be added to a plastic waste amount as a filler (5, 10, 15% PW by the total weight of the bitumen) to improve the final behaviour of the mastics much more, also in the light of the modified bitumen used here as a top reference showing high performance. Three solutions have been judiciously investigated, as follows:

- the HLP01 solution with 5% LF by the total weight of B50/70 +5% PW by the total weight of B50/70
- the HLP015 solution with 5% LF by the total weight of B50/70 +10% PW by the total weight of B50/70
- the HLP02 solution with 5% of LF by the total weight of B50/70 +15% PW by the total weight of B50/70

This research aims to make a contribution in terms of eco-sustainable mastics, proposing a), solutions that involve only plastic waste materials as filler, totally reproducing the performance of traditional limestone mastics (maintaining the weight ratios of the materials for an effective comparison), and b) solutions that combine two types of fillers, such as PW by highest percentage (5, 10 and 15 %) and

LF (5%) by lowest percentage by the total weight of the bitumen, obtaining three final mastics solutions (HLP01, HLP015, HLP02). The purpose is to explain whether the superficial interaction between PW and LF can offer, at the same weight ratio seen above for making mastics, solutions that show a) higher stiffness than previous mastics presented here, and b) high deformation recovery capacity under repeated dynamic loading and unloading cycles.

So, two further parameters were calculated to achieve the objectives set, as follows:

a) $J_{nr}ratio_{(HLP)}$ is the ratio between J_{nr} of HLP015 and J_{nr} of HP01, and the ratio between J_{nr} of HLP02 and J_{nr} of HP015

b) $J_{tot}ratio_{(HLP)}$ is the ratio a) between J_{tot} calculated for HLP015 and J_{tot} calculated for HP01, and b) between J_{tot} calculated for HLP02 and J_{tot} calculated for HP015.

In this case, as in the previous one (Table 7.13a), $J_{nr}ratio_{(HLP)}$ and $J_{tot}ratio_{(HLP)}$ give comparable values for each of the two alternative mastics keeping test temperature and stress level constant; it is observed that on average the ratios change from 40 to 50°C for all mastics (an average increase of 32% for the HLP015/HP01 ratio and 29% for the HLP02/HP015 ratio). The values in Table 7.13b summarise the deformations associated with the limestone filler- plastic waste + bitumen interaction; the values of the deformations are lower than those given by the limestone mastics and mastics made up with PW, as shown in Table 7.13a, confirming the hypothesizes mentioned above. The best performance is returned once again by HLP02 at all test temperatures and stress levels.

7.2.5 Identification of the best solution with plastic waste

In order to simplify the overall response for the solutions investigated here, be they mastics (HL01, HL015, HL02, HP01, HP015, HP02, HLP01, HLP015, HLP02) or bitumens (B50/70, HMB), a cluster analysis was carried out to answer the following questions:

1) Is it possible to group the solutions investigated here into different homogenous groups, defining them as similar from the viewpoint of discriminating explanatory variables?
2) What variables and corresponding range of values can be used to define homogeneous groups?

The cluster analysis focuses on identifying N homogeneous groups, each of which consists of n objects that reach the highest degree of association for all the elements in the same group and minimum correlation otherwise. The data partition used is a crisp partition (bivalent approach). Each element of a group can be represented as a point with *m* coordinates, and each coordinate constitutes an attribute of the element. The simplest measure of affinity is the distance between two points in the same group. The objective function used to make the groups works according two main purposes: a) minimizing the Euclidean distance between each point within an identified group and the relative center, which does not generally coincide with any of the collected points, and b) maximizing the Euclidean distance for all the identified centers of the others groups [70].

So, the first step focused on making the layout of the matrix to be processed; it involves a) all the bituminous solutions explored here, and b) the parameters measured in laboratory that define the main rheological properties investigated.

The matrix consists of a number of rows ranging from 1 to *j-th*, equal to the number of bituminous solutions investigated (a total of 11 solutions were investigated of which 9 were mastics : HL01, HL02, HL015, HP01, HP015, HP02, HLP01, HLP015, HLP02 and 2 were bitumens: B50/70 and HMB), and a number of columns ranging from 1 to *k-th*, equal to the number of the most characteristic rheological parameters measured (a total of 8 parameters were considered: R&B, Dynamic viscosity at 100°C, $G^*_{(0.1-10Hz)T}$ (mean value calculated over 20 values of frequency for each test temperature, a total of six mean global measurements are obtained), $G'_{(0.1-10Hz)T}$(as it did for G*), $G''_{(0.1-10Hz)T}$ (as it did for G*), $\delta_{(0.1-10Hz)T}$ (as it did for G*) $J_{nr(0.1-10Hz)T}$ (the mean value of J_{nr} parameters for each test temperature including all measurements at two stress levels, a total of two mean global measurements were obtained at each test temperature.), $J_{tot(0.1-10Hz)T}$ (as it did for $J_{nr(0.1-10Hz)T}$)).

The normalization of all parameters was produced using Equation 42.

$$n_{ij} = \frac{a_{i\_k,j} - min\ a_{i\_k,j}}{max\ a_{i\_k,j} - min\ a_{i\_k,j}} \quad (42)$$

where:

- $a_{i\_k,j}$ is the *i-th* value assumed by the *k-th* parameter for the investigated *j-th* bituminous solution;
- $min\ a_{i\_k,j}$ is the minimum value *a*, from all *i-th* values measured for each *k-th* parameter, related to each *j-th* investigated bituminous solution
- $max\ a_{i_k,j}$is the maximum value *a*, from all *i-th* values measured for each *k-th* parameter, related to each *j-th* investigated bituminous solution

Table 7.14 shows the results of the normalization procedure.

As a result of several iterations, the optimal number of clusters was three, as shown in Table 7.15 and Figure 7.30; in particular, in order to group the elements congruently, it was verified that the numbers tending towards 1 meant the increase in the good performance of the solution with respect to the parameter, and vice versa if it tended to zero. Thus, since an increase of normalized values of G*, G’, Ring and Ball and Dynamic viscosity at 100°C means that the mastics and or bitumen enhance their good performance, while an increase of G'', δ, $J_{nr(0.1\text{-}10Hz)T}$ and $J_{tot(0.1\text{-}10Hz)T}$ normalized values, it means that the solution investigated decreased its performance within an elastic area compared to its reference solution. It was therefore decided to replace the last parameters with their complement at 1 and so a cluster analysis was carried, the results for which are shown in Table 7.15.

Table 7.14 Standardized Mean Values according to Equation 11

Properties	Mastics									Binders	
	HL01	HL015	HL02	HP01	HP015	HP02	HLP01	HLP015	HLP02	B50/70	HMB
R&B	0.039	0.049	0.068	0.223	0.367	0.978	0.250	0.400	1.000	0.000	0.995
Dynamic viscosity at 100°C	0.002	0.005	0.014	0.323	0.600	0.786	0.368	0.667	1.000	0.000	0.347
$\delta_{(0.1-10Hz)0°C}$	1.000	0.829	0.844	0.514	0.457	0.088	0.392	0.546	0.000	0.821	0.136
$\delta_{(0.1-10Hz)10°C}$	1.000	0.882	0.419	0.353	0.316	0.192	0.520	0.292	0.040	0.910	0.000
$\delta_{(0.1-10Hz)20°C}$	1.000	0.922	0.920	0.737	0.542	0.167	0.703	0.537	0.036	0.974	0.000
$\delta_{(0.1-10Hz)30°C}$	1.000	0.956	0.970	0.817	0.683	0.263	0.831	0.687	0.234	0.996	0.000
$\delta_{(0.1-10Hz)40°C}$	0.995	0.969	0.961	0.801	0.644	0.294	0.796	0.607	0.239	1.000	0.000
$\delta_{(0.1-10Hz)50°C}$	0.999	0.988	0.988	0.755	0.707	0.106	0.710	0.271	0.033	1.000	0.000
$G^*_{(0.1-10Hz)0°C}$	0.451	0.939	0.393	0.470	0.736	0.436	0.513	0.716	1.000	0.000	0.339
$G^*_{(0.1-10Hz)10°C}$	0.128	0.580	0.482	0.714	0.681	0.421	0.288	0.623	1.000	0.000	0.470
$G^*_{(0.1-10Hz)20°C}$	0.108	0.391	0.112	0.257	0.628	0.490	0.397	0.608	1.000	0.000	0.417
$G^*_{(0.1-10Hz)30°C}$	0.021	0.128	0.189	0.245	0.615	0.635	0.290	0.608	1.000	0.000	0.635
$G^*_{(0.1-10Hz)40°C}$	0.034	0.127	0.173	0.205	0.486	0.637	0.363	0.567	1.000	0.000	0.793
$G^*_{(0.1-10Hz)50°C}$	0.033	0.107	0.107	0.167	0.464	0.910	0.302	0.527	1.000	0.000	0.770
$G'_{(0.1-10Hz)0°C}$	0.111	0.803	0.047	0.186	0.860	0.943	0.260	0.563	1.000	0.000	0.682
$G'_{(0.1-10Hz)10°C}$	0.089	0.458	0.455	0.707	0.636	0.628	0.281	0.593	0.946	0.000	1.000
$G'_{(0.1-10Hz)20°C}$	0.073	0.301	0.095	0.247	0.599	0.751	0.287	0.583	1.000	0.000	0.814
$G'_{(0.1-10Hz)30°C}$	0.011	0.091	0.117	0.211	0.530	0.698	0.300	0.523	1.000	0.000	0.749
$G'_{(0.1-10Hz)40°C}$	0.018	0.068	0.083	0.172	0.429	0.688	0.263	0.504	1.000	0.000	0.739
$G'_{(0.1-10Hz)50°C}$	0.008	0.030	0.030	0.116	0.400	0.748	0.178	0.471	1.000	0.000	0.547
$G''_{(0.1-10Hz)0°C}$	0.587	1.000	0.803	0.980	0.955	0.620	0.749	0.895	0.218	0.452	0.000
$G''_{(0.1-10Hz)10°C}$	0.604	1.000	0.527	0.636	0.980	0.468	0.790	0.978	0.119	0.493	0.000
$G''_{(0.1-10Hz)20°C}$	0.423	0.529	0.592	0.557	1.000	0.188	0.596	0.964	0.213	0.403	0.000
$G''_{(0.1-10Hz)30°C}$	0.391	0.784	0.382	0.636	1.000	0.000	0.720	0.758	0.149	0.230	0.183
$G''_{(0.1-10Hz)40°C}$	0.234	0.359	0.359	0.452	0.910	0.320	0.675	1.000	0.000	0.179	0.011
$G''_{(0.1-10Hz)50°C}$	0.096	0.260	0.340	0.382	0.861	0.185	0.666	1.000	0.130	0.027	0.000
$J_{nr(0.1-10Hz)40°C}$	0.585	0.668	0.663	0.221	0.094	0.029	0.205	0.024	0.000	1.000	0.011
$J_{tot(0.1-10Hz)40°C}$	0.577	0.661	0.657	0.213	0.083	0.017	0.195	0.010	0.000	1.000	0.002
$J_{nr(0.1-10Hz)50°C}$	0.822	0.774	0.72	0.216	0.149	0.04	0.289	0.118	0.000	1	0.054
$J_{tot(0.1-10Hz)50°C}$	0.815	0.765	0.708	0.194	0.124	0.035	0.269	0.093	0.000	1.000	0.039

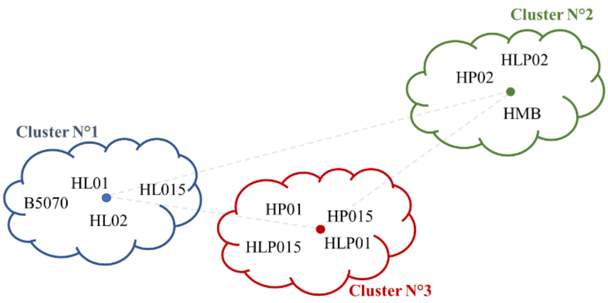
Table 7.15 Mean Standardized Value for each laboratory variable following the results of the cluster analysis

Case ID	Cluster N°1	Cluster N°2	Cluster N°3
R&B	0.039	0.991	0.310
Dynamic viscosity at 100°C	0.005	0.711	0.490
$1-\delta_{(0.1-10Hz)0°C}$	0.126	0.925	0.523
$1-\delta_{(0.1-10Hz)10°C}$	0.197	0.923	0.630
$1-\delta_{(0.1-10Hz)20°C}$	0.046	0.933	0.370
$1-\delta_{(0.1-10Hz)30°C}$	0.019	0.834	0.246
$1-\delta_{(0.1-10Hz)40°C}$	0.019	0.822	0.288
$1-\delta_{(0.1-10Hz)50°C}$	0.006	0.954	0.389
$G^*_{(0.1-10Hz)0°C}$	0.446	0.592	0.609
$G^*_{(0.1-10Hz)10°C}$	0.297	0.636	0.577
$G^*_{(0.1-10Hz)20°C}$	0.153	0.630	0.473
$G^*_{(0.1-10Hz)30°C}$	0.084	0.756	0.439
$G^*_{(0.1-10Hz)40°C}$	0.084	0.810	0.405
$G^*_{(0.1-10Hz)50°C}$	0.062	0.893	0.365
$G'_{(0.1-10Hz)0°C}$	0.240	0.875	0.467
$G'_{(0.1-10Hz)10°C}$	0.250	0.858	0.554
$G'_{(0.1-10Hz)20°C}$	0.117	0.855	0.429
$G'_{(0.1-10Hz)30°C}$	0.055	0.815	0.391
$G'_{(0.1-10Hz)40°C}$	0.042	0.809	0.342
$G'_{(0.1-10Hz)50°C}$	0.017	0.765	0.291
$1-G''_{(0.1-10Hz)0°C}$	0.290	0.721	0.105
$1-G''_{(0.1-10Hz)10°C}$	0.344	0.804	0.154
$1-G''_{(0.1-10Hz)20°C}$	0.513	0.867	0.221
$1-G''_{(0.1-10Hz)30°C}$	0.553	0.889	0.222
$1-G''_{(0.1-10Hz)40°C}$	0.717	0.890	0.241
$1-G''_{(0.1-10Hz)50°C}$	0.820	0.895	0.273
$1-J_{nr(0.1-10Hz)40°C}$	0.271	0.987	0.864
$1-J_{tot(0.1-10Hz)40°C}$	0.276	0.994	0.875
$1-J_{nr(0.1-10Hz)50°C}$	0.171	0.969	0.807
$1-J_{tot(0.1-10Hz)50°C}$	0.178	0.975	0.830

Figure 7.30 is the graphic representation of the result of the cluster analysis; the eleven bituminous solutions investigated have been grouped into three clusters, as follows:

- cluster 1: all the limestone mastics (HL01, HL015, HL02) and neat 50/70 bitumen, which showed low resistance to the permanent deformations. Above all, they generally returned low values for R&B, Dynamic viscosity at 100°C, $G^*_{(0.1-10Hz)T}$, $G'_{(0.1-10Hz)T}$, and high values for the $G''_{(0.1-10Hz)T}$, $\delta_{(0.1-10Hz)T}$, $J_{nr(0.1-10Hz)T}$ and $J_{tot(0.1-10Hz)T}$ parameters
- cluster 2: HP02, HLP02 and HMB, that have shown the best performance in terms of stiffness, elastic recovery of total deformation, and low non-recoverable creep compliance values
- cluster 3: HP01, HP015, HLP01 and HLP015 showed intermediate performance compared with two previous clusters.

The cluster analysis showed the largest distance between clusters 1 and 2, while cluster 3 shows the same lowest distance from clusters 1 and 2.



a)

Cluster	1	2	3
1	-	3.690	2.100
2	3.690	-	2.493
3	2.100	2.493	-

b)

Figure 7.30 Cluster results: a) elements falling within each group, b) distances between three pairs of centers

Figure 7.31 illustrates even better the meaning of the results of the cluster analysis: the nomogram shows in a simple way a summary indication of the total performance (TPI) of each mastic and binder here investigated. TPI is the sum of the normalized values of the 8 characteristic mechanical parameters involved in the cluster analysis associated with each solution. As stated above, an adjustment was made to $G''_{(0.1-10Hz)T}$, $\delta_{(0.1-10Hz)T}$, $J_{nr(0.1-10Hz)T}$ and $J_{tot(0.1-10Hz)T})$ to give consistency to the data processing and uniformity in the interpretation of the results, so that for normalized values tending to 1 it means that the solution gives a high performance, and vice versa when the normalized value is close to 0.

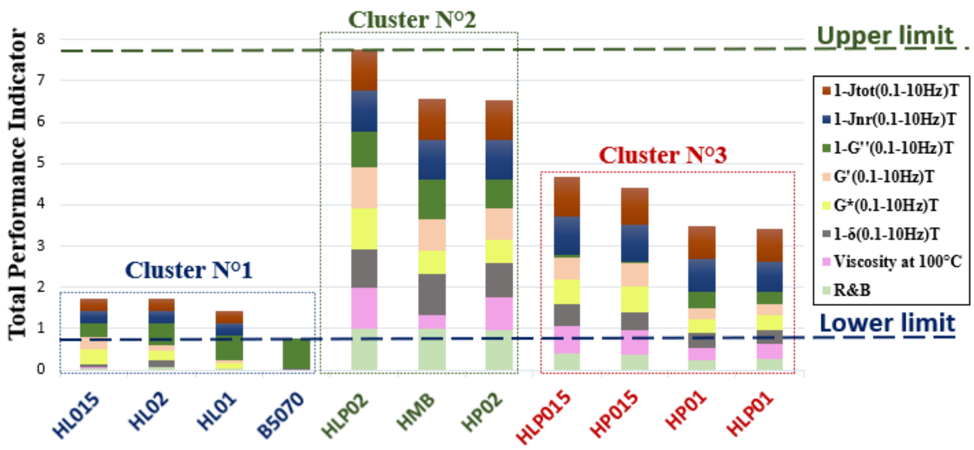


Figure 7.31 Nomogram to identify the behaviour of each mastic and binder in relation to high rheological performance following the cluster analysis results

Figure 7.31 shows that the highest TPI value of 7.8 was reached by HLP02, followed by HP02 and HMB: this means that HLP02 can be suggested as a replacement for traditional limestone mastic since just 5% of LF was used for making the mastic, and the remaining filler is made up of 15% PW by the total weight of the bitumen. HLP02 gives the best overall performance compared with the other solutions.

7.3 Investigation of hot and cold bituminous mixtures containing Jet grouting waste

The research presented in this section focused on mixing and analyzing four different asphalt mixtures: 1) a traditional Hot Mix Asphalt (HMA) obtained by adopting virgin limestone aggregates and neat 50/70 neat bitumen; 2) HMA containing JW (HMAJ); 3) Cold mix asphalt with RAP and limestone aggregates (CIRJ) and 4) Cold mix asphalt containing JW, RAP and limestone aggregates (CRAJ). The possibility of re-using JW in a hot mixture or when it is added to RAP in a cold mix asphalt instead of a portion of virgin aggregates was evaluated by analyzing main mechanical and volumetric properties. The experimental program is reported in Figure 7.32.

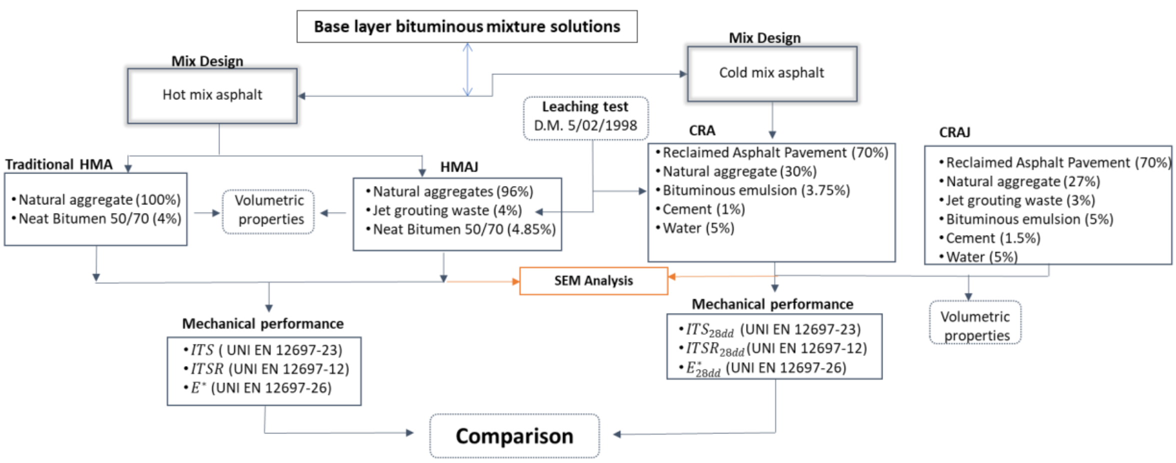


Figure 7.32 Experimental program of the investigation of hot and cold bituminous mixture containing jet grouting waste

7.3.1 Materials

Limestone aggregates and fillers

The virgin aggregates and fillers used are from a limestone quarry located in Southern Italy. Table 7.16 shows the main features of the different fractions of the aggregates along with their individual standards.

Table 7.16 Aggregates main properties

Type	Density [g/cm3] EN 1097-6	Los Angeles [%] EN 1097-2	Shape Index [%] EN 933-4	Flattening Index [%] EN 933-3	Equivalent sand [%] EN 933-8	Rigden voids [%] EN 1097-4
31.5-16mm	2.68	-	4	16	-	-
10-16mm	2.69	20.61	4	8	-	-
6-12mm	2.71	21.14	8	11	-	-
sand	2.71	-	-	-	80	-
filler	2.68	-	-	-	-	41

Jet grouting waste

The main properties of JW are reported in the above section 7.1. A total grading composition was adopted for the design of bituminous mixtures from which it is possible observed that JW is a mixture of filler and sand.

Reclaimed asphalt pavement (RAP)

To improve the environmental aspects of bituminous road mixtures, the effects of Cold Reclaimed Asphalt were studied with the addition of JW for a base layer mix design. The RAP used for this research was obtained by milling and stockpiling old asphalt pavements. The RAP included both basalt and limestone aggregates, whose properties are shown in Table 7.17. RAP aggregate was used as black rock [71], i.e. aggregates coated with an old bitumen film that does not contribute to the internal cohesion of the mixture. Many properties of the bitumen extracted from RAP (EN 12697-1) are shown in Table 7.18.

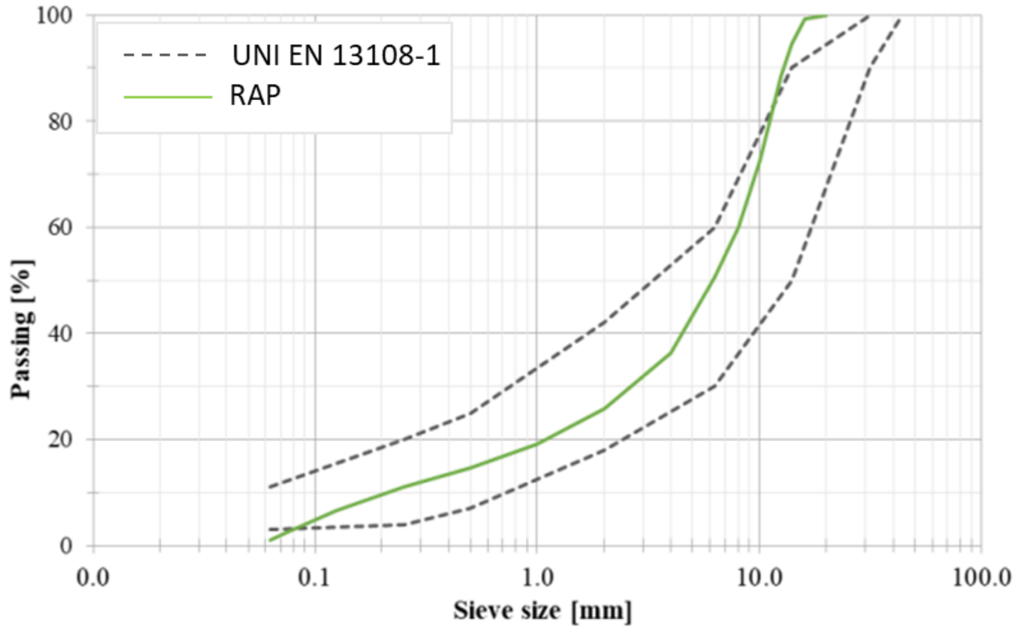
Table 7.17 RAP main properties

Parameter	Unit	Value	Standard
Specific gravity	g/cm3	2.52	EN 1097-6
Water absorption	%	1.6	EN 1097-6
Sand equivalent	%	71	EN 933-8
Flakiness Index	%	10	EN 933-3

Table 7.18 Binder recovery from RAP properties

			Amount of recovery binder equals 4.41% (EN 12697-1)
Properties	Unit	Standard	Value
Penetration at 25°C	dmm	EN 1426	54
Softening point	°C	EN 1427	50.71
Dynamic viscosity at 160°C	Pa s	EN 13702	0.39
Frass	°C	EN 12593	-6

The RAP percentage passing through sieves is shown in Figure 7.33a; it can be observed that it is necessary to add fresh natural limestone aggregates to improve the gradation in order to fall within the EN 13108-1 envelope (see Figure 7.33b). Figure 7.33c shows the revised grading curve for the RAP plus JW, based on the target mixture AC32 BASE, where the RAP equals 70% of the weight of the total aggregates, JW amounts to 4% of the weight of total aggregates, and 26% of the weight of the total aggregates is accounted for by added natural aggregates.



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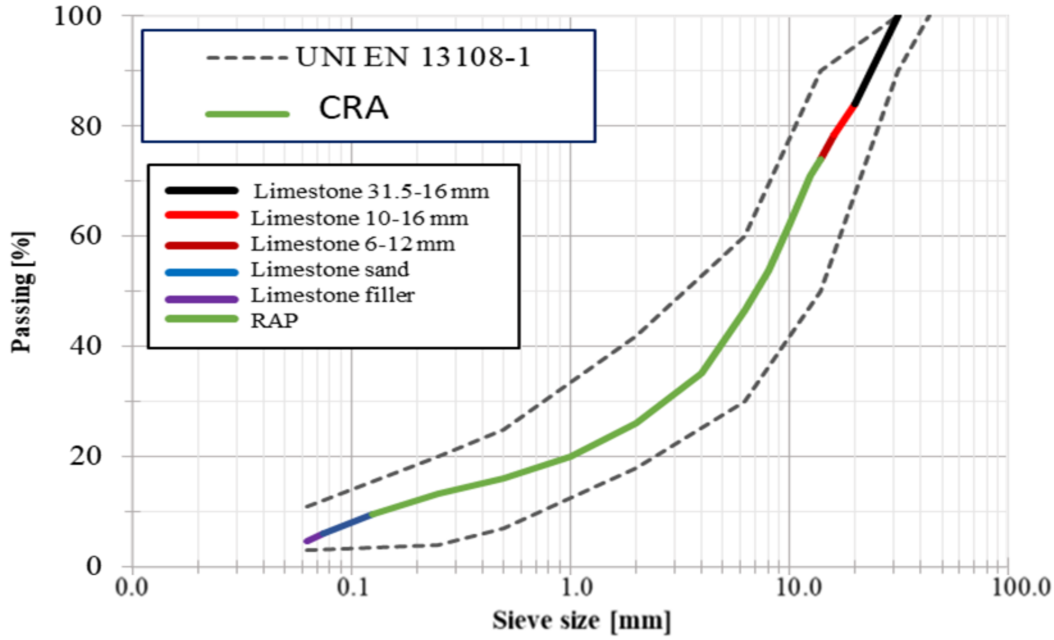

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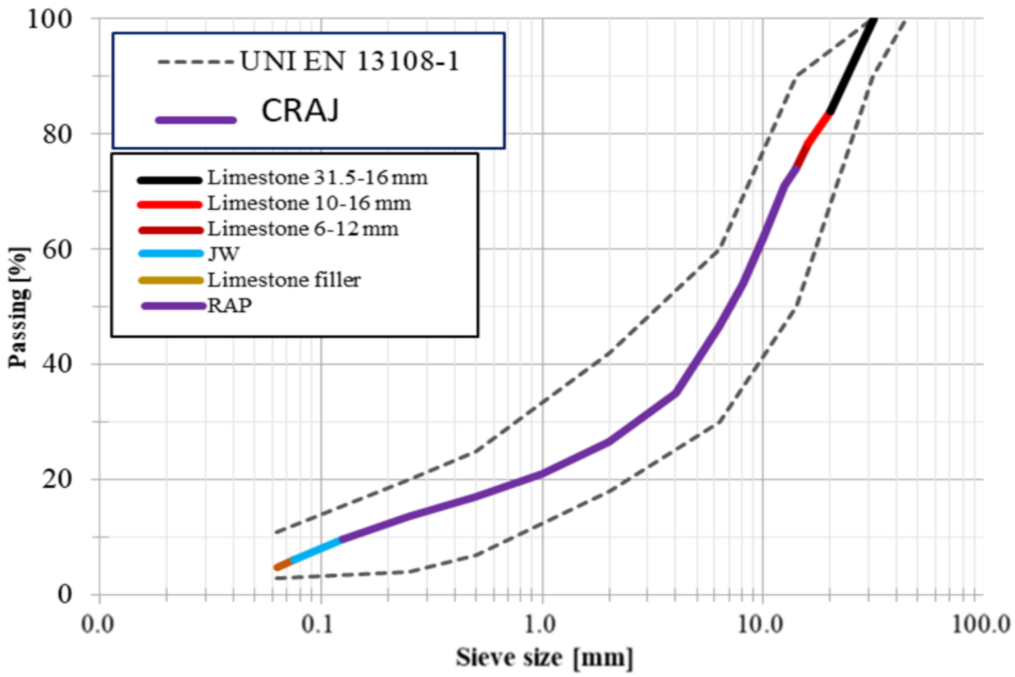


Figure 7.33 RAP grading curve: a) original RAP gradation, b) revised RAP grading with virgin aggregates (CRA) and c) revised RAP grading with virgin aggregates and JW (CRAJ)

Binders

A standard 50/70 penetration grade bitumen (see Table 7.1) was used for HMA and HMAJ solutions. A Portland cement 325R, and an over-stabilized bituminous emulsion (60% of SBS modified bitumen content and 40% water content) were adopted for the CRA and CRAJ solutions. The main properties of cement and emulsion bitumen are shown in Table 7.19.

Table 7.19 Properties of binder in CRAJ mixture: a) bitumen emulsion, b) Portland cement

Characteristics	Unit	Value	Standard	Characteristics	Unit	Value	Standard
	a)				**b)**		
water content	%	40	EN 1428	Constituents and composition	1.Portland clinker 65-79% 2.Blast furnace slag+secondary raw materials 35-21%		
pH value	-	4.2	EN 12850				
settling tendency at 7 days	%	5.8	EN 12847	Initial setting time	min	112	EN 196-3
				Compressive strength			EN 196-1
				1.at 2 days	MPa	27.8	
				2.at 28 days	MPa	61.2	
				volume constancy	mm	0.52	EN 196-3

7.3.2 Mix design phase

HMA and HMAJ mix design solutions

In order to accomplish the mix design phase of a target mixture AC32 BASE, the SUPERPAVE procedure [72] was adopted. Three different trial grading curves were supposed for the HMA and HMAJ solutions, and they were then compared with the specification requirements as: a) EN13108-1 (see Table 1 in EN 13108-Overall limits of target composition – basic sieve set plus set 2); b) SUPERPAVE gradation requirements; c) the Fuller curve to be avoided. Point a) aims to identify a design aggregate structure lying within eight control points determined for a specified nominal size associated with the grading curve. Point b) aims to avoid a restricted zone where humped gradation can arise: it may indicate an over-sanded mixture and/or a mixture that possesses too much fine sand in relation to the total; it consequently poses compaction problems during construction and offers reduced resistance to permanent deformation during its performance life (see Figure 7.34).

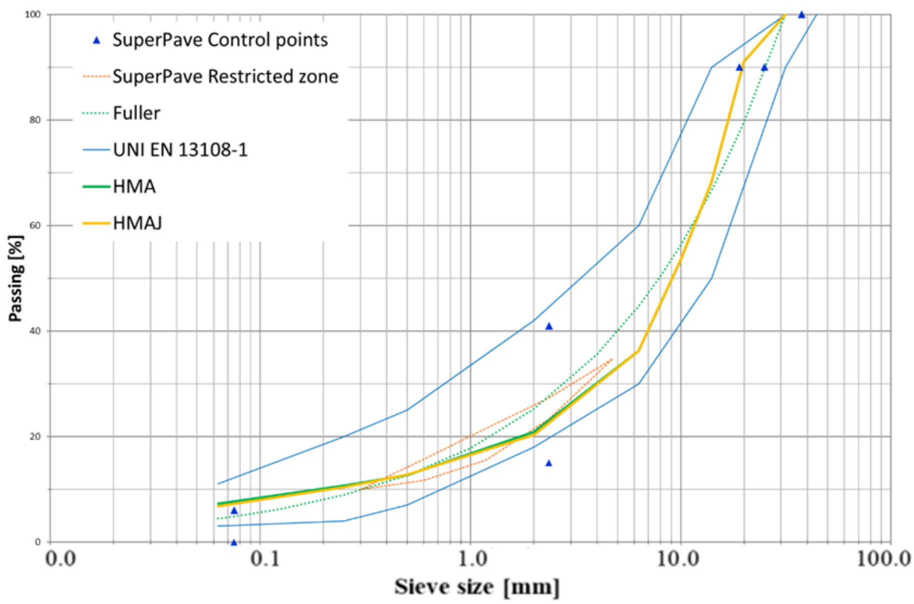


Figure 7.34 HMA and HMAJ grading curve

During the subsequent step, the blends were assessed by compacting specimens using a gyratory compactor at a trial bitumen dosage, and their volumetric properties were evaluated. The trial bitumen dosage Pbi was determined for each blend by estimating first of all the effective specific gravity by using Equation 43.

$$G_{se=}G_{sb} + 0.8(G_{sa} - G_{sb}) \tag{43}$$

Where, G_{sb} = the aggregate's bulk specific gravity; G_{sa}= apparent specific gravity of aggregate.

The next step was to estimate the volume of binder absorbed into the aggregate (V_{ba}) by Equation 44.

$$V_{ba} = \frac{P_s \times (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_b}{G_{se}}\right)} \times \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right) \tag{44}$$

Where, Ps = percent of aggregate (assumed to be 0.95); Va is the volume of air voids (assumed to be 0.04); Pb =Percent of binder (assumed to be 0.05); Gb = specific gravity of binder (assumed 1.02 g cm-3).

The volume of the effective binder (Vbe) was then calculated using Equation 45.

$$V_{be} = 0.176 - 0.0675 \cdot \ln S_n \tag{45}$$

Where, Sn =is the nominal maximum sieve size of the aggregate blend in millimetres.

Lastly, for the initial trial bitumen dosage Pbi (per mass of mixture) was calculated by adopting Equation 46.

$$P_{bi} = \frac{G_b \times (V_{be} + V_{ba})}{(G_b \times (V_{be} + V_{ba})) + W_s} \times 100 \tag{46}$$

Where, Ws is the mass aggregate, in grams, calculated using Equation 47.

$$W_s = \frac{P_s \times (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)} \tag{47}$$

Table 7.20 shows the investigated volumetric properties of the mixtures that will be subjected in the next second step to the further SUPERPAVE requirements in order to identify the best grading curve among the trial solutions that fits an Optimal Bitumen Content (OBC).

Table 7.20 Trial blends volumetric properties for HMA and HMAJ according to the SUPERPAVE procedure

Trial blends of HMA and HMAJ solutions	Gse	Gsb	Gb	Pb	Ps	Va	Vba	Sn	Ws	Vbe	Pbi
HMA 1	2.757	2.698	1.020	0.050	0.950	0.040	0.018	25.000	2.317	0.082	0.0421
HMA 2	2.754	2.698	1.020	0.050	0.950	0.040	0.017	25.000	2.315	0.082	0.0418
HMA 3	2.756	2.699	1.020	0.050	0.950	0.040	0.018	25.000	2.316	0.082	0.0419
HMAJ 1	2.820	2.699	1.020	0.050	0.950	0.040	0.037	25.000	2.363	0.082	0.0488
HMAJ 2	2.879	2.700	1.020	0.050	0.950	0.040	0.056	25.000	2.407	0.082	0.0549
HMAJ 3	2.954	2.701	1.020	0.050	0.950	0.040	0.078	25.000	2.460	0.082	0.0621

In order to define OBC of each of the six blends, two specimens for each trial blend (4,500gr each, with a diameter of 150mm) were prepared using a gyratory compactor made with a constant compaction pressure of 600kPa, at an external angle of 1.25° (see Figure 7.35). Specimens were mixed at 158°C. They were then aged short-term by placing the loose mix in a flat pan in a forced draft oven at compaction temperature for 2 hours.

Figure 7.35 Gyratory compactor available at La.Stra

The number of gyrations used for compaction was established based on the design's maximum temperature of the paving location and the traffic level according to the Superpave specifications. The number of gyrations for initial compaction, design compaction, and maximum compaction were N_{ini}=8 gyrations, N_{des}=100 gyrations and N_{max}=160 gyrations respectively.

Each specimen was compacted at the maximum number of gyrations, continually monitoring the height of the specimen during the compaction process. When the compaction phase was complete, the specimens were extruded from the mold and allowed to cool for 24h at 25°C.

Next, the bulk specific gravity (G_{mb}) of each specimen was determined according to EN 12697-6 Procedure B. The G_{mm} of each blend was determined using the procedure suggested by EN 12697-5 Procedure C. G_{mb} was then divided by G_{mm} to determine the % G_{mm} at N_{max}; the % G_{mm} at any number of gyrations (N_x) was then calculated by multiplying % G_{mm} at N_{max} by the ratio of the heights at N_{max} and N_x.

The most important points of comparison are % G_{mm} at N_{ini}, N_{des}, N_{max}. The average %G_{mm} was determined for N_{ini}, N_{des} and N_{max} for all investigated solutions. The percentage of air voids and voids in the mineral aggregate (VMA) were then evaluated at N_{des}. The air voids percentage was calculated from Equation 48:

$$V_a = 100 - \%G_{mm}@Ndes \tag{48}$$

The percentage of voids in the mineral aggregate (VMA) was calculated from Equation 49:

$$\%VMA = 100 - \left(\frac{\%Gmm@Ndes \times Gmm \times P_s}{G_{sb}}\right) \tag{49}$$

Table 7.21 shows the compaction summary for each trial blend.

Table 7.21 Compaction summary for each trial blend after gyratory compaction

Specimen curve	Initial percentage of bitumen (by mass of mixture), Pbi, %	%Air Voids	%Gmm@Nini	%Gmm@Nmax	% VMA
HMA 1	4.209	4.4	85.2	97.3	13.5
HMA 2	4.176	4.4	86.1	97.8	13.3
HMA 3	4.194	4.4	86.1	98.1	13.4
HMAJ 1	4.886	3.8	88.3	97.9	12.8
HMAJ 2	5.497	3.2	88.6	98.9	12.7
HMAJ 3	6.209	2.8	90.5	99.1	12.9

An estimated bitumen content to achieve 4 percent air voids (96% G_{mm}@N_{des}) was calculated for each trial blend using the Equation 50 below:

$$P_{b\ estimated} = P_{bi} - 0.4 \cdot (4 - V_a) \tag{50}$$

Where, Pbi is the initial trial percent bitumen content and Va is the percentage of air voids at Ndes. The volumetric (VMA and VFA) and mixture compaction properties are then estimated at this bitumen content, as follows:

$$VMA_{estimated} = VMA_{initial} + C \cdot (4 - V_a) \tag{51}$$

Where, $VMA_{initial}$ is the VMA value associated with initial trial percent bitumen content, C is a constant equal to 0.1 if the Va is less than 4.0% and equal to 0.2 if the Va is greater than 4.0% according to the Superpave procedure.

$$VFA_{estimated} = 100 \times \frac{\%VMA_{estimated} - 4}{\%VMA_{estimated}} \tag{52}$$

$$\%G_{mm\ estimated}@N_{ini} = \%_{Gmm\ trial}@\ N_{ini} - (4 - V_a) \tag{53}$$

$$\%G_{mm\ estimated}@N_{max} = \%_{Gmm\ trial}@\ N_{max} - (4 - V_a) \tag{54}$$

Table 7.22 below shows the advanced-estimated compaction mixture properties of six trial blends by varying the initial percentage of bitumen content, made up with 4.0% air voids content at N_{des}.

Table 7.22 Advanced-estimated compaction mixtures properties at 4.0% of air voids content at Ndes

Specimen curve	Initial percentage of bitumen (by mass of mixture), Pbi	Estimated percentage of bitumen (by mass of mixture), Pbe	%VMA estimated	%VFA estimated	%Gmm estimated@Nini	%Gmm estimated@Nmax
HMA 1	4.209	4.37	13.42	70.19	85.6	97.7
HMA 2	4.176	4.34	13.22	69.74	86.5	98.2
HMA 3	4.194	4.35	13.32	96.97	86.5	98.5
HMAJ 1	4.886	4.81	12.82	68.8	88.1	97.7
HMAJ 2	5.497	5.18	1278	68.7	87.8	98.1
HMAJ 3	6.209	5.73	13.02	69.28	89.3	97.9

The volumetric properties in Table 7.22 for each trial blend were then compared with the Superpave requirements criteria shown in the same Table 7.22.

Analysing the results in Table 7.22, the trial blend HMA1 is the best alternative for the HMA solution, while HMAJ1 is the best alternative for HMAJ solution which makes it possible to fulfil the SUPERPAVE recommendations.

Two further specimens were then made for HMA1 and HMAJ1 solutions at new bitumen content percentages as suggested by the SUPERPAVE procedure in order to define the relative OBC as follows: estimated asphalt content (Pb estimated), at ± 0.5% of Pb estimated and at +1.0% of the Pb estimated, where Pb estimated was calculated by Equation 50.

The OBC for HMA and HMAJ solutions was established by plotting three different scatter-plots, with Va, VMA and VFA on the y-axis one at a time, all estimated at each of four new additional bitumen contents; the previously defined bitumen contents are on the x-axis. From an analysis of the results, the OBC for HMA1 is 3.8%, while for HMAJ1 it is 4.30% by the total weight of the aggregates, as shown in the Table 7.23.

Table 7.23 Compaction summary and OBC of final HMA and HMAJ solutions

Solution	Pb	Va	VMA	VFA	%Gmm@Nini	%Gmm@Nmax
HMA	3.8	4	14.12	71.67	85.62	1.1
HMAJ	4.3	4	15.05	74.02	85.18	1.1
Superpave reuirements	-	4	>13	65-75	≤89	0.6-1.2

In conclusion, a total of 4% of filler was adopted for the traditional HMA solution made up with only limestone aggregates; the same percentage was also used for HMAJ solution in terms of JW as a filler.

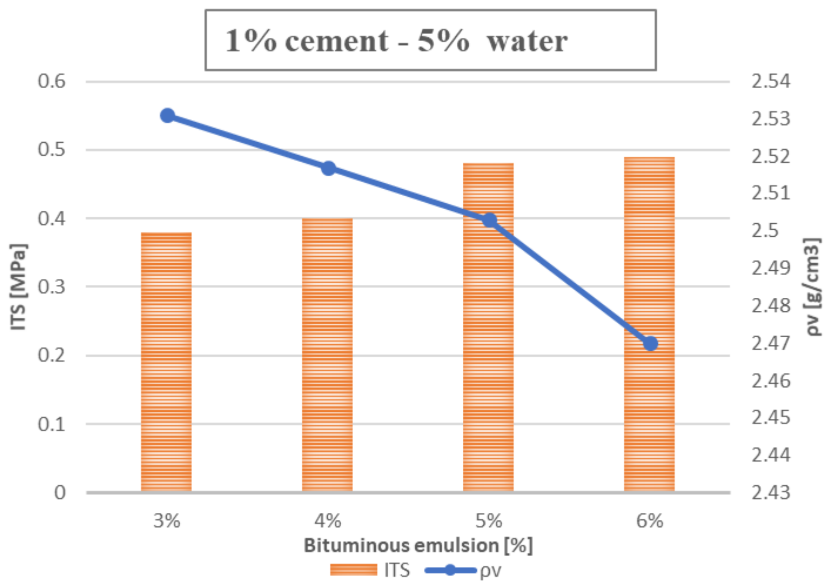
CRA and CRAJ mix design

Before moving on to assess the best bituminous emulsion content, the optimum water+cement content was assessed by preparing specimens reflecting some hypothesized water (from 3% to 7% by the total weight of the aggregates with an increment of 1%) and cement variations (from 0.25% to 1% by the total weight of the aggregates with an increment of 0.25%) that match some values suggested in the literature [71][73]. Three specimens were prepared for each of the twenty possible suggested water + cement combinations for each mixture:

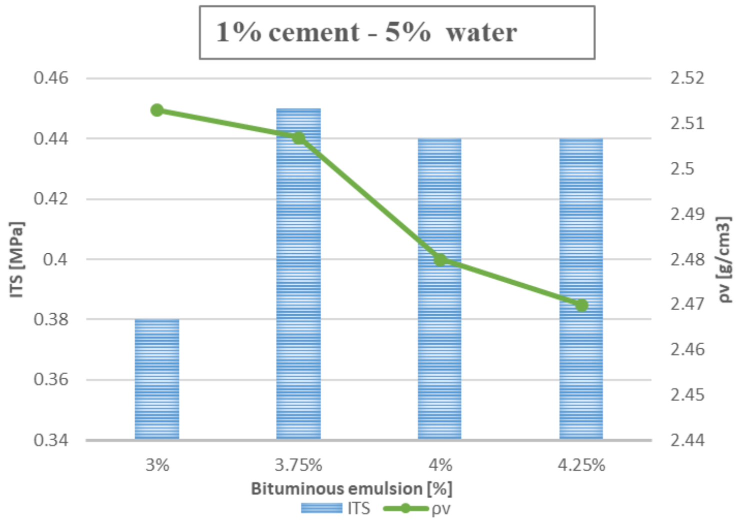
The natural aggregates in the case of CRA and natural aggregates in the case of CRAJ and the JW were heated to 105°C in advance before being added to the RAP that was oven pre-heated to 60°C, as materials start from different moisture contents and the aim is to reach constant mass conditions. The blends were then mixed in a planetary mixer for 15 approximately minutes and then compacted using a gyratory compactor at Nmax.

The laboratory protocol followed here aims to stop the iterations (preparing specimens by changing the water + cement combination, and then by adding bituminous emulsion) when the cold mix asphalt reaches a final specific gravity not so far from a traditional hot mix.

The first steps concluded with a specific gravity for the cold asphalt mixtures in absence of the bituminous emulsion (bulk density by dimensions according to EN 12697-06_procedure D) with 5% water and 0.5% cement equals 2.12 g/cm^3 for CRA and 5% water and 1.5% cement equals 2.19g/cm^3 for CRAJ. As mentioned above, this values needs to be increased, since the density value of a traditional HMA solution designed here equals 2.52 g/cm^3 (bulk density using the saturated surface dry method according to EN 12697-06_procedure B). The next phase focused on optimum bituminous emulsion content by investigating for both the mixtures the effects of four percentages (from 3% to 6% by the total weight of the aggregates) [74][75]. Three specimens were prepared using a gyratory compactor at 160 gyrations (N_{max}) adding the emulsion content pre-heated to 60°C. It was observed that in the end, the most appropriate solution for CRA consists of 0.5% cement, 5% water, and 3.75% over-stabilized bituminous emulsion, while for CRAJ consists of 1% cement, 5% water, and 5% over-stabilized bituminous emulsion, both with a specific gravity of 2.50 g/cm^3 (see Figure 7.36).



a)



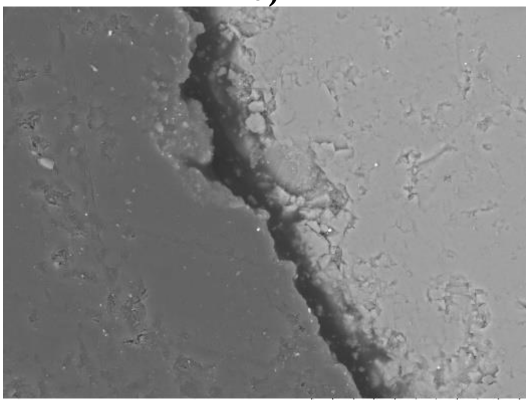
b)

Figure 7.36 Mean values of ITS and maximum density: a)CRA and b) CRAJ

7.3.3 SEM characterization of the mixtures

The morphology of the three mixtures was investigated by a Scanning Electron Microscopy (SEM) to observe the microstructure, the geometric shapes of the particles and their adhesion with the binder. Tiny part belonging to each of three study mixtures was extracted and then mounted in a cold epoxy resin, as a first step, and subsequently it was grinded using a diamond disk with a grain size of 60 μm until a flat section appeared making visible both the aggregate and bituminous mastic; preparation specimen ended with polishing by using a diamond disks of 10 μm and 5 μm. To make each of three prepared specimens suitable for SEM analysis, they have been coated by a thin gold layer using a Quorum Technologies K650X sputter coater (see Fig. 8a). Each specimen has been observed by a Hitachi TM3000 microscope. Figure 7.37b refers to HMA solution; SEM characterization shows a low adhesion between binder and aggregate that’s also confirmed by the break at the interface of 10μm almost, probably born of high surface stress that caused binder shrinkage and detachment of the binder from the aggregates. Figure 7.37c refers to the HMAJ solution returning a homogeneous mixture characterized by a binder that wraps perfectly particles than circumstance observed in Figure 7.37b. Figure 7.37d refers to CRAJ solution at the 28th day of curing time in condition of full maturation of the mixture; the results show how the binder (cement plus bituminous emulsion) flows more fluent and fills more voids making more cohesive matrix than previous cases study , also showing a greater thickness of the binder around the aggregates.

a)



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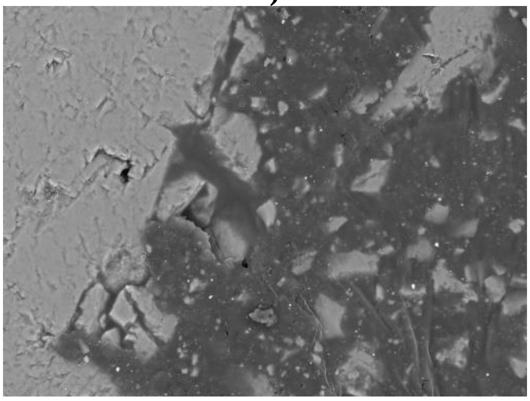
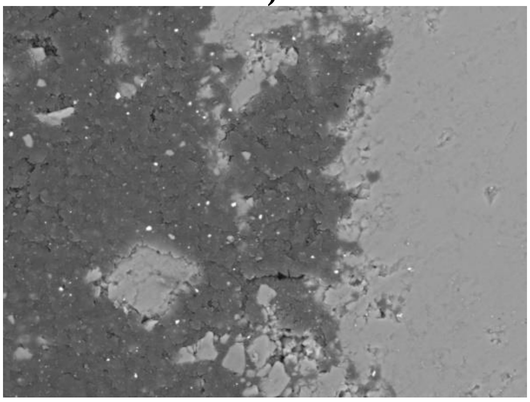


c)



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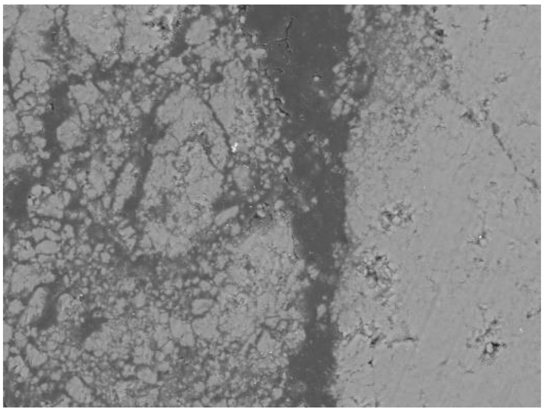


e)

Figure 7.37 SEM characterization: a) specimen type; 1500 X magnification of b) HMA, c) HMAJ, d) CRA and e) CRAJ

Figures 52c and 52d show the geometric irregularity in the surface texture and nonspherical shape of the aggregate-filler particles of HMAJ and CRAJ solutions. The rough surface of JW filler and RAP than the traditional limestone aggregate offers a good internal friction and interlocking. This condition favours an effective filler-binder bond; as a result, the binder appears much more homogeneously distributed on the aggregate surface and well absorbed by the filler and the aggregate affecting the final stiffness of the mixture.

7.3.4 Comparing HMA, HMAJ and CRAJ in terms of ITS

Since one of the main objectives of this study is to find a mix design for cold recycling mixtures, in particular when JW is added, such as to allow the same or higher mechanical performance as a traditional HMA, the CRA and CRAJ mixture curing process was evaluated by monitoring the ITS value over a period of 28 days.

The ITS (EN 12697-23) of the CRAJ was carried out after 1, 5, 10, 14, 20, 25, and 28 days, starting from the compaction phase of each specimen that was prepared according to the procedures shown in the previous sections and then stored at ambient temperature for all the time before the test (three specimens were tested at each curing day) (see Figure 7.38). The ITS_{CRAJ} (ITS of a CRAJ mixture) value, measured at 25°C for each specimen, as shown in Figure 7.39, reaches the same ITS_{HMA} (ITS of an HMA solution) value after 14 days of curing time, but it reaches the same value as ITS_{HMAJ} (the ITS of a HMAJ solution) after 28 days. The ITS_{CRA} reaches the value of ITS_{HMA} after 28 days of curing time. As partly shown in the literature review, the results here presented highlighted that, on the basis of the base layer solution found here, CRAJ gives a better performance than CRA and the traditional HMA. More specifically, less than 15 days are needed to match HMA performance, while 28 days are needed to exceed HMA performance, and especially to match HMAJ performance. It should be noted that increases in ITS are not constant over time. In fact, from 5 to 10 days and from 10 to 14 days, the ITS showed increases of 25% and 5% respectively. The increase in ITS gradation is greater in the first stage (5-10 days) than in the remaining period of the curing time, since the cohesive behaviour of the mixture is more consolidated in the last step of the process.

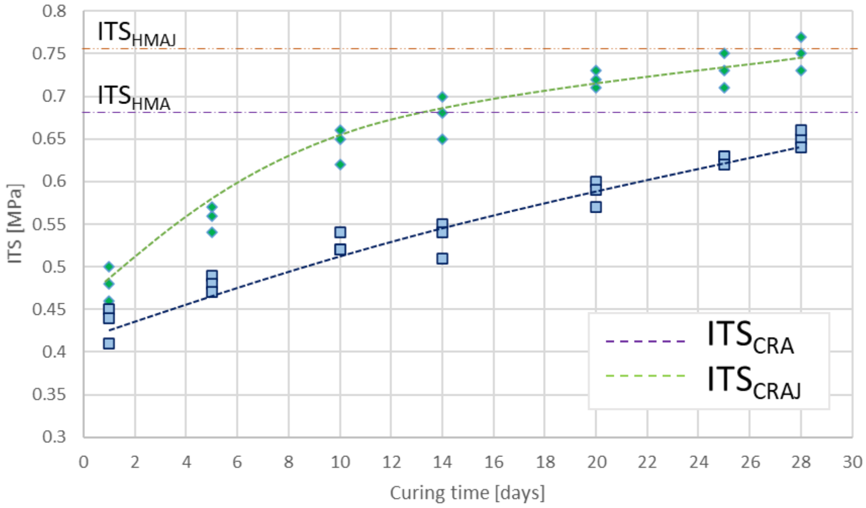


Figure 7.38 ITS evolution vs curing time for CRA and CRAJ mixtures

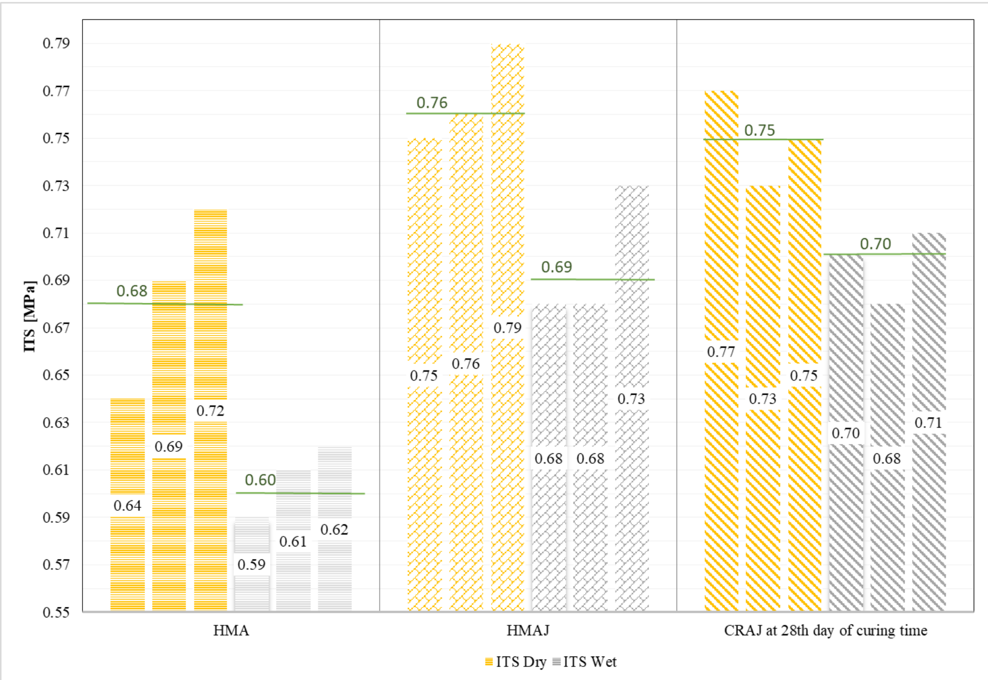


Figure 7.39 Dry (yellow bars) and wet (grey bars) ITS

Since the CRAJ results are better than CRA in terms of ITS, using the ITS results, a one-way ANOVA was carried out to test the following H_0 hypotheses:

a) May the H_0 hypothesis that dry ITS_{HMA}=dry ITS_{HMAJ} be rejected at a significance level of 0.05?

b) May the H_0 hypothesis that dry ITS_{HMA}=dry $ITS_{CRAJ28dd}$ be rejected at a significance level of 0.05? The results in Table 7.24 confirm that the mean dry ITS for HMA is statistically different, being lower than the ITS value for HMAJ; it can be also seen that the mean dry ITS for HMA is statistically different from CRAJ, estimated after 28 days' curing time, given that it is observed that it is higher in this last case.

A further question has been investigated using one-way ANOVA, as follows:

c) May the H_0 hypothesis that dry ITS_{HMAJ}= dry $ITS_{CRAJ28dd}$ be rejected at a significance level of 0.05? The test does not reject this hypothesis, which confirms that the mean dry ITS of the prepared HMAJ specimens are not statistically different from the ITS of CRAJ mixtures at 28 days of curing time.

Table 7.24 One-way ANOVA results for the dry ITS mean values

Test on dry specimens	*Origin of the variance*	*Sum of squares*	*Mean Square*	*F calculations*	*Level of statistical sgnificance*	*F critical*
HMA-HMAJ	Between the groups	0.0064	0.0064	25.60	0.0369	18.51
	Inside the groups	0.0005	0.0003			
	Total value	0.0069				
$HMA-CRAJ_{28dd}$	Between the groups	0.0124	0.0124	13.01	0.0226	7.71
	Inside the groups	0.0038	0.0010			
	Total value	0.0162				
$HMAJ-CRAJ_{28dd}$	Between the groups	0.0001	0.0001	0.06	0.8348	18.51
	Inside the groups	0.0027	0.0014			
	Total value	0.0028				

The effect of water on compacted bituminous mixtures was examined by preparing three specimens with each of the three mixtures (HMA, HMAJ, CRAJ). Each specimen was immersed in a water bath at a temperature of 40°C for 72 hours (EN 12697-12) and then compared with the results from EN 12697-23. According to the results in Figure 7.39, appropriate re-use of JW is achieved when it is added to the CRAJ process, since it helps increase the ITS value with respect to a traditional HMA, and above all it affects the stability of mechanical performance after imbibition, unlike the other two solutions.

7.3.5 Dynamic characterisation

The dynamic characterisation of the optimized mixture was carried out on the HMA, HMAJ and CRAJ solutions since the aim of the research was to obtain a cold mixture with JW that achieve the same performance of a traditional hot bituminous mixtures. The stiffness and the triaxial compression results are described below.

7.3.5.1 Stiffness assessment

The Indirect Tensile Stiffness Modulus test (ITSM) was performed (EN 12697-26 Annex C) under a load with a haversine waveform. The size of the specimens corresponded to the nominal maximum aggregate size of the mixture, resulting in a diameter of 150 mm and a height of 60 mm. The time imposed when the applied load increased from zero to maximum was 0.1 seconds such that the pulse repetition period was 3.0 seconds. The peak load value of 350 kN was chosen to achieve a target peak transient horizontal deformation of 0.005% of the specimen diameter.
ITSM, in MPa, was measured for each load pulse using Equation 51:

$$ITSM = \frac{F \cdot (\nu + 0.27)}{(z \cdot h)} \tag{51}$$

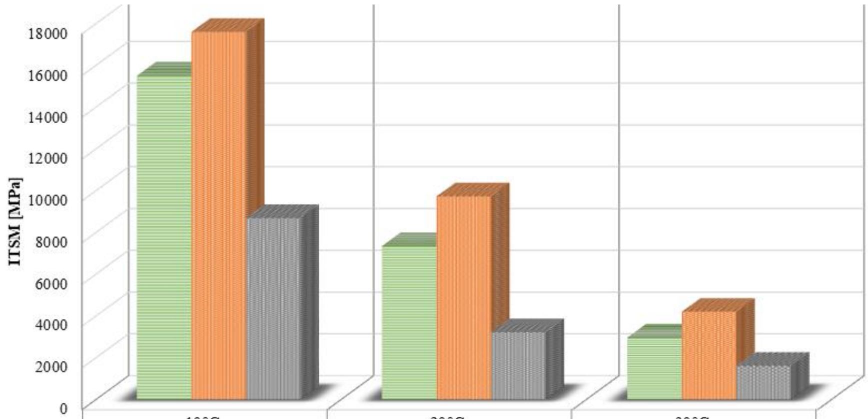
where

- F is the peak value of the applied vertical load, N
- z is the amplitude of the horizontal deformation obtained during the load cycle, mm
- h is the mean thickness of the specimen, equal to 60 mm
- ν is Poisson's ratio, equal to 0.35

Four specimens for HMA and HMAJ solutions were prepared and then tested at three temperatures (10°C; 20°C; 30°C) after conditioning for 4 hours at test temperatures. Figure 7.40 shows the test configuration. The mean values of ITSM for HMA and HMAJ are shown in Figure 7.41, where a linear increase in stiffness from 30°C to 10°C is almost equal for the two mentioned mixes; in particular, at the same test temperature an increase in ITSM was recorded with the HMAJ superseding the HMA by 13%, 32% and 41%.
Figure 7.41 also shows the mean value of ITSM measures for CRAJ specimens at the three test temperatures mentioned above; a laboratory protocol was followed before proceeding to ITSM evaluation of CRAJ specimens as follows: 1) a total of 21 specimens were prepared and compacted according to the procedures shown in the previous sections; 2) all the specimens were stored at ambient temperature with natural indirect exposure to the sun and natural ventilation to the upper part for 28 days in a place where no other activities were carried out to avoid interference with other sources of energy; 3) sets of three specimens were randomly extracted after 3, 5, 10, 14, 20, 25, and 28 days and subjected to ITSM testing after conditioning for 4 hours at each test temperature (10, 20,

30°C); 4) Figure 7.42 shows, for example, the evolution of ITSM at 30°C of CRAJ specimens vs curing time. Figure 7.42 shows that stiffness increased up to 14 days but remained almost constant between 14 days and 28 days, reaching a maximum value of 1610MPa on the 28th day of curing, since all curing time phenomena are strictly related to water evaporation that affects the reduction of water volume and a sharp increase in air void volume during the first phase as well as emulsion breaking and cement hydration, all connected to environmental conditions [71]. Figure 7.41 also shows ITSM values for CRAJ specimens at all test temperatures, in line with the previously explained procedures.

Figure 7.40 ITSM device available at La.Stra



	10°C	20°C	30°C
HMA	15500	7350	2960
HMAJ	17600	9730	4200
CRAJ	8680	3220	1610

Figure 7.41 Mean values of ITSM for HMA, HMAJ and CRAJ solutions at three test temperatures

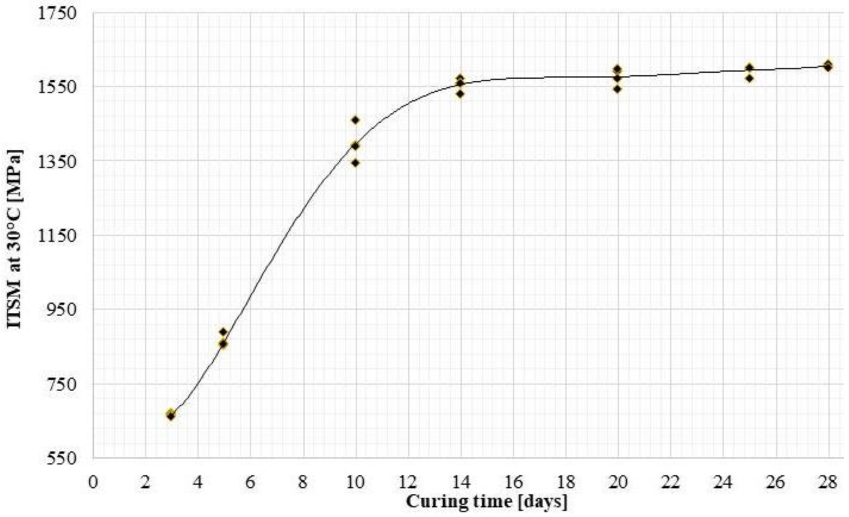


Figure 7.42 ITSM measured at 30°C vs curing time for CRAJ mixture

7.3.6 Triaxial Cyclic compression test

To determine the resistance to permanent deformation of HMA, HMAJ and CRAJ mixtures, a cyclic compression test with confinement was carried out (EN 12697-25, see Figure 7.43).

Two cylindrical test specimens for each mixture were prepared, each of which had a diameter of 100 mm and a height of 75 mm. The test was performed at 40°C; CRAJ specimens were preliminarily conditioned for 72h at test temperature. An haversinusoidal pressure of $\sigma_a(t)$ (see Equation 52) was applied.

$$\sigma_C + \sigma_a(t) = \sigma_C + \sigma_V \cdot (1 + \sin(2\pi \cdot f \cdot t)) \quad (52)$$

where

- σ_C is the confining stress, kPa
- $\sigma_a(t)$ is the cyclic assailing pressure as a function of time, kPa
- σ_V is the amplitude of the haversinusoidal pressure, kPa
- f is the frequency, Hz
- t is time

The results shown in Figure 7.44 show how CRAJ solution returns a lower cumulative strain value up to 2500 load cycles than HMA solution while for remaining load cycles till 3600 it exceeds it, unlike HMAJ that appears the more proper solution in terms of creep resistance.

Figure 7.43 Triaxial Cyclic compression device available at La.Stra.

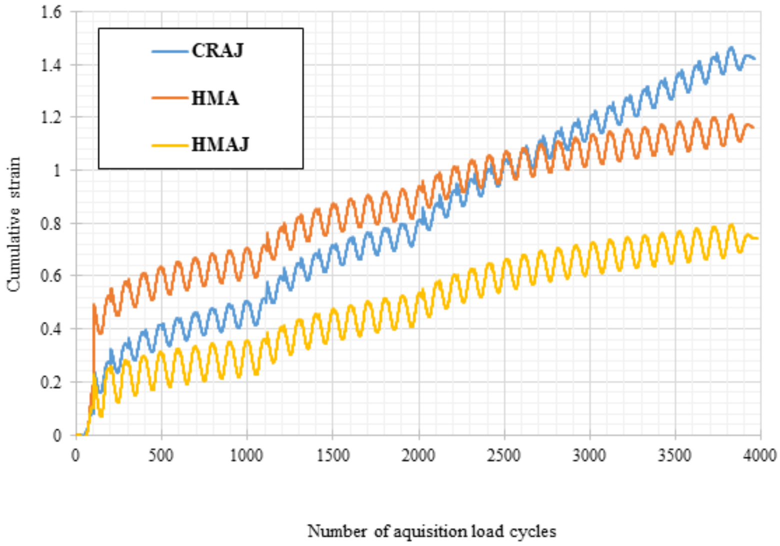


Figure 7.44 Cumulative strain vs number of load cycles of HMA, HMAJ and CRAJ

8 Performance assessment of pavement structure with alternative solution as base layer

8.1 Life Cycle Assessment

The life cycle assessment observes and analyses a product or service over its entire life cycle in order to determine its environmental impacts (ISO 14040). The LCA methodology is a systematic set of procedures for compiling and examining the inputs and outputs of materials, energy, waste, pollutant emissions (Life cycle inventory, LCI) and the associated environmental impacts (Life cycle impacts assessment, LCIA) directly attributable to the functioning of a product or service system throughout the unit processes of its life cycle (ISO 14040 and ISO 14044). In LCA, a unit process is defined as the "smallest element considered in the life cycle inventory analysis for which input and output flows are quantified" (ISO 14040).

The present section deals with an extraordinary maintenance work on a 1.6 km of existing rural road pavement with a width of 10.5m and a thickness of 5cm, 6cm and 16cm respectively for the wearing course, the binder layer and the base layer and the laying of a new contiguous section of 1 km located under a tunnel (see Figure 8.1) by providing four alternative design solutions of flexible pavement containing the alternative mixtures for the design of the base layer.

Figure 8.1 Case study overview

The main goal of this section is to compare four different flexible road pavement layouts, resulting from the maintenance intervention, with wearing course and binder layer in traditional hot mix asphalt (respectively HMAW and HMAB), unbound granular material as subbase layer and a base layer in bituminous mixture complying with four different solutions deriving from the optimization phase above discussed: 1) traditional hot mix asphalt (HMA) (Layout 1), 2) hot mix asphalt containing jet grouting waste (HMAJ) in alternative to a part of traditional limestone aggregates as filler and sand (Layout 2), 3) cold in-place reclaimed asphalt containing RAP (CRA) (Layout 3), and 4) cold in-place reclaimed asphalt containing RAP and JW (Layout 4).

The research aims to create a complete procedure for the comparative analysis of the solutions supporting the decision makers that takes into account not only the mechanical variables linked to the performance of the mixtures which were investigated through the laboratory phase, but also in terms of LCA for the environmental sustainability. The flow chart of the study is reported in Figure 8.2.

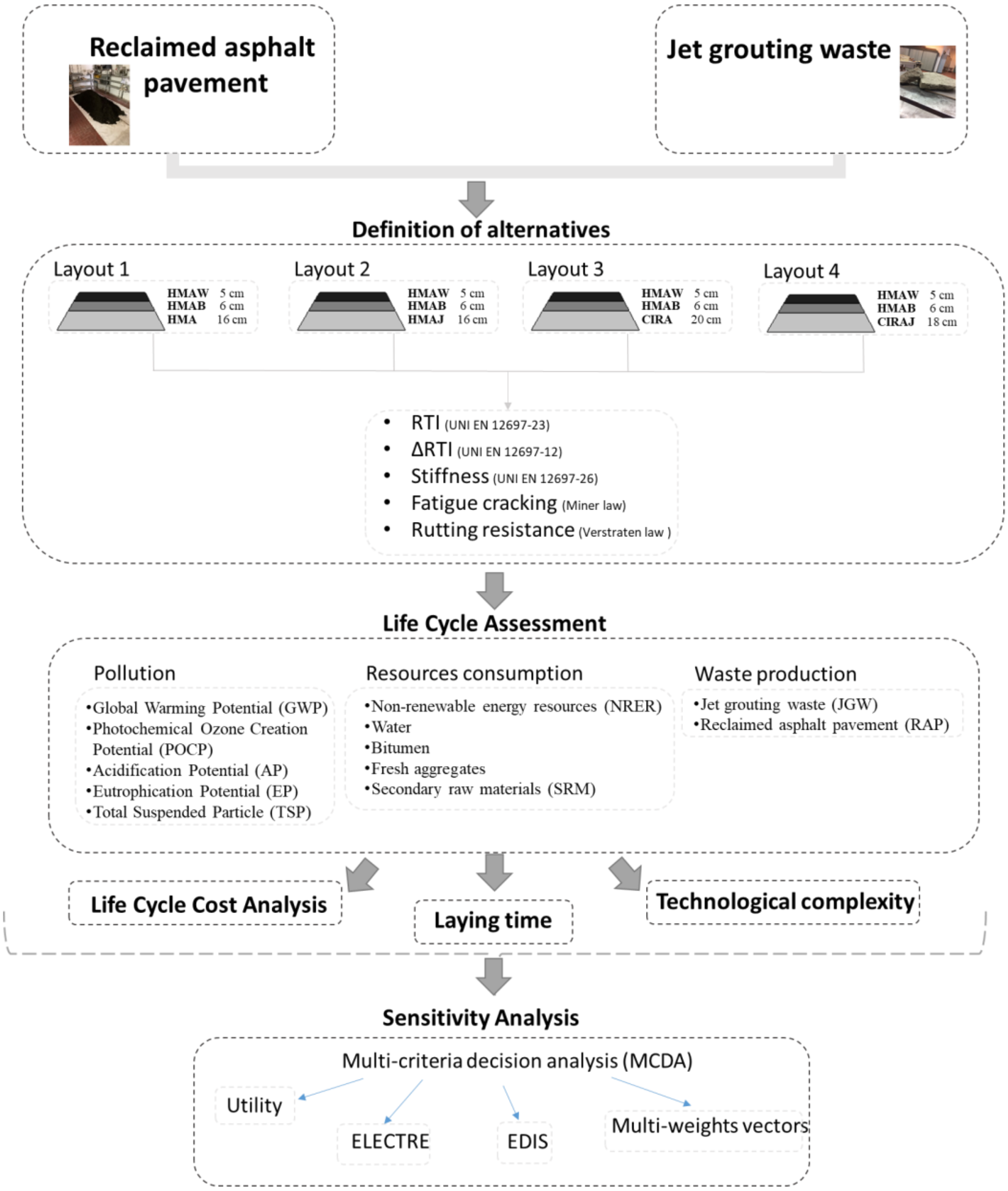


Figure 8.2 Performance assessment of pavement structure with alternative solution as base layer

8.1.1 Design of the four layout solutions

Taking into account data obtaining from the laboratory phase for base layer, and grouped with the data of HMA for the wearing course and binder layer collected from previous studies [75][76], as reported in Table 8.1, the stress-strain behaviour of the four layouts modelled as an elastic, homogeneous and isotropic multilayer was investigated. The results of the stress-strain analysis are reported in Figure 8.3 for Layouts 1 and 2 and in Figure 8.4 for Layouts 3 and 4.

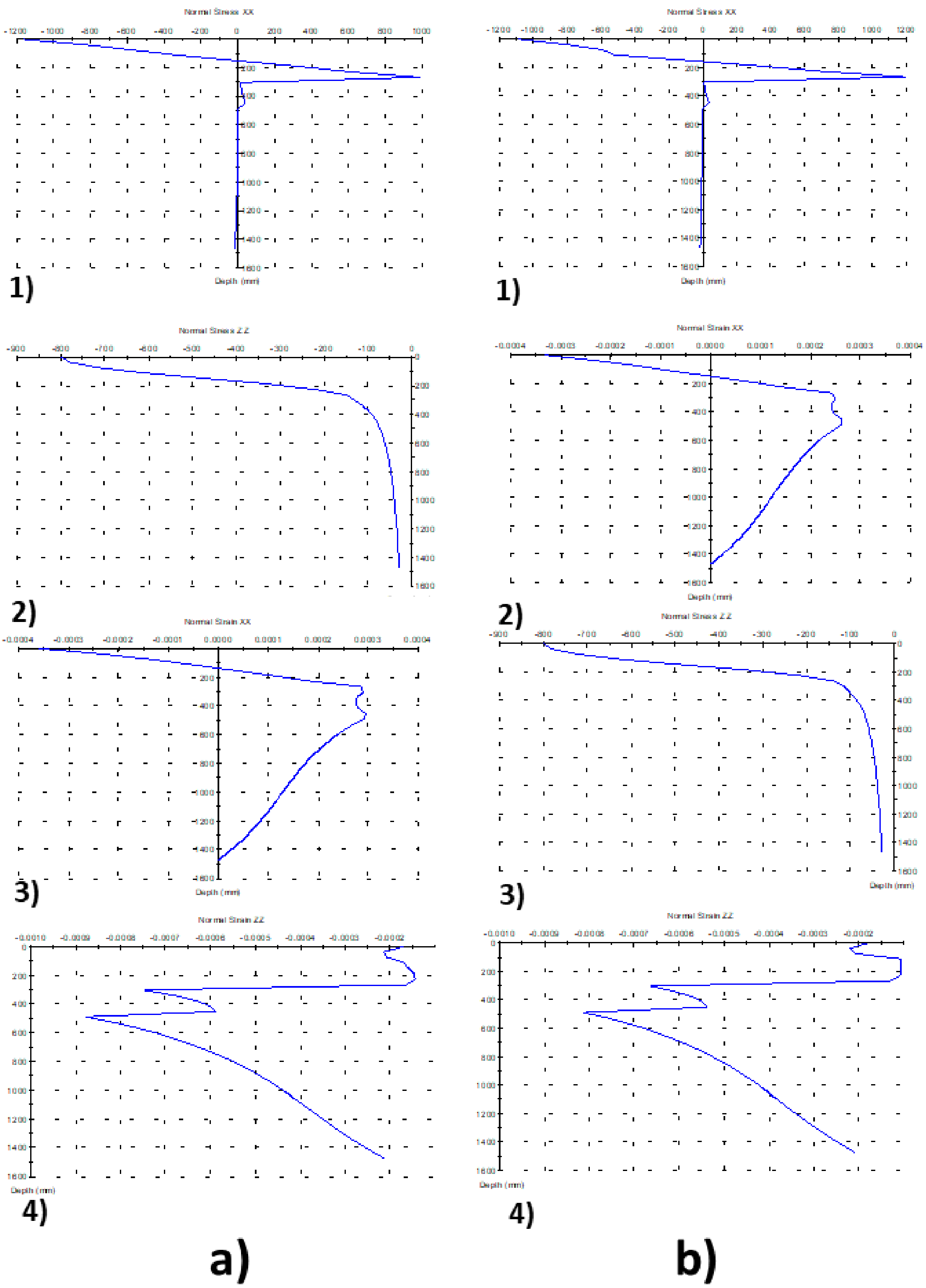


Figure 8.3 Inner stress-strain of hot mix design layouts: a) Layout 1 with HMA as base layer and b) Layout 2 with HMAJ as base layer: 1) normal stress xx, 2) normal stress zz, 3) normal strain xx and 4) normal strain zz

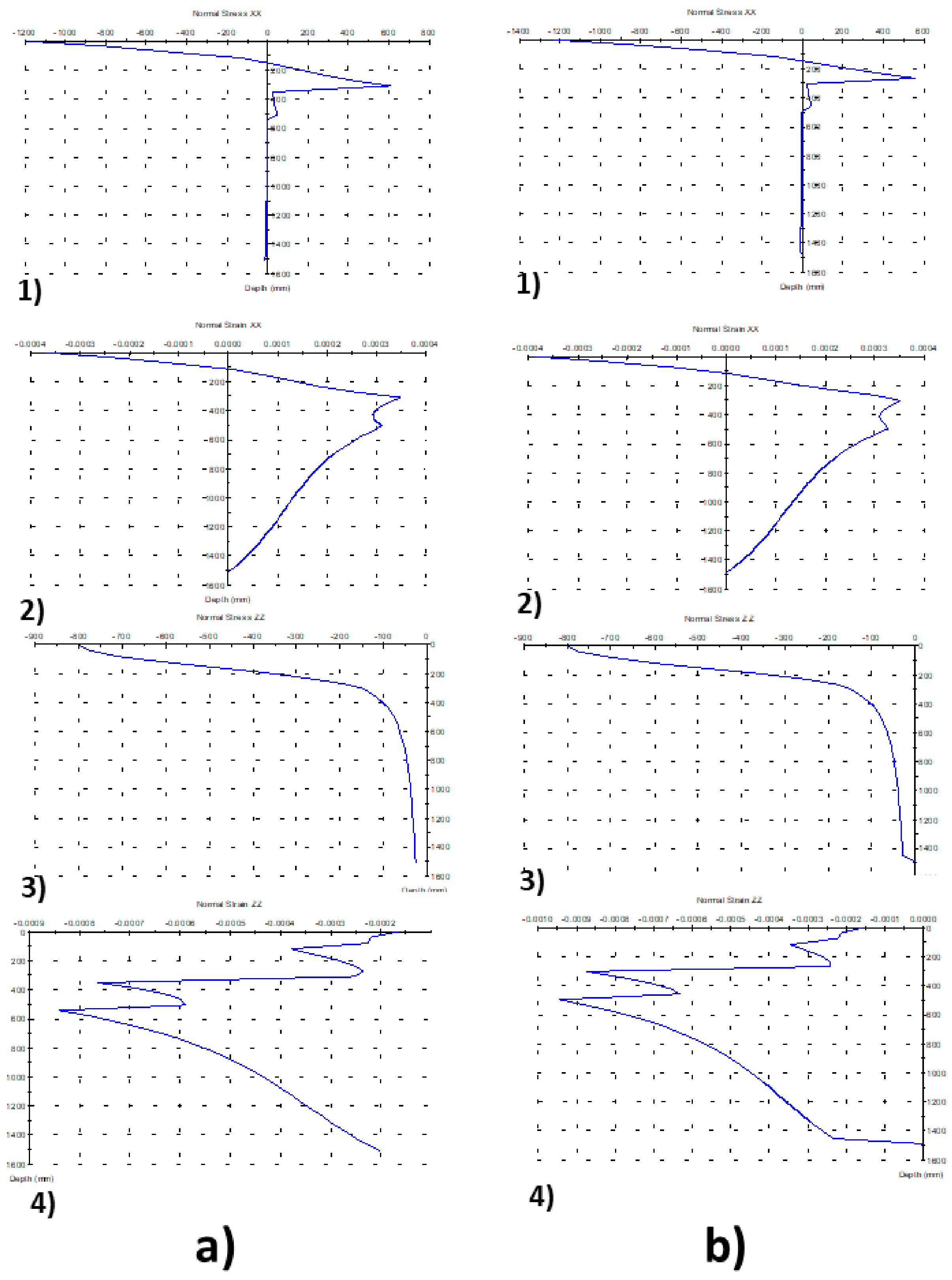


Figure 8.4 Inner stress-strain of cold mix design layouts: a) Layout 3 with CRA as base layer and b) Layout 4 with CRAJ as base layer: 1) normal stress xx, 2) normal stress zz, 3) normal strain xx and 4) normal strain zz

Table 8.1 Composition and Mechanical properties of the mixtures

Layer	Bituminous mixture type	Bitumen [%]	Bituminous emulsion [%]	Cement [%]	Water [%]	ITS [MPa] EN 12697-23	ΔRTI [-] EN 12697-12	Stiffness [MPa] EN 12697-26		
								10°C	20°C	30°C
Wearing course	HMAW	6	-	-	-	1.3	11%	12935	6297	2254
Binder	HMAB	5.5	-	-	-	0.85	9%	13375	6630	2435
Base	HMA	4	-	-	-	0.68	12%	15500	7350	2960
	HMAJ	4.85	-	-	-	0.77	9%	17600	9730	4200
	CRA	-	3.75	1	5	0.64	6%	5860	2970	1490
	CRAJ	-	5	1	5	0.73	4%	8680	3220	1610

Fatigue cracking and rutting have been verified for the four hypothesized layouts according to Equation 53 and 54 [59]:

$$DC = \sum_{i=1}^{P} \sum_{j=1}^{A} \frac{n_{i,j}}{N_{i,j}} < 1 \quad \textit{Miner law} \tag{53}$$

where

- $n_{i,j}$ is the number of actual passage of *j*-th axle loads in the *i*-th period of analysis
- $N_{i,j}$ is the repetition of the number of *j*-th axle loads in the *i*-th period of analysis that leads to failure the layout

$$\delta p = \sum_i \sum_j \varepsilon_{ij} \cdot h_j < 2\text{cm} \qquad \textit{Verstraten law} \tag{54}$$

where

- ε_{ij} ·is the permanent deformation after *n* load cycles of *i*-th layer in the *j*-th period of analysis [59]
- h_j is the thickness of the *j*-th layer

The results in terms of mean fatigue cracking $\overline{\text{DC}}$ and rutting $\overline{\delta\text{p}}$, evaluated at the average seasonal temperatures for each layout, are reported in Table 8.2.

In order to preserve by fatigue cracking and rutting, fixed the useful life at 15 years, the configuration of the four designed layouts resulted in different base layers' thicknesses: compared to Layout 1, where the size of the base layer is equal to 16 cm, Layout 2 required the same configuration; on the other hand, to satisfy the safety verifications, Layout 3 and Layout 4 required an increase of the base layer respectively equal to 4 cm and 2 cm, compared to the standard configuration of Layout 1.

Nevertheless, all the results in terms of $\overline{\text{DC}}$ and $\overline{\delta\text{p}}$ are less than the maximum values to satisfy the verifications. In particular, comparing the alternatives with respect to Layout 1 with HMA as base layer in terms of $\overline{DC}$, the Layout 2 with HMAJ as base layer shows a decrease of 21.9%, the Layout 3 with CRA as base layer shows a decrease of 75.0% and the Layout 4 with CRAJ as base layer shows a decrease of 59.0% of fatigue life; in terms of $\overline{\delta p}$, the reduction for Layout 2 is equal to 0.09 cm, while for Layout 3 it increases of 0.47 cm and for Layout 4 it increases of 0.33 cm.

It can be noticed that the behaviour of the cold bituminous mixtures in terms of fatigue cracking responses differently from the behaviour in terms of rutting, contrary to what happens for the hot bituminous mixtures; the decrease of fatigue cracking for Layouts 3 and 4 is due to the higher ITS (see section 7.3) of the cold bituminous mixtures for base layer, while their increase of rutting is attributable to the greater thicknesses of the base layers and also due to their lower stiffness, which causes higher vertical deformation, as it is noticeable from Equation 54.

The total amount of the materials needed for the laying of the four designed alternatives is reported in Table 8.2.

Table 8.2 Results of fatigue cracking and rutting resistance evaluation

Layer type	Material	AADT [veh/dd]	Stiffness [MPa] 10°C	20°C	30°C	Layer thickness [cm]	$\overline{DC}$ [-]	$\overline{\delta p}$ [cm]
			Layout 1					
Wearing course	HMAW	4620	12935	6297	2254	5	0.32	0.24
Binder	HMAB		13375	6630	2435	6		
Base	**HMA**		**15500**	**7350**	**2960**	**16**		
Subbase	Unbound Granular			183.95		20		
Subgrade	Soil			82.29		-		
			Layout 2					
Wearing course	HMAW	4620	12935	6297	2254	5	0.25	0.15
Binder	HMAB		13375	6630	2435	6		
Base	**HMAJ**		**17600**	**9730**	**4200**	**16**		
Subbase	Unbound Granular			183.95		20		
Subgrade	Soil			82.29		-		
			Layout 3					
Wearing course	HMAW	4620	12935	6297	2254	5	0.08	0.62
Binder	HMAB		13375	6630	2435	6		
Base	**CRA**		**5860**	**2970**	**1490**	**20**		
Subbase	Unbound Granular			183.95		20		
Subgrade	Soil			82.29		-		
			Layout 4					
Wearing course	HMAW	4620	12935	6297	2254	5	0.13	0.57
Binder	HMAB		13375	6630	2435	6		
Base	**CRAJ**		**8680**	**3220**	**1610**	**18**		
Subbase	Unbound Granular			183.95		20		
Subgrade	Soil			82.29		-		

Table 8.3 Total quantity of raw materials and bituminous mixtures needed for the construction of each layer

		Wearing course	Binder layer	Base layer			
	Units	HMAW	HMAB	HMA	HMAJ	CRA	CRAJ
Aggregates							
Limestone 31.5-16mm	t	-	-	625.93	620.86	1328.54	1186.07
Limestone 10-16 mm	t	-	592.73	2225.54	2207.50	581.24	518.91
Limestone 6-12 mm	t	-	747.35	2155.99	2138.51	-	-
Limestone 3-6 mm	t	-	335.02	-	-	-	-
Basalt 10-16 mm	t	429.31	-	-	-	-	-
Basalt 5-10 mm	t	643.96	-	-	-	-	-
Basalt 3-6 mm	t	321.98	-	-	-	-	-
Limestone sand	t	643.96	824.66	1460.51	1296.90	166.07	-
Limestone filler	t	107.33	77.31	486.84	358.72	415.17	296.52
JW	t	-	-	-	275.94	-	222.39
RAP	t	-	-	-	-	5812.38	5189.06
Binders							
Bitumen	t	2260.31	2712.37	7233.00	7233.00	-	-
Bituminous emulsion	t	-	-	-	-	326.79	387.48
Cement	t	-	-	-	-	89.52	80.57
Water	t	-	-	-	-	321.54	256.13
Mixtures							
Total	t	4406.85	5289.44	14187.81	14131.43	9041.25	8137.13

8.1.2 Planning of the unitary process

The present study aims to assess the life cycle of the road pavement maintenance and construction works from the stages of extraction and manufacturing of fresh materials to the laying of the flexible pavement, according to the four proposed layouts. Figures 63-64-65-66 show the life cycle flow diagrams of respectively Layout 1, Layout 2, Layout 3 and Layout 4, involving all the unit processes connected to the yard operations, excluding the land consolidation works for the tunnel construction. In the present study, the inventory input flows of each designed layout (see Table 8.2) involve materials (aggregates, water, secondary raw materials and crude oil used to produce bitumen and bituminous emulsion) and non-renewable energy sources (natural gas, crude oil and coal used as fuels); the output flows concern waste production (RAP and JW) and pollutants emissions to air (CO_2, SO_x, NO_x, N_2O, CO, CH_4, PAH, Volatile organic compounds (VOC), TSP, NH_3) deriving from the burning of fuels in vehicles and equipment's engines, from the industrial manufacturing processes and from the industrial production of electricity and fuels. These flows are subsequently transformed through the characterisation step into 11 impact indicators divided into 3 categories: 1) Pollution (GWP, POCP, AP, EP, TSP), 2) Resource use (NRER, Water, Bitumen, Aggregates, SRM) and 3) Waste production (JW and RAP).

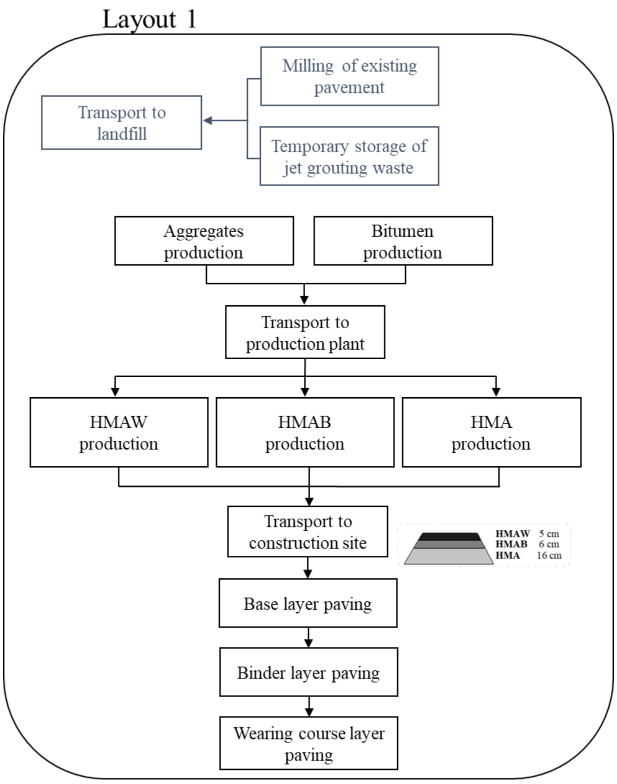


Figure 8.5 Life cycle flow diagram of Layout 1 with HMA as base layer

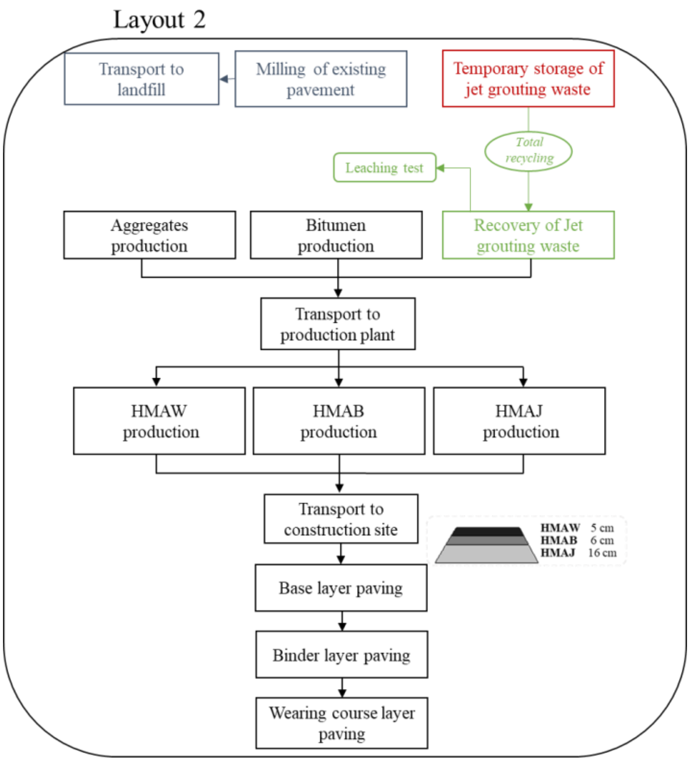


Figure 8.6 Life cycle flow diagram of Layout 2 with HMAJ as base layer

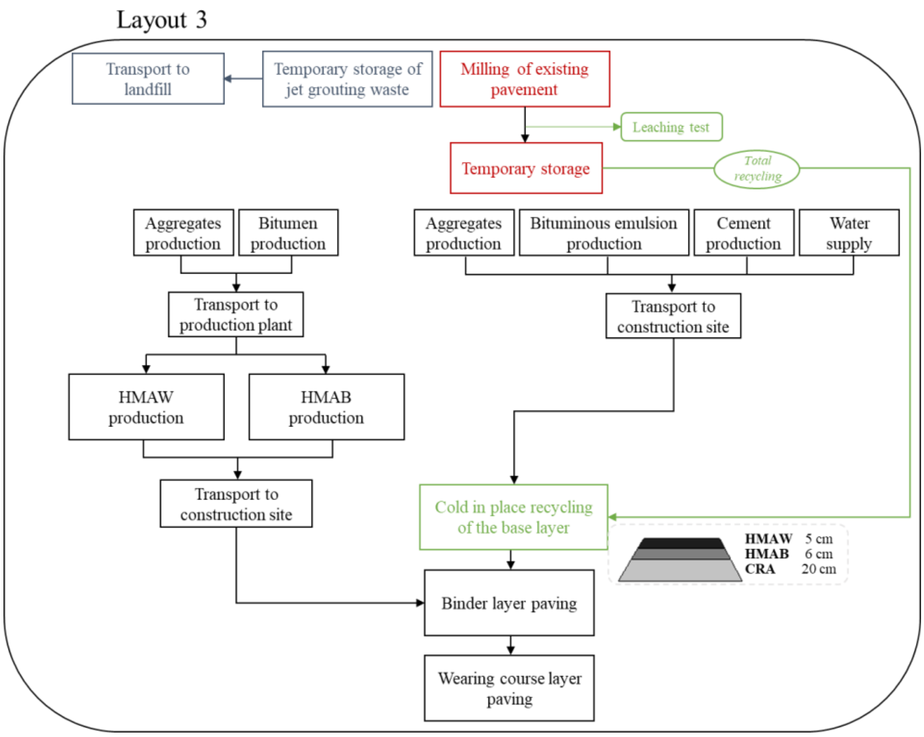


Figure 8.7 Life cycle flow diagram of Layout 4 with CRA as base layer

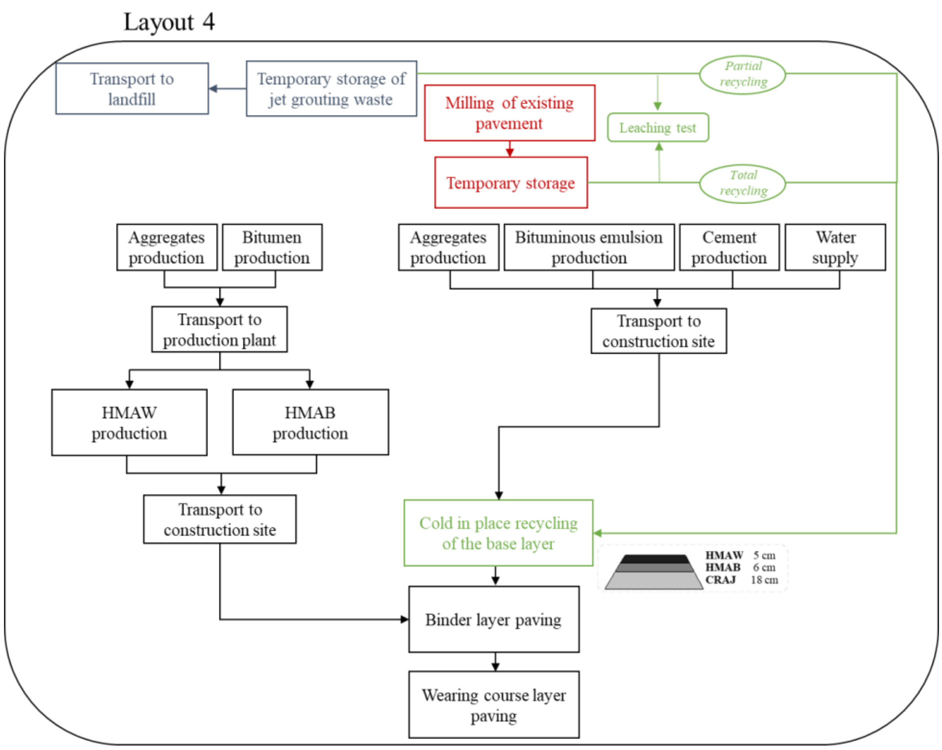


Figure 8.8 Life cycle flow diagram of Layout 4 with CRAJ as base layer

For the realization of the Layout 1 with HMA as base layer, which involves the construction of the road pavement under assessment with all the bituminous layers realized in hot bituminous mixtures (see Figure 8.5), the unit processes to be considered, from the extraction of raw materials to the construction of the bituminous layer of the flexible pavement, and the relative input and output flows are listed below:

- *Demolition of the existing road pavement*. The demolition of the existing road pavement's base layer (16 cm), binder layer (6 cm) and wearing course (5 cm) by means of a milling machine produced an output flow of about 3144.89 cubic meters of RAP. The quantity of RAP remains the same despite the layout under exam. The difference between the pavement layouts is the destination of the waste material: in the case of Layout 1 and Layout 2, the RAP is directly hauled to landfill after the milling operations, while, in the case of Layout 3 and Layout 4, it is temporary stored within the yard, far from the area of intervention, subjected to leaching test to ensure its environmental compatibility and reemployed in the cold bituminous mixtures for base layer. The input flow for this process consists of the amount of gasoil fuel needed for the milling machine, estimated through the equipment's productivity and the average hourly fuel consumption; the output flows of the demolition phase are, besides the production of RAP, the pollutants emissions of the milling machine's diesel engine and the industrial production of the input fuels, whose estimation methods will be shown below
- *Disposal of RAP and JW*. The amount of material that is not reemployed in the base layer mixture is then hauled away by trucks to the nearest landfill, located 45 kilometers from the yard, which is authorized to dispose both RAP and JW. In the case of Layout 1, the input flow of this unit process is equal to 5189.12 tonnes of RAP, deriving from the output flow of the demolition process of the existing road pavement, in addition to 276.94 tonnes of JW, deriving from the land consolidation during the tunnel construction works. Another input flow of the disposal process is the diesel fuel needed for the transportation of waste materials to landfill, which is a function of the distance between yard and landfill (45 km) and the average distance travelled by the truck with 1 liter of gasoil fuel. The output flows of this unit process are the pollutants emissions during transportation and industrial production of fuels. Lastly, the input waste materials become an output flow of this process when they are disposed of in landfill
- *Bitumen production and transport to the plant*. This group of phases goes from crude oil extraction to transport of bitumen by ship (from the petrochemical complex of Siracuse, Sicily, to the port of Naples, for approximately 245 Nm) and tanker (from the port of Naples to the bituminous mixture production plant, for approximately 40 km). For the Layout 1, a

total weight of 527.26 tonnes of bitumen was needed for the production of the three hot bituminous mixtures (see Table 8.3). The input flows of the bitumen production and transport phases consist of the amount of crude oil used as raw material, water and fuels consumed. The output flows of the process are the pollutant emissions deriving from the combustion of fuels in the phases of crude oil extraction, transport, refinery and storage. The input and output flows are related to the average European production of the total amount of bitumen needed for the production of the bituminous mixtures

- *Aggregates extraction, crushing and rindling, and transport of aggregates to bituminous mixtures production plant*. This set of phases, named *aggregates production*, also consists of a series of unit processes, starting from the extraction of aggregates by means of excavators, the transport of aggregates to the crushing and rindling plant through dumpers, the manufacturing phase and, finally, their transport to the bituminous mixtures production plant. Two different quarries and crushing and rindling plants were analysed: the basalt ones, placed at a distance of 4.0 kilometers, whose aggregates were needed in the wearing course's composition, and the limestone ones, placed at a distance of 0.5 kilometers, whose aggregates were employed in the base and binder layers. Both basalt and limestone crushing and rindling plants were located at similar distances from the bituminous mixtures production plant, respectively 73 and 67 kilometers away. The input flows of the whole aggregates production phase consist of: a) the quantity of basaltic and limestone aggregates needed for the realisation of Layout 1 (see Table 8.3), b) the amount of fuels used in the equipment (excavators, dumpers and wheel loaders), estimated through the calculation of the equipment's productivity or through the data provided by a local facility (described below) and by the estimation of the average hourly fuel consumption, c) the amount of fuels used for the aggregates transport, equal to the division of the above mentioned travelling distances by the average distance travelled by the truck with 1 liter of gasoil fuel and d) the amount of fuels used for the production of electricity, calculated through their calorific values and through data regarding the average unit consumption of electricity per tonne of aggregates at the crushing and rindling plants. The output flows of these phases are the pollutants emissions deriving from the combustion of the input fuels (whose estimation methods will be shown below) and the aggregates after unloading into the dedicated storage areas of the bituminous mixtures production plant
- *Production of hot bituminous mixtures* and *transport of hot bituminous mixtures to the yard*. The amounts of materials derived from the mix design results of the mixtures for base layer

(HMA), binder layer (HMAB) and wearing course (HMAW) (see Table 8.3) are processed in the bituminous mixtures production plant. The reference plant is mainly composed of cold aggregates supply system, drum dryer, natural gas burner, dust collector, hot aggregates elevator, vibrating screen, filler supply system, weighing and mixing system and bitumen supply system. All these components are powered by electricity from the grid. After the manufacturing phase, materials are loaded in the trucks and transported to the yard, located at a distance of about 20 kilometers from the plant. A total weight of 12205.69 tonnes was produced with hot plant technology for the construction of Layout 1 (see Table 8.3). The input flows of this phase are: a) the raw materials coming from the respective production processes, b) the amount of natural gas, calculated by multiplying the quantities of hot bituminous mixtures by the average unit consumption of fuel, c) the amount of gasoil fuel used for the moving of aggregates by means of wheel loaders and trucks and d) the fuels used for the production of electricity. The output flows are the pollutants emissions produced by the equipment’s engines, the industrial production of the input fuels and electricity and the natural gas burner, as well as the hot bituminous mixtures intended for the laying operations

- *Hot bituminous mixtures laying*. During this process, the truck adds the hot bituminous mixtures (HMA, HMAB and HMAW) into the paver’s hopper, the paving machine lays it over the width of the road and, finally, the roller-compactor provides the optimum compaction. This procedure is repeated for each layer or part of the layer. Data regarding the productivity of the hot paving operations and the working hours of the machinery were provided. The input flow of the laying process, besides the hot bituminous mixtures unloaded by the trucks, is the amount of gasoil fuel needed for the paver and the roller-compactor, while the output flows are the pollutants emissions produced by the equipment’s engines and the industrial production of the input fuels

For the Layout 2 with HMAJ as base layer (see Table 8.2) the unit processes are the same of Layout 1, with the only difference that in this case the base layer is composed by hot bituminous mixtures containing JW (HMAJ), so the inventory input and output flows are referred to the Layout 2 configuration. For this reason, the only output waste of the demolition process is the RAP, while the JW is totally recovered: a mass of 275.94 tonnes of dried JW was temporary stored in the yard far from the intervention area, subjected to a leaching test to assess its environmental compatibility, transported to the hot bituminous mixtures production plant and then milled through a grinding process (*JW recovery*). The input flow of the *JW recovery* process is the fuel used for the waste transportation and milling and the output flows are the gaseous emissions generated from fuels production and use.

In the case of Layout 3 with CRA as base layer (see Table 8.2), the bituminous mixture for base layer is produced through a cold in-place recycling technology and involves the total reemployment of the RAP derived from the milling of existing distressed road pavement (see Figure 8.7). Therefore, the unit process and the input and output flows are synthetized below as follows:

- *Demolition of the existing road pavement*. The type and the calculation methodologies of the input and output flows are above described in the case of Layout 1
- *RAP recovery*. The waste derived from demolition of existing road pavement (5198.12 tonnes, see Figure 8.7) were temporary stored within the yard, far from the area of intervention and then they were subjected to leaching test to ensure their environmental compatibility. A bituminous mixtures recovery plant supplied part of the material used for the base mix composition (623.26 tonnes, calculated as the difference between the amount of RAP reported in Table 8.3 and the RAP produced from the demolition process, equal to 5189.12 tonnes); therefore, its recovery procedures were not included in the system boundary. The input flow of this process is the gasoil fuel used for the moving of RAP and the output flows are the gaseous emissions generated from fuels production and use
- *Bitumen production and transport to the plant.* The above-mentioned considerations about bitumen manufacturing processes are the same described in the case of the Layout 1
- *Bituminous emulsion production and transport to the plant*. The bituminous emulsion production phase involves the production and transport of emulsifier, hydrochloric acid and bitumen, the water heating and the emulsion production. For the cold in-place recycling of the RAP deriving from the demolition of the existing bituminous pavement and supplied from an external facility, 326.79 tons of bituminous emulsion were needed (see Table 8.3). The input flows of the bituminous emulsion production and transport phase consist of the amount of crude oil, water and fossil fuels consumed. The output flows of the process are the pollutant emissions deriving from both bitumen and bituminous emulsion production. The input and output flows related to the average European production of bituminous emulsion needed for the production of the base layer (see Table 8.3)
- *Cement production*. The cold in-place recycling approach requires the adding of cement to the cold bituminous mixture for base layer. The cement used in the present case study is produced in the same site of the hot bituminous mixtures production plant. In the Layout 3, 89.52 tonnes of Portland cement were required for the mix design (see Table 8.3). Data

regarding the inventory input and output flows of the cement production were not available, but it was possible to collect the final LCIA results of the average Italian cement production

- *Aggregates extraction, crushing, rindling, and transport to the plant*. The activity involves the above-mentioned operations and input and output flows, but the reference quantities are specific for the Layout 3 configuration (see Table 8.3).
- *Cold in-place recycling of the base layer*. This phase involves the reemployment of RAP produced from the demolition of the existing road pavement. The cold-in-place process is typically performed using a set of machines, which includes an emulsion tanker, a water tanker, a cement tanker and a mixing machine that create the bituminous mixture composition, a grader, a wheel loader and a combination of pneumatic and vibratory rollers that spread the cold mixture on the road surface and provide a proper compaction of the base layer. The input flow for this phase, besides the raw and secondary materials required in the cold bituminous mixture composition, whose quantities are reported in Table 8.3, is the gasoil fuel necessary to transport raw materials to the yard and to lay the cold bituminous mixture for the base layer. The output flows of the cold-in place recycling process are the pollutants emissions deriving from the combustion of fuel in the trucks and equipment's engines
- *Production of hot bituminous mixtures* and *transport of hot bituminous mixtures to the yard*. The hot bituminous mixtures for binder layer (HMAB) and wearing course (HMAW) are produced in the manufacturing plant and transported to the yard by trucks. The input and output flows are equal to the ones that were already discussed for the layouts 1 and 2 (for the total volumes of wearing course and binder layer's mixtures see Table 8.3), excluding data regarding the production and transport of the base layer's hot bituminous mixture
- *Hot bituminous mixtures laying*. Again, the laying operations are referred to the same wearing course and binder layer as reported for the layouts 1 and 2

Lastly, the unit processes regarding the life cycle of Layout 4 with CRAJ as base layer (see Table 8.2) are the same of the Layout 3 with different amount of materials (Table 8.3). Furthermore, the JW is partially recovered to be used in the CRAJ mixture for base layer. The amount of reemployed JW is equal to 222.39 tonnes.

8.1.3 Life cycle inventory

In the present study, data resulted from an experimental phase, regarding the composition of the mixtures and the use of secondary raw materials (see Table 8.3), as well as the road pavement layout design, and from the support of a local reference company, regarding the plants' energy consumption, the modes of transportation, the type and model of the construction equipment, the average distances between extraction and production plants, yard and landfill, and the productivity of the hot bituminous mixtures laying operations (see Table 8.4).

Table 8.4 Data results of limestone and basalt aggregates production, hot bituminous mixtures production and laying and waste disposal

Primary data provided by the local reference company	Units	Quantity
Production of basaltic aggregates		
Productivity	t/h	300.00
Electricity	kWh/t	5.95
Distance from the asphalt plant	km	73
Production of limestone aggregates		
Productivity	t/h	375.00
Electricity	kWh/t	2.87
Distance from the asphalt plant	km	67
Production of hot bituminous mixtures		
Electricity	kWh/t	4.37
Natural gas	m^3/t	8.79
Distance from the yard	km	20
Laying of hot bituminous mixtures		
Productivity	m^3/t	25.00
Disposal of RAP and JW		
Distance yard-landfill	km	45

Referring to the experimental results reported in 7.3 and to the quantification of the main input and output flows of the LCI of the four proposed road pavement layouts (see Table 8.2), several articulated information were collected and as many calculation methodologies were applied.
The unit inventory data regarding bitumen and bituminous emulsion production, respectively reported in Table 8.5 and in Table 8.6, were collected from the LCI of Eurobitume [78] and were multiplied by the binders quantities resulting from the mix design and applied to the construction works under assessment (see Table 8.3).

Table 8.5 Life Cycle Inventory of 1 tonne of bitumen by Eurobitume

	Inventory	Units	Bitumen production and transport
Raw materials	Crude oil	kg	1000.00
Consumption of energy and non-energy resources	Natural gas	kg	20.10
	Crude oil	kg	40.90
	Coal	kg	1.03
	Water	l	143.00
Pollutant emissions to air	CO_2	g	174.24
	SO_2	g	781.00
	NO_x	g	770.00
	CO	g	613.00
	CH_4	g	595.00
	PAH	g	46.80
	VOC	g	331.00
	TSP	g	161.20

Table 8.6 Life Cycle Inventory of bituminous emulsion containing 1 tonne of bitumen by Eurobitume

	Inventory	Units	Bituminous emulsion production and transport
Raw materials	Crude oil	kg	1001.07
Consumption of energy and non-energy resources	Natural gas	kg	21.93
	Crude oil	kg	44.88
	Coal	kg	5.32
	Water	l	977.21
Pollutant emissions to air	CO_2	g	203746.03
	SO_2	g	875.55
	NO_x	g	835.16
	CO	g	629.46
	CH_4	g	639.55
	PAH	g	62.65
	VOC	g	337.61
	TSP	g	185.54

The features of the actually functioning equipment (equipment models are reported in Table 8.7) were obtained from the technical sheets available online and were used to evaluate the fuel consumption of each of them during the unit processes of the road pavement life cycle.

The estimation of the *fuel consumption* of a specific equipment involved in a unit process results from Equation 55:

$$FC_{x,i} = UFC_x \cdot P_{x,i} \cdot Q_i \tag{55}$$

where:

- $FC_{x,i}$ is the fuel consumption of equipment x during the unit process i [l]
- UFC_x is the unit fuel consumption of equipment x [l/h]

- $P_{x,i}$ is the productivity of equipment x during the unit process i and depends on the function of the specific equipment and on the physical configuration of its work environment (the estimation methodologies for each equipment will be shown below)
- Q_i is the amount of material or the extention of the surface that must be excavated, loaded, hauled, layed or compacted in the unit process i and can be expressed in [t], [m^3] or [m^2] depending on the specific case.

The *unit fuel consumption of equipment* x, UFC_x, is estimated through Equation 56 [79]:

$$UFC_x = \frac{K \cdot GHP \cdot LF}{KPL} \tag{56}$$

where:

- K is the fuel consumption rate of the engine [kg/hp · h] and is equal to 0.17 kg/hp · h for a diesel engine
- GHP is the engine's power [hp] and is set equal to the nominal maximum power stated on the technical sheet of each equipment
- LF is the load factor, that is assumed to be 0.54 for a medium load condition
- KPL is the fuel's specific weight and is equal to 0.835 kg/l for gasoil fuel

The UFC_x and the $FC_{x,i}$ for each unit process of the life cycle of the four proposed layouts are reported in Table 8.7.

Table 8.7 Hourly and total fuel consumption of the specific equipment involved in the unit processes of the life cycle of the four layouts

Unit process	Type	Model	Quantity	Hourly fuel consumption [l/h]	Total fuel consumption [l]			
					Layout 1	Layout 2	Layout 3	Layout 4
Milling of existing pavement	Milling machine	Wirtgen W200i	1	106.00	**4209.06**			
Aggregates extraction	Excavator with hammer	Caterpillar 374 (limestone quarry)	3	59.20	37350.60	36397.36	20612.96	19041.65
		Caterpillar 374 (basalt quarry)	3	59.20	**6606.43**			
	Excavator	Caterpillar 320 (limestone quarry)	2	20.35	732.03	713.35	403.99	373.20
		Caterpillar 326F L (limestone quarry)	1	25.05	450.71	439.21	248.74	229.78
		Hitachi ZX240N-6 (basalt quarry)	1	21.86	**188.26**			
	Dumper	Perlini DP 705 (limestone quarry)	2	95.34	2511.06	2446.97	1385.80	1280.16
		Caterpillar 730C2 (limestone quarry)	2	63.22	1665.18	1622.68	918.98	848.92
		Perlini DP 705 (basalt quarry)	3	95.34	**3267.24**			
Aggregates crushing and rindling	Wheel loader	Caterpillar 926 M (limestone plant)	2	19.17	1623.35	1590.24	873.84	812.58
		Caterpillar 963 k (limestone plant)	1	24.21	1025.27	1004.36	551.90	513.21
		Caterpillar 966 M (basalt plant)	1	39.01	**65.34**			
		Caterpillar 980 M (basalt plant)	1	53.30	**89.28**			
JW recovery	Wheel loader	Caterpillar 926 M	1	19.17	0.00	82.19	0.00	66.24
	Jaw mill	RM 70GO! 2.0	1	19.34	0.00	13.68	0.00	11.03
RAP recovery	Wheel loader	Caterpillar 926 M	1	19.17	**0.00**		5158.80	4605.57
HMA production	Wheel loader	Caterpillar 926 M	1	19.17	3378.73	3316.76	**1620.60**	
Laying of HMA	Paver	Vogele SUPER 1803-2	1	21.79	**6447.98**		**2626.96**	
	Roller compactor	HAMM HD 75	1	9.32	**2756.31**		**1122.94**	
Cold in-place recycling of the base layer	Pulvimixer	WR 240	1	76.51	**0.00**		**2794.76**	
	Grader	Caterpillar 120M2	1	18.16	**0.00**		**884.50**	
	Rubber-iron roller compactor	ASC 170	1	19.34	**0.00**		**706.37**	
	Iron-iron roller compactor	AV 70 X	1	10.09	**0.00**		**368.54**	
	Rubber roller compactor	AP 240	1	12.44	**0.00**		**454.53**	

The estimation of the *productivity of equipment* x during the unit process i, $P_{x,i}$, requires a different modelling Equation for each case. The productivity of the backhoe excavator that moves rocks from the extraction front to the dumper's loading bed is estimated with Equation 57 [80]:

$$P_{backhoe\ excavator,\ \ aggregates\ extraction} = \frac{BC \cdot FF \cdot OE}{CT} \tag{57}$$

where:

- BC is the bucket capacity $[\mathrm{cu.yd.}]$ as reported in the technical sheets
- FF is the fill factor and is used to account for the different bulking properties of the types of material being excavated and hauled. In the case of poorly blasted rocks, the fill factor is equal to 0.5
- OE is the operational efficiency $[\mathrm{min/h}]$ and is based on the number of minutes spent working per hour. In the present case, it is estimated to be 50 minutes per hour
- CT is the cycle time of the backhoe excavator $[\mathrm{s}]$ and is set equal to 20 seconds for average job conditions, which include dumpers located close to the excavators

The productivity of the dumpers that haul rocks from the quarry to the crushing and rindling plant is estimated with Equation 58 [80]:

$$P_{dumper,\ \ aggregates\ extraction} = \frac{VH \cdot OE}{CT} \tag{58}$$

where:

- VH is the vehicle hauling capacity $[\mathrm{m}^3]$
- OE is the operational efficiency $[\mathrm{min/h}]$ and again is set equal to 50 minutes per hour
- CT is the cycle time of the dumper $[\mathrm{min}]$ and is given by Equation 59:

$$CT = VT + FT \tag{59}$$

where:

- VT is the variable or travel time $[\mathrm{min}]$ and depends on the average speed, assumed equal to 2 $\mathrm{km/h}$, and the distance between quarry and crushing and rindling plant, equal to 0.5 km for limestone aggregates production and 4.0 km for basalt aggregates production

- FT is the fixed time [min], which is equal to the sum of the loading time LT, the dumping time and the spotting time. Dumping and spotting time are estimated with the suggested values for average job conditions and end dump and are equal to 1.30 and 0.30 minutes respectively. The loading time is a function of the capacity and cycle time of the loading equipment and the capacity of the dumper and is calculated through Equation 60:

$$LT = n° \; of \; loader \; cycles \; required \; to \; load \; dumper \cdot \; loader \; CT \qquad (60)$$

where:

- $loader\ CT$ is the loader cycle time [s] and again is equal to 20 s
- The $n°\ of\ loader\ cycles\ required\ to\ load\ dumper$ is equal is given by Equation 61 and should be rounded up to a whole number

$$n° \; of \; loader \; cycles \; required \; to \; load \; dumper = \frac{Volume \; capacity \; of \; dumper}{Volume \; capacity \; of \; loader} \qquad (61)$$

where the volume capacities are reported on the technical sheets of the respective equipment

The productivities of the wheel loaders, $P_{wheel\ loader,i}$ that move aggregates both in the crushing and rindling plant and in the hot bituminous mixtures production plant are estimated with Equation 62 [80]:

$$P_{wheel\ loader,i} = \frac{BC \cdot OE}{CT} \qquad (62)$$

where:

- BC is the bucket capacity of the wheel loader $[\mathrm{m}^3]$ and is reported on the technical sheet
- OE is the operational efficiency $[\mathrm{min/h}]$ and again is set equal to 50 minutes per hour
- CT is the cycle time of the wheel loader $[\mathrm{min}]$ and is given by Equation 59, where the fixed time is equal to 0.55 min for articulated wheeled loaders and 0.3 min for crawler loaders, and the variable time depends on the average speed (2 $\mathrm{km/h}$) and the unit process in which the wheel loader is operating. The travel distance is equal to 60 m in the crushing and rindling plants and 150 m and 300 m during the recovery of JW and RAP respectively. The

$P_{wheel\ loader}$ operating in the hot bituminous mixtures production plant is estimated by modelling the travel distance as reported in Figure 8.9 and weighting the resulting productivity on the amount of aggregates required by the hot bituminous mixtures design (see Table 8.2).

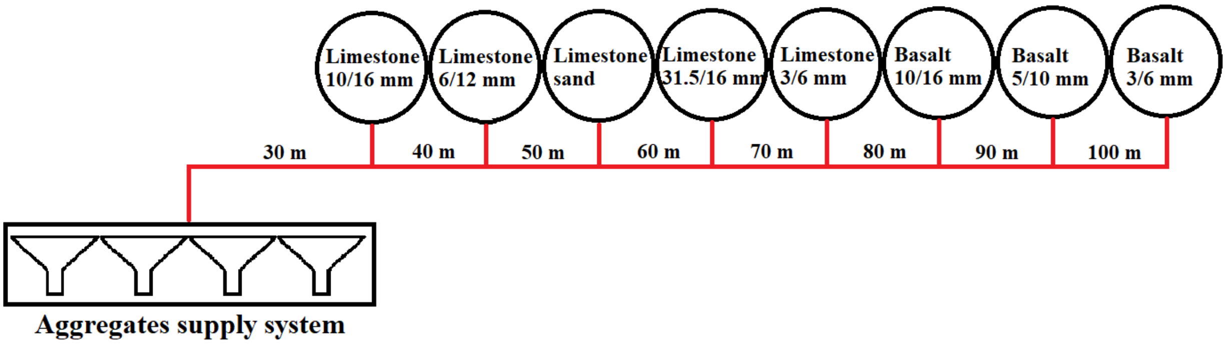


Figure 8.9 Model of the travel distance of the wheel loader that moves aggregates from the piles to the aggregates supply system in the hot bituminous mixture production plant

The resulting productivities of excavators, dumpers and wheel loaders are reported in Table 8.8. The equipment's productivities that were not estimated through the above-mentioned methodologies were selected directly from the technical sheets or provided by the local reference company as the mean values of field's investigation results (see Table 8.8). In particular, the productivities of milling machine, jaw mill and pulvimixer were available in the technical sheets, while the reference company provided the productivities of excavators with hammer, paver and roller for the laying of hot bituminous mixtures.

Lastly, the productivity of the set of machines performing the cold in-place recycling of RAP in Layout 3 and Layout 4 is set equal to the productivity of the pulvimixer since all the other equipment are disposed in series to the pulvimixer.

Table 8.8 Equipment types, models, quantities and productivities for each unit process of the life cycle

Unit process	Type	Model	Quantity	Units	$P_{x,i}$
Milling of existing pavement	Milling machine	Wirtgen W200i	1	m^3/h	79.2
Aggregates extraction	Excavator with hammer (limestone)	Caterpillar 374	3	t/h	46.9
	Excavator with hammer (basalt)	Caterpillar 374	3	t/h	37.5
	Excavator	Hitachi ZX240N-6	1	m^3/h	60.0
		Caterpillar 320	2	m^3/h	60.0
		Caterpillar 326F L	1	m^3/h	90.0
	Dumper	Perlini DP 705	5	m^3/h	15.1
		Caterpillar 730C2	2	m^3/h	6.8
Aggregates crushing and rindling	Wheel loader	Caterpillar 966 M	1	m^3/h	112.8
		Caterpillar 980 M	1	m^3/h	174.5
		Caterpillar 926 M	2	m^3/h	53.2
		Caterpillar 963 k	1	m^3/h	59.5
JW recovery	Wheel loader	Caterpillar 926 M	1	m^3/h	24.8
	Jaw mill	RM 70GO! 2.0	1	t/h	150.0
RAP recovery	Wheel loader	Caterpillar 926 M	1	m^3/h	13.09
Hot bituminous mixtures production	Wheel loader	Caterpillar 926 M	1	m^3/h	[35.2÷86.2] (*)
Laying of hot bituminous mixtures	Paver	Vogele SUPER 1803-2	1	t/h	41.25
	Roller compactor	HAMM HD 75	1	t/h	41.25
Cold in-place recycling of the base layer	Pulvimixer	WR 240	1	m^2/h	750.0
	Wheel loader	Caterpillar 926 M	1	m^2/h	750.0
	Grader	Caterpillar 120M2	1	m^2/h	750.0
	Rubber-iron roller compactor	ASC 170	1	m^2/h	750.0
	Iron-iron roller compactor	AV 70 X	1	m^2/h	750.0
	Rubber roller compactor	AP 240	1	m^2/h	750.0

(*) The productivity of the wheel loader that deals with the moving of aggregates from the aggregates piles to the aggregates supply system lays in the range reported in table. The different productivities are inversely proportional to the distance of each pile from the aggregates supply system, which influences the cycle time of the machine

Unlike construction equipment, trucks' technical sheets also provide information about the average distance travelled with 1 liter of gasoil fuel in full and empty conditions, as reported in Table 8.9; the fuel consumption of each transportation phase i (i.e. from crushing and rindling plant to hot bituminous mixture production plant, from hot bituminous production plant to the yard, from the yard to landfill) is estimated through Equation 63:

$$FC_i = \sum_{m=size\ or\ material} n°\ trips_{m,i} \cdot \left(\frac{D_i}{FC_{full}} + \frac{D_i}{FC_{empty}}\right) \tag{63}$$

where:

- m rapresents the different aggregate sizes, hot bituminous mixtures and waste materials

- FC_{full} and FC_{empty} are the average distances travelled by the truck with 1 liter of gasoil fuel in full and conditions [km/l] and are reported in Table 8.8
- D_i is the travelled distance in the i-th transportation phase [km]
- $n°\ trips_{m,i}$ is the number of trips required for the trasportation of the m-th aggregate size or material taking into account the volumes to be moved in i-th transportation phase, and is calculated by Equation 64:

$$n°\ trips_{m,i} = \frac{M_{m,i}}{W_m \cdot VH} \tag{64}$$

where:

- $M_{m,i}$ is the amount of the m-th aggregate size or material to be moved in the i-th transportation phase [t]
- W_m is the specific weight of the m-th aggregate size or material [t/m^3], as reported in Table 8.10
- VH is the vehicle hauling capacity [m^3], equal to 14 m^3 in the case of dump trucks moving aggregates, hot bituminous mixtures and waste and 20 m^3 in the case of tanker trucks moving fillers and cement.

When the transportation concerns liquids with a density equal or close to water's density (i.e. water and bituminous emulsion), Equation 64 is written as the ratio between $M_{m,i}$ and VH, which is expressed in tonnes and is equal to 40 tonnes.

The fuel consumption of each transportation phase for each of the four proposed layouts is reported in Table 8.11.

Table 8.9 Average distances travelled by trucks in different load conditions as reported in the technical sheet of a typical truck

Load condition	Units	Average distance travelled with 1 liter of gasoil fuel
Fully-loaded	[km/l]	3.0
Empty	[km/l]	3.6

Table 8.10 Loose density of the materials

Material and size	Units	Loose Density
Limestone 31.5-16mm	t/m^3	1.36
Limestone 10-16 mm	t/m^3	1.36
Limestone 6-12 mm	t/m^3	1.30
Limestone 3-6 mm	t/m^3	1.40
Basalt 10-16 mm	t/m^3	2.90
Basalt 5-10 mm	t/m^3	2.90
Basalt 3-6 mm	t/m^3	2.90
Limestone sand	t/m^3	1.45
Limestone filler	t/m^3	2.70
Bituminous mixtures	t/m^3	1.65
Milled JW	t/m^3	2.60
JW	t/m^3	1.50
Portland cement	t/m^3	1.40
Water	t/m^3	1.00
Bitumen	t/m^3	1.02
Bituminous emulsion	t/m^3	1.00

Table 8.11 Origin, destination, material transported and total fuel consumption of the transportation phases of the four road pavement layouts

Unit process	Origin	Destination	Material transported	Total gasoil fuel consumption [l]			
				Layout 1	Layout 2	Layout 3	Layout 4
Disposal of RAP and JW	Yard	Landfill	RAP and JW	6407.50	6215.00	220.00	82.5
Aggregates production and transport to the plant	Crushing and rindling plant	Hot bituminous mixtures production plant	Limestone and basaltic aggregates (all sizes)	22770.61	22279.28	13230.56	12370.72
JW recovery	Yard	Hot bituminous mixtures production plant	JW	0.00	97.78	0.00	0.00
Hot bituminous mixtures production and transport	Hot bituminous mixtures production plant	Yard	Hot bituminous mixtures	**6477.78**		**2640.00**	
Cold in-place recycling of the base layer	Hot bituminous mixtures production plant	Yard	Fresh aggregates, cement, water, bituminous emulsion	**0.00**		1906.67	1625.56

The pollutants emissions to air deriving from trucks and construction equipment's diesel engines, manufacturing processes and other combustion processes linked to the production of electricity and fuels have been obtained from emission factors reported in the "Air pollutant emission inventory guidebook" by EMEP/EEA [81] and, concerning GHG emissions, from the "Guidelines for National Greenhouse Gas Inventories" by IPCC [82].

For each unit process, the total amount of a specific pollutant emission to air M_s is calculated by Equation 65:

$$M_s = \sum_S M_{s,S} \tag{65}$$

where:

- s are the assessed pollutants ($CO_2, SO_x, NO_x, N_2O, CO, CH_4, PAH, VOC, TSP, NH_3$)
- S are the sources of emissions (i.e. electricity production, EP, fuels production, FP, combustion in diesel engines, DE, and hot bituminous mixtures production, AP)

Concerning the electricity production from non-renewable sources, the amount of each pollutant emission to air is calculated by multiplying data regarding the amount of electricity produced from each non-renewable fossil fuel by the corresponding emission factor, as reported in Equation 66:

$$M_{s,EP} = \sum_i EF_{s,EP,i} \cdot E_{EP,NR,i} \tag{66}$$

where:

- $M_{s,EP}$ is the mass of the substance s emitted during the production of electricity [g]
- $EF_{s,EP,i}$ is the mass of the substance s emitted during the production of 1 GJ of electricity with the fossil fuel i [g/GJ], as reported in Table 8.12
- $E_{EP,NR,i}$ is the amount of electricity produced from the i-th non renewable fossil fuel and is equal to the product between the total amount of electricity and the relative percentage reported in Table 8.12 [GJ]

It should be noted that the total amount of electricity is calculated as the product between: a) the average unit consumption of electricity per tonne of limestone or basaltic aggregates at the crushing and rindling plant and the total amount of limestone or basaltic aggregates required for the construction of the bituminous layers in each layout (see Table 8.3) or b) the average unit consumption of electricity per tonne of hot bituminous mixture produced in the manufacturing plant (see Table 8.4) and the total amount of hot bituminous mixtures required for the construction of the hot bituminous layers in each layout (see Table 8.3).

Table 8.12 Distribution of electricity produced from non-renewable fossil fuels in Italy (Autorità di Regolazione per Energia Reti e Ambiente, 2018)

Coal [%]	Natural gas [%]	Gasoil fuel [%]
14.40	38.57	3.27

Concerning the gasoil fuel production, the amount of each pollutant emission to air is calculated by multiplying the total amount of energy needed for the production of gasoil fuel from each non-renewable fossil fuel by the corresponding emission factor, as reported in Equation 67:

$$M_{S,FP} = \sum_i EF_{S,FP,i} \cdot E_{FP,i} \cdot M_f \tag{67}$$

where:

- $M_{S,FP}$ is the mass of the substance *S* emitted during the fuel production [g]
- $EF_{S,FP,i}$ is the mass of the substance *S* emitted during the production of gasoil fuel resulting from the consumption of 1 GJ of energy produced with the fossil fuel i $[\mathrm{g/GJ}]$
- $E_{FP,i}$ is the amount of allocated energy used to produce 1 tonne of gasoil fuel from the i-th fossil fuel $[\mathrm{GJ}]$ and is equal to the product between $AE_{gasoil\ fuel}$ and the relative percentage reported in Table 8.13
- M_f is the total mass of gasoil fuel $[\mathrm{t}]$ used in each unit process of the life cycle (see Table 8.7 and Table 8.11)

8.1.4 Allocation of the collected data

The allocation process is defined as the act of "partitioning the input and/or output flows of a process to the product system under study" (ISO 14040). In the present study, an allocation of energy between gasoil and the other co-products of the refining process is performed basing on mass balances.
The energy needed for the production of 1 tonne of gasoil fuel obtained with each fossil fuel is equal to the ratio between the energy needed for the refining of 1 tonne of crude oil and the average Italian mass yield of gasoil fuel (see Table 8.13)[83], multiplied by the relative percentage of energy produced by that fossil fuel (see Table 8.13).

Table 8.13 Average European data regarding the refinery process by Eurobitume, average Italian mass yeld of gasoil fuel by Petroleum Union [83] and derived values

	Units	Quantity
Total energy used to refine 1 tonne of crude oil	[MJ/t crude oil]	817.19
with refinery gas	[%]	80
with heavy fuel oil	[%]	20
Average Italian mass yeld of gasoil fuel	[t gasoil/t feed]	40.1
Energy needed for the refining process per tonne of gasoil fuel produced	[MJ/t gasoil]	2037.87
with refinery gas	[MJ/t gasoil]	1630.30
with heavy fuel oil	[MJ/t gasoil]	407.57

The allocation of energy between gasoil fuel and the other co-products of the refining process is performed with Equation 68:

$$AE_{gasoil\ fuel} = E_{Refinery,1\ t\ of\ gasoil\ fuel} \cdot MY_{gasoil\ fuel} \tag{68}$$

where:

- $AE_{gasoil\ fuel}$ is the energy allocated to the production of 1 tonne of gasoil fuel [MJ/t gasoil]
- $E_{Refinery,1\ t\ of\ gasoil\ fuel}$ is the energy needed for the refining process per tonne of gasoil fuel produced through each fossil fuel [MJ/t gasoil]
- $MY_{gasoil\ fuel}$ is the average Italian mass yield of gasoil fuel [t gasoil/t feed], as reported in Table 8.13

Concerning the pollutant emissions deriving from the internal combustion of diesel engines, the mass of the s-th substance is calculated by multiplying the amount of gasoil fuel burnt in the i-th equipment's engine by the corresponding emission factor, as reported in Equation 69:

$$M_{s,DE} = \sum_i EF_{s,DE,i} \cdot M_{f,i} \tag{69}$$

where:

- $M_{s,DE}$ is the mass of the subtance S emitted during the fuel combustion in the equipment's diesel engines [g]
- $EF_{s,DE,i}$ is the mass of the substance S emitted by burning 1 tonne of gasoil fuel in the i-th type of equipment's engine [g/t fuel]

- $M_{f,i}$ is the amount of gasoil fuel used for the i-th type of equipment's engine $[\mathrm{t}]$. Table 8.7 and Table 8.11 show the estimated amount of gasoil fuel for each equipment in the unit processes of the four layouts' life cycles.

Concerning the manufacturing of hot bituminous mixtures with natural gas, the mass of each pollutant emission is calculated by multiplying the amount of energy needed for the asphalt production by the specific emission factors, as reported in Equation 70:

$$M_{S,AP} = EF_{S,AP} \cdot E_{AP} \tag{70}$$

where

- $M_{S,AP}$ is the mass of the subtance S emitted during the asphalt production [g]
- $EF_{S,AP}$ is the mass of the substance S emitted during the production of asphalt resulting from the consumption of 1 GJ of energy produced with natural gas $[\mathrm{g/GJ}]$
- E_{AP} is the amount of energy needed for the asphalt production $[\mathrm{GJ}]$ and is given by Equation 71:

$$E_{AP} = CV_{NG} \cdot v_{NG} \cdot V_{NG} \cdot M_A \tag{71}$$

where

- CV_{NG} is the calorific value of natural gas $[\mathrm{MJ/kg}]$, equal to 49.4 $\mathrm{MJ/kg}$
- v_{NG} is the density of natural gas $[\mathrm{kg/m^3}]$, equal to 0.678 $\mathrm{kg/m^3}$
- V_{NG} is the unit volume of natural gas used per tonne of hot bituminus mixture produced $[\mathrm{m^3/t}]$, as reported in Table 8.4
- M_A is the mass of hot bituminous mixture produced $[\mathrm{t}]$, as reported in Table 8.3 for the four road pavement layouts

All the above-listed models are simplified by assuming unitary efficiency of the heat exchanges.

Table 8.14 Emission factors of industrial production

Pollutant emissions to air	Units	Manifacturing industries with gaseous fuels (*) $EF_{s,AP}$	Electricity production with coal $EF_{s,EP,coal}$	Electricity production with natural gas $EF_{s,EP,natural\ gas}$	Electricity production with gasoil $EF_{s,EP,gasoil}$	Petroleum refining with refinery gas $EF_{s,FP,refinery\ gas}$	Petroleum refining with heavy fuel oil $EF_{s,FP,h.f.o.}$
CO_2	kg/TJ	56100	107000	56100	74100	57600	77400
SO_x	g/GJ	0.67	820.0	0.3	46.5	0.281	495.000
NO_x	g/GJ	74	209.0	89.0	65.0	63.000	142.000
N_2O	kg/TJ	0.1	1.5	0.1	0.6	0.1	0.6
CO	g/GJ	29	8.7	39.0	16.2	12.100	15.100
CH_4	kg/TJ	1	1	1	3	1	3
VOC	g/GJ	23	1.0	2.6	0.8	2.580	2.300
TSP	g/GJ	0.78	11.4	0.9	6.5	0.890	35.400

(*) Hot bituminous mixture production using natural gas

Table 8.15 Emission factors of non-road mobile machinery and trucks engines

Pollutant emissions to air	Units	Construction equipment $EF_{s,DE,NRMM}$	Trucks $EF_{s,DE,autovehicles}$
CO_2	g/t fuel	3.160 E+03	3.169 E+06
NO_x	g/t fuel	3.279 E+04	3.337 E+04
N_2O	g/t fuel	1.350 E+02	5.100 E+01
CO	g/t fuel	1.072 E+04	7.580 E+03
CH_4	g/t fuel	5.500 E+01	-
VOC	g/t fuel	3.385 E+03	1.920 E+03
TSP	g/t fuel	2.086 E+03	9.400 E+02
NH_3	g/t fuel	8.000 E+00	1.300 E+01

Emissions of SO_2 deriving from the burning of fuels containing sulphur are calculated according to Equation 72:

$$M_{SO_2} = 2 \cdot \sum_j \sum_1 k_{s,1} \cdot b_{j,1} \tag{72}$$

where:

- $k_{s,i}$ is the weight related sulphur content of fuel of type *1* [kg/kg fuel] and it is assumed equal to 0.00001 kg/kg fuel for gasoil fuel
- $b_{j,1}$ is the total consumption of fuel of type *1* in [kg] by source category *j*

Once the data collection and calculation have been carried out according to the above-mentioned methodologies, the LCI phase is completed.

8.1.5 The Life Cycle Impact Assessment

The last step of the LCA technique consists in the LCIA, which involves three main phases: a) selection of *categories*, which are defined as classes representing environmental issues of concern to which life cycle inventory analysis results may be assigned, *impact indicators*, which quantify the negative effects to human health, environment and natural resources, and *characterisation models*, which are used to convert LCI results into impact indicators, b) allocation of the LCI results to the impact indicators (classification) and c) calculation of impact indicators results (characterisation) (ISO 14040 and ISO 14044).

Data collected in the LCI was modelled using 11 impact indicators selected from EN 15804 and their characterization models listed in the LCA Handbook [82]. The selected impact indicators concern three different impact categories: pollution (GWP, POCP, AP, EP, TSP), resources consumption (NRER, Aggregates, Bitumen, Secondary raw materials (SRM), Water) and waste production (JW and RAP).

Some of the LCI results perfectly match with the previously listed impact indicators such as Aggregates, Bitumen, SRM, Water, JW and RAP and TSP, since classification and characterisation consist in setting the LCI result equal to the corresponding impact indicator, while in the case of NRER simple operations on the LCI results are required.

The impact indicators regarding cement production have been acquired from the "Environmental declaration of average Italy grey cement" published by Associazione Italiana Tecnico Economica del Cemento (2016) [84] (see Table 8.16).

Table 8.16 LCIA of Italian average production of 1 tonne of Portland cement

Category	Impact indicators	Units	Quantity
Pollution	GWP	kg CO_2 eq. in 100 years	964.00
	POCP	kg C_2H_4 eq.	0.51
	AP	kg SO_2 eq.	2.13
	EP	kg NO_3 eq.	0.32
	TSP	kg	(*)
Resources consumption	NRER	MJ	6545.00
	Water	l	845.83
	Bitumen	t	1470.00
	Aggregates	t	1.00
	SRM	t	0.06
Waste production	RAP and JW	t	0.005

(*) not assessed

The allocation of the pollutant emissions to air $(CO_2, SO_x, NO_x, N_2O, CO, CH_4, PAH, VOC, NH_3)$ to the impact indicators is performed through the concept of characterisation factors, which allow comparing the ability of different substances to cause the same environmental impact. These factors convert the assigned LCI results into a common unit of an impact indicator I_c, expressed as "equivalent" (eq.) due to the applied conversion process, as explained in Equation 73:

$$I_c = \sum_s CF_{s,c} \cdot M_s \tag{73}$$

where:

- I_c is the c-th impact indicator
- $CF_{s,c}$ is the characterisation factor of the s-th substance for the c-th impact indicator
- M_s is the mass of the s-th substance emitted into atmosphere during the unit process under analysis, calculated though the Equations 66, 67, 69, 70 and 72 according to the source of emission.

The total impact indicators and their characterisation models used in the present study are synthesised as follows:

- *GWP*. This indicator refers to the impact of GHG on the radiative forcing of the atmosphere, causing the temperature at the earth's surface to rise. It was developed to allow comparisons of the global warming effect of different gases with respect to the effect of carbon dioxide (CO_2). The period of time to which GWP is referred is equal to 100 years, therefore the unit of measurement is kilograms of CO_2 eq. in 100 years. For each unit process, GWP was calculated using Equation 74:

$$I_{GWP} = CF_{CO_2,GWP} \cdot M_{CO_2} + CF_{CH_4,GWP} \cdot M_{CH_4} + CF_{N_2O,GWP} \cdot M_{N_2O} + CF_{CO,GWP} \cdot M_{CO} + CF_{PAH,GWP} \cdot M_{PAH} \tag{74}$$

where the characterisation factors $CF_{s,GWP}$ are reported in Table 8.17 [79]

Table 8.17 Characterisation factors for GWP

Pollutant emissions to air	Units	$CF_{s,GWP}$
CO_2	kg CO_2eq. in 100 years	1
CH_4	kg CO_2eq. in 100 years	25
N_2O	kg CO_2eq. in 100 years	320
CO	kg CO_2eq. in 100 years	2
PAH	kg CO_2eq. in 100 years	3

- *POCP*. This indicator refers to the production of ozone from VOC emissions that are mainly considered as an environmental problem due to their significance in the formation of photochemical oxidants, especially ozone, which may cause damage both to vegetation and human health. The unit of measurement is kilograms of C_2H_4 eq. and the impact indicator is calculated through Equation 75:

$$I_{POCP} = CF_{CO,POCP} \cdot M_{CO} + CF_{VOC\ from\ industrial\ production,POCP} \cdot \left(M_{VOC,EP} + M_{VOC,FP} + M_{VOC,AP}\right) + CF_{VOC\ from\ engines,POCP} \cdot M_{VOC,DE} \quad (75)$$

where the characterisation factors $CF_{s,POCP}$ are reported in Table 8.18 [79]

Table 8.18 Characterisation factors for POCP

Pollutant emissions to air	Units	$CF_{s,POCP}$
CO	kg C_2H_4 eq.	0.03
VOC from industrial production	kg C_2H_4 eq.	0.50
VOC from diesel engines	kg C_2H_4 eq.	0.60

- *AP*. This indicator refers to the increase of the acidity of water and soil systems due to the reaction of sulphur dioxide (SO_2) with water in the atmosphere to form acid rains. This effect alters the pH of water and soils and may cause damage to the organic and inorganic materials. The acidification potential is calculated through Equation 24, using the unit of measurement kilograms of SO_2eq.:

$$I_{AP} = CF_{SO_x,AP} \cdot M_{SO_x} + CF_{NO_x,AP} \cdot M_{NO_x} + CF_{NH_3,AP} \cdot M_{NH_3} \quad (76)$$

where the characterisation factors $CF_{s,AP}$ are reported in Table 8.19 [85]

Table 8.19 Characterisation factors for AP

Pollutant emissions to air	Units	$CF_{s,AP}$
SO_x	kg SO_2 eq.	1.00
NO_x	kg SO_2 eq.	0.70
NH_3	kg SO_2 eq.	1.88

- *EP*. This indicator refers to the environmental impacts caused by excessive levels of macronutrients. Due to the increasing generation of biomass and the consequently heavier sedimentation of dead organic material, the oxygen dissolved in deep water is consumed faster through aerobic decomposition, which may cause an elevated biomass production. The unit of measurement is kilograms of NO_3 eq. and the impact indicator is calculated through Equation 77:

$$I_{EP} = CF_{NO_x,EP} \cdot M_{NO_x} + CF_{N_2O,EP} \cdot M_{N_2O} + CF_{NH_3,EP} \cdot M_{NH_3} \tag{77}$$

where the characterisation factors $CF_{s,EP}$ are reported in Table 8.20 [80]

Table 8.20 Characterisation factors for EP

Pollutant emissions to air	Units	$CF_{s,EP}$
NO_x	kg NO_3 eq.	0.30
N_2O	kg NO_3 eq.	0.64
NH_3	kg NO_3 eq.	0.82

- *TSP*. This indicator refers to the amount of suspended particles with a diameter less than 50-100 μm, originated from anthropogenic processes such as combustion, which may induce several health problems, especially to the respiratory tract. The unit of measurement is kilograms and the impact indicator is quantified through Equation 78:

$$I_{TSP} = M_{TSP} \tag{78}$$

- *NRER*. This indicator refers to the amount of non-renewable primary and secondary energy resources (gasoil fuel, heavy fuel oil, natural gas, coal and refinery gas) employed during the unit processes of the life cycle. It is measured in Megajoule and calculated through Equation 79:

$$I_{NRER} = M_f \cdot CV_f + \sum_i E_{EP,NR,i} + E_{AP} + \sum_i E_{FP,i} \cdot M_f \quad (79)$$

where

- $M_f \cdot CV_f$ is the amount of energy [MJ] generated from the fuel combustion (assuming unitary efficiency of heat exchange), equal to the product of the mass of fuel used in the unit process M_f (see Table 8.7 and Table 8.11) and the corresponding calorific value of the fuel CV_f
- $\sum_i E_{EP,NR,i}$ is the total amount of energy [MJ] consumed for the production of electricity
- E_{AP} is the amount of energy [MJ] generated from the combustion of natural gas (specific for the hot bituminous mixture production)
- $\sum_i E_{FP,i} \cdot M_f$ is the amount of energy [MJ] needed for the production of gasoil fuel

- *Water.* This indicator refers to the amount of water used in each unit process of the life cycle and it is measured in tonnes
- *Aggregates.* This indicator quantifies the amount of limestone or basaltic aggregates used in each stage of the life cycle as requested by the mix design of each bituminous layer (see Table 8.3) and it is measured in tonnes
- *Bitumen.* This indicator is set equal to the amount of bitumen used as such in the hot bituminous mixtures or emulsified to be introduced in the cold in-place recycling approach and it is measured in tonnes
- *SRM.* This indicator refers to the amount of secondary raw materials, namely JW and RAP, reemployed in each stage of the life cycle and it is measured in tonnes. SRM originate from the corresponding waste materials, after they are subjected to the recovery procedures, tested and introduced in the mix design according to the quantities reported in Table 8.3

Waste production. This indicator measures the amount of non-hazardous special waste, namely JW and RAP, produced in each phase of the life cycle that were not reemployed in the bituminous mixtures. It is measured in tonnes.

8.1.6 Interpretation of the results

The research here presented has provided a range of feasible solutions for a base layer in bituminous mixture of a flexible pavement for an extraordinary maintenance work on an existing road pavement and the laying of a new contiguous section located under a tunnel. Four solutions have been designed, different from each other for the base layer: Layout 1 with HMA as base layer, Layout 2 with HMAJ as base layer, Layout 3 with CRA as base layer and Layout 4 with CRAJ as base layer. Each mixture for the base layer, as those for the superficial layer (wearing course and binder layer) that were realized in traditional hot bituminous mixtures for all the designed alternatives, has been carefully investigated in laboratory to validate its mechanical performance.

The key objective of the present work is to identify a procedure to guide the decision-maker to the choice of the most appropriate solution not only from a mechanical but also environmental sustainability and costs point of view.

Once the unit processes and the relative input and output flows of each alternative have been investigated with the support of a local bituminous mixtures production plant, two quarries and a landfill, it was possible to assess 11 impact category indicators to evaluate the environmental performance knowing 1) the productivity and the amount of electricity necessary for both basaltic and limestone aggregates production, 2) the distances of aggregates production plants from the bituminous mixtures production plant, 3) the amount of electricity and natural gas for the production of hot bituminous mixtures in plant and its distance from the yard, 4) the productivity of the laying of bituminous mixtures and 5) the distance of the yard from the landfill. Once the above mentioned data have been collected, with the support of prediction Equations derived from literature and listed in the previous section , it has been possible to calculate the amount pollutant substances emitted into atmosphere during the unit processes.

The LCIA results of the Layouts 1-2 and Layouts 3-4 are reported in Table 8.21 and Table 8.22 respectively.

Table 8.21 LCIA results: a) Layout 1 with HMA as base layer and b) Layout 2 with HMAJ as base layer

			Activities													
			End of the useful life of the pavement		Binder production			Aggregates production			Waste recovery		Bituminous mixtures		Pavement construction	
Category	Impact indicators	Units	Milling of existing road pavement	Disposal of RAP and JW	Bitumen production and transport to the plant	Bituminous emulsion production and transport to the plant	Cement production	Aggregates extraction	Aggregates crushing and rindling	Aggregates transport to the plant	*JW recovery*	RAP recovery	Production of hot bituminous mixtures	Transport of hot bituminous mixtures to the yard	Laying of hot bituminous mixtures	Cold in-place recycling of the base layer
								a) Layout 1 with HMA as base layer								
Pollution	GWP	$kg\ CO_2eq.$ in 100 years	420.30	438.14	100429.89	-	-	5269.49	5674.93	61810.62	-	-	209981.49	17583.87	919.09	-
	POCP	$kg\ C_2H_4$ eq.	8.27	7.39	114.39	-	-	103.73	5.66	26.25	-	-	51.31	7.47	18.09	-
	AP	$kg\ SO_2eq.$	81.24	125.89	696.00	-	-	1018.57	76.76	447.38	-	-	285.75	127.27	177.66	-
	EP	$kg\ NO_3$ eq.	34.97	53.90	121.83	-	-	438.44	26.03	191.54	-	-	111.96	54.49	76.47	-
	TSP	kg	7.35	5.06	84.99	-	-	92.20	5.20	17.99	-	-	9.13	5.12	16.08	-
Resources consumption	NRER	MJ	143454.79	218382.67	1458142.85	-	-	1798577.16	172147.93	776075.97	-	-	223230.08	220777.90	313704.06	-
	Water	l	0.00	0.00	75.51	-	-	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-
	Bitumen	t	0.00	0.00	527.26	-	-	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-
	Aggregates	t	0.00	0.00	0.00	-	-	11678.43	0.00	0.00	-	-	0.00	0.00	0.00	-
	SRM	t	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-
Waste production	RAP and JW	t	0.00	5465.06	0.00	-	-	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-
								b) Layout 2 with HMAJ as base layer								
Pollution	GWP	$kg\ CO_2eq.$ in 100 years	420.30	424.97	111169.22	-	-	5160.65	5533.43	60476.90	274.99	-	209975.30	17583.87	919.09	-
	POCP	$kg\ C_2H_4$ eq.	8.27	7.17	126.62	-	-	101.58	5.55	25.69	0.30	-	51.19	7.47	18.09	-
	AP	$kg\ SO_2eq.$	81.24	122.11	770.42	-	-	997.53	75.15	437.73	3.77	-	284.55	127.27	177.66	-
	EP	$kg\ NO_3$ eq.	34.97	52.28	134.86	-	-	429.38	25.52	187.40	1.62	-	111.44	54.49	76.47	-
	TSP	kg	7.35	4.91	94.08	-	-	90.29	5.10	17.61	0.24	-	9.02	5.12	16.08	-
Resource consumption	NRER	MJ	143454.79	211821.81	1614067.32	-	-	1761427.09	168374.16	759330.18	6599.91	-	221118.27	220777.90	313704.06	-
	Water	l	0.00	0.00	83.58	-	-	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	-
	Bitumen	t	0.00	0.00	583.64	-	-	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	-
	Aggregates	t	0.00	0.00	0.00	-	-	11346.11	0.00	0.00	0.00	-	0.00	0.00	0.00	-
	SRM	t	0.00	0.00	0.00	-	-	0.00	0.00	0.00	0.00	-	275.94	0.00	0.00	-
Waste production	RAP and JW	t	0.00	5189.12	0.00	-	-	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	-

Table 8.22 LCIA results: a) Layout 3 with CRA as base layer and b) Layout 4 with CRAJ as base layer

			Activities													
			End of the useful life of the pavement		Binder production			Aggregates production			Waste recovery		Bituminous mixtures		Pavement construction	
Category	Impact indicators	Units	Milling of existing road pavement	Disposal of RAP and JW	Bitumen production and transport to the plant	Bituminous emulsion production and transport to the plant	Cement production	Aggregates extraction	Aggregates crushing and rindling	Aggregates transport to the plant	JW recovery	RAP recovery	Production of hot bituminous mixtures	Transport of hot bituminous mixtures to the yard	Laying of hot bituminous mixtures	Cold in-place recycling of the base layer
									a) Layout 3 with CRA as base layer							
Pollution	GWP	kg CO_2eq. in 100 years	420.30	15.04	47440.77	47584.27	86294.69	3358.36	3724.49	35914.23	-	515.13	85572.39	12341.89	374.45	547.50
	POCP	kg C_2H_4 eq.	8.27	0.25	54.03	47.64	45.65	66.11	3.20	15.25	-	10.14	21.38	5.24	7.37	10.78
	AP	kg SO_2eq.	81.24	4.32	328.77	314.13	190.67	649.16	45.48	259.94	-	99.57	121.13	89.33	72.38	105.83
	EP	kg NO_3 eq.	34.97	1.85	57.55	53.90	28.65	279.43	14.94	111.29	-	42.86	47.64	38.24	31.16	45.55
	TSP	kg	7.35	0.17	40.15	39.92	0.00	58.76	2.96	10.46	-	9.01	4.15	3.59	6.55	9.58
Resource consumption	NRER	MJ	143454.79	7498.12	688793.14	684302.92	661607.35	1146271.00	104507.73	450928.45	-	175824.12	99264.54	154961.09	127805.36	186871.09
	Water	l	0.00	0.00	35.67	210.23	131.20	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	321.54
	Bitumen	t	0.00	0.00	249.06	215.37	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
	Aggregates	t	0.00	0.00	0.00	0.00	89.52	7214.64	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
	SRM	t	0.00	0.00	0.00	0.00	6.00	0.00	0.00	0.00	-	0.00	0.00	0.00	5812.38	0.00
Waste production	RAP and JW	t	0.00	276.00	0.00	0.00	0.45	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
									b) Layout 4 with CRAJ as base layer							
Pollution	GWP	kg CO_2eq. in 100 years	420.30	5.64	47440.77	56651.78	77665.22	3178.94	3514.01	33580.22	7.72	459.89	85572.39	11578.81	374.45	547.50
	POCP	kg C_2H_4 eq.	8.27	0.10	54.03	56.72	41.09	62.58	3.00	14.26	0.15	9.05	21.38	4.92	7.37	10.78
	AP	kg SO_2eq.	81.24	1.62	328.77	373.99	171.60	614.48	42.71	243.05	1.49	88.89	121.13	83.81	72.38	105.83
	EP	kg NO_3 eq.	34.97	0.69	57.55	64.17	25.78	264.50	14.01	104.06	0.64	38.26	47.64	35.88	31.16	45.55
	TSP	kg	7.35	0.07	40.15	47.52	0.00	55.62	2.77	9.78	0.13	8.05	4.15	3.37	6.55	9.58
Resource consumption	NRER	MJ	143454.79	2811.79	688793.14	814701.57	595446.61	1085033.38	98253.94	421623.30	2633.34	156968.75	99264.54	145380.16	127805.36	186871.09
	Water	l	0.00	0.00	35.67	250.30	118.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	256.13
	Bitumen	t	0.00	0.00	249.06	256.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Aggregates	t	0.00	0.00	0.00	0.00	80.57	6725.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SRM	t	0.00	0.00	0.00	0.00	5.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5411.45	0.00
Waste production	RAP and JW	t	0.00	53.61	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The first activity that gives immediately attention is the milling of the existing pavement, which is present in each layout since whatever the type of intervention to be performed, is only relevant for the evaluation of the global environmental burden of each layout, but is not relevant for the comparison between the alternatives. The quantity of demolished existing pavement is the same for all the alternatives, therefore the emissions produced by the equipment needed to carry out the operation is fixed.

On the contrary, a bigger difference occurs for the disposal of RAP and JW, since the quantity of JW compared to Layout 1, as reported in Table 8.21 and Table 8.22, has been totally reemployed in Layout 2, while it has been reduced for 95.0% in the Layout 4; besides, the quantity of RAP has been reduced of 95.0% for Layout 3 and the quantity of RAP and JW has been reduced of 99.0% for Layout 4. This implies that the number of trips needed to transport the JW and the RAP to landfill is radically reduced with the increasing quantity of materials reemployed in the mixtures. Consequently, as it possible to notice in Figure 8.10, in comparison to Layout 1 an average emission reduction in terms of GWP, POCP, AP, EP and TSP has been proved equal to 3.0% with the reuse of a total quantity of JW on site in the base layer of Layout 2, equal to 96.6% with the reemployment of total quantity of RAP in the base layer of Layout 3 and equal to 98.7% with the combined reuse of both JW and RAP in the base layer of Layout 4.

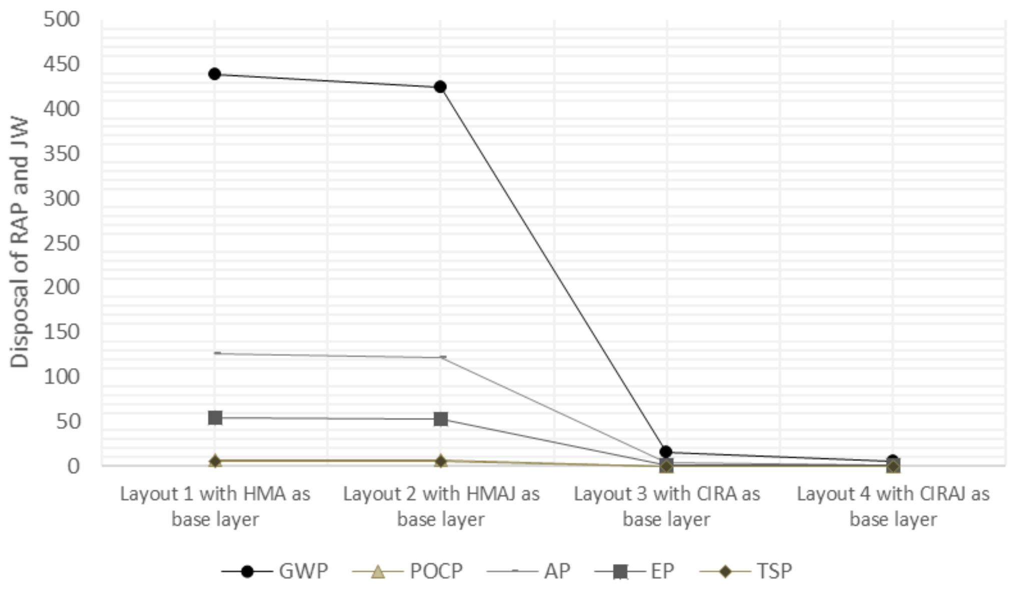


Figure 8.10 Pollution impact indicators results of "Disposal of RAP and JW"

Concerning the impacts deriving from the production of the binder for all layers, it is important to point out that the pollutants emitted in the bitumen production phase (see Figure 8.11) are therefore recorded in absolute value identical for Layout 3 and Layout 4 where the use of this virgin binder is present only in wearing course and binder layer mixtures, designed according to a mix design that does not vary from Layout 1 to Layout 4. Therefore, as showed in Figure 8.11, in the Layout 3 and Layout 4 the values of pollution impact indicators in terms of GWP, POCP, EP, AP and TSP are the same. Regarding the pollution impact indicators emitted in the bitumen production phase (see Figure 8.11), in the case of the Layout 2 they exceed the ones of the Layout 1 of 11%, since the mix design of HMAJ (base layer of the Layout 2) required an increase of 0.85% of bitumen.

One of the main technological differences related to hot and cold mix design process with and without waste refers to the presence of cement and bituminous emulsion in the cold mixtures. Therefore, the quantity of cement into cold mixtures affects the GWP with an increase of 11.1% for Layout 3 compared to Layout 4; although in both cases the mixtures have been optimized with the same cement content of 1.0% of total weight of aggregates (RAP plus fresh aggregates), this difference in terms of GWP is due to the different base layer thikness; in particular, the Layout 3 has been designed with a base layer thickness of 2 cm more than the base layer of Layout 4 (see Table 8.2). Comparing the four solutions, it is possible to notice an increase of 80.0% in terms of average value of GWP (sum of the contribution of cement, bitumen and bituminous emulsion production and their transportation to the plant) for Layout 3 and Layout 4 with respect to Layout 1; on the contrary, in terms of TSP there is an average reduction of 11.0%, since the influence of cement production in terms of TSP has not been assessed.

In the light of the average reduction of the pollution impact indicators of the bituminous emulsion compared to bitumen production, in particular, equal to 14.5% for Layout 3 and Layout 4 compared to Layout 1 and Layout 2, it follows that if all the layers of a flexible pavement were manufactured in cold in-situ reclaimed asphalt it could observed an average global pollution reduction; therefore, this is a suggestion to identify other solutions for the base layer of a flexible pavement in cold bituminous mixture with a lower cement content with respect to the present study.

About the aggregates production (aggregates used in the production of a) wearing course, b) binder layer, c) base layer in HMA and HMAJ respectively for Layout 1 and Layout 2 and d) correction of the grading curve for the base layer in CRA and CRAJ respectively for Layout 3 and Layout 4 and basalt aggregates used in the wearing course of all the alternatives designed) it takes place in three different unit processes: extraction of aggregates and transport to manufacturing plant, aggregates crushing and rindling and transport of aggregates to bituminous mixtures production plant.

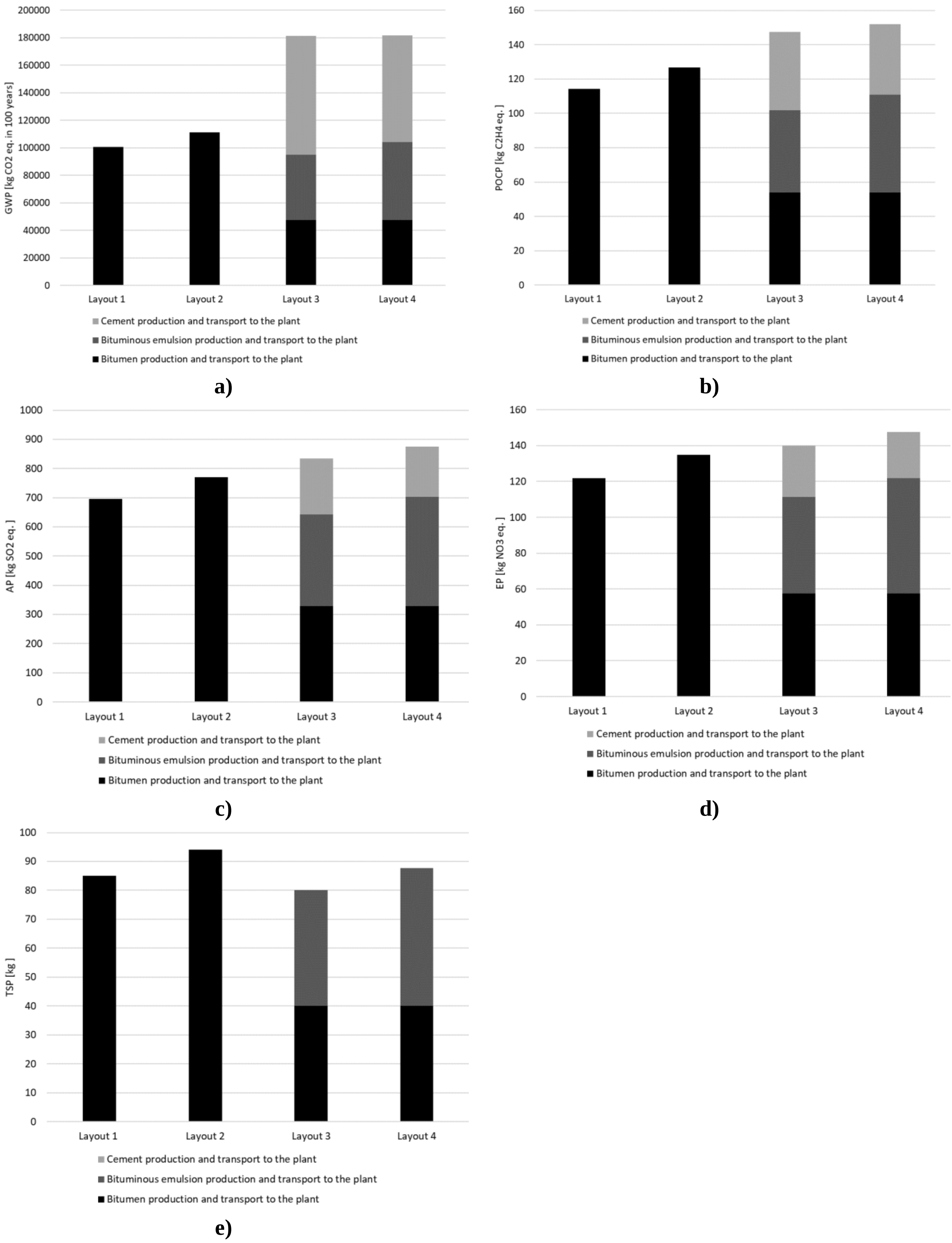


Figure 8.11 Pollution impact indicators results of cement production, bituminous emulsion production and bitumen production and relative transport to the plant: a) GWP, b) POCP, c) AP, d) EP and e) TSP

Regardless of the type of aggregates production process, the results (see Figure 8.12) return a total mean value of pollution impact indicators in the Layout 3 and Layout 4 lower than Layout 1 and Layout 2, where the latter records a slightly reduction of 2% with respect to the Layout 1, but anyway on average reduction greater than 65% with respect to the Layout 3 and Layout 4.

Figure 8.12 shows that under aggregates extraction process GWP is lower than remaining impact indicators in the pollution category; on the contrary, the aggregates transport process impacts less in terms of POCP, AP EP and TSP but more in terms of GWP. The non-linearity between the aggregates consumption and their environmental burdens is related to the influence of the transportation phases, of which the fuel consumption and the relative pollutant emissions remain almost the same; in fact, even if there is a substantial difference in terms of fresh aggregates quantity between the alternatives with hot bituminous mixtures as base layer and the alternatives with cold bituminous mixtures as base layer, the transportation phase is carried out, for all the alternatives, with the same number of trips, calculated according to the Equation 64.

The introduction of 4% of JW in base layer of Layout 2 reduced on average 2% of the pollution impact indicators for all process of the aggregates production; in the case of Layout 3, where 70% of virgin aggregates is substituted with RAP in the bituminous mixture for base layer, is showed a further average reduction of 40%; concerning the Layout 4 with an additional substitution of 3% of fresh aggregates with JW, the GWP, POCP, EP, AP and TSP have been reduced by on average 43% compared to Layout 1 with a base layer containing 100% limestone material.

The reduction of fresh aggregates used into mix design process of layers keeps abreast with secondary raw materials inclusion (see Table 8.21-8.22). The JW reusing influenced the GWP, POCP, EP, AP and TSP value of Layout 2 and Layout 4 where JW is reused into mix design process of base layers. In particular a difference equal to 97.1% between Layout 2 and Layout 4 has been recorded in terms of GWP; this large difference is due to the transport of JW to bituminous mixtures production plant that has been assessed in the case of HMAJ production for the base layer of Layout 2. Besides, adopting a solution of a flexible pavement with CRAJ as base layer, the POCP, AP, EP and TSP respectively reduce on average of 49.6%, 60.5%, 60.3% and 44.8% with respect to a solution of flexible pavement with HMAJ as base layer (see Table 8.22).

Regarding the RAP recovery (see Table 8.23), this process only affects the Layout 3 and Layout 4 where the base layer is realized with cold bituminous mixtures; in addition, comparing the two solutions, the Layout 4 exhibits an average reduction equal to 10.7% compared to Layout 3 in terms of pollution impact indicators, since in Layout 3 the handling of the additional RAP supplied by a bituminous mixtures recovery plant has been taken into account.

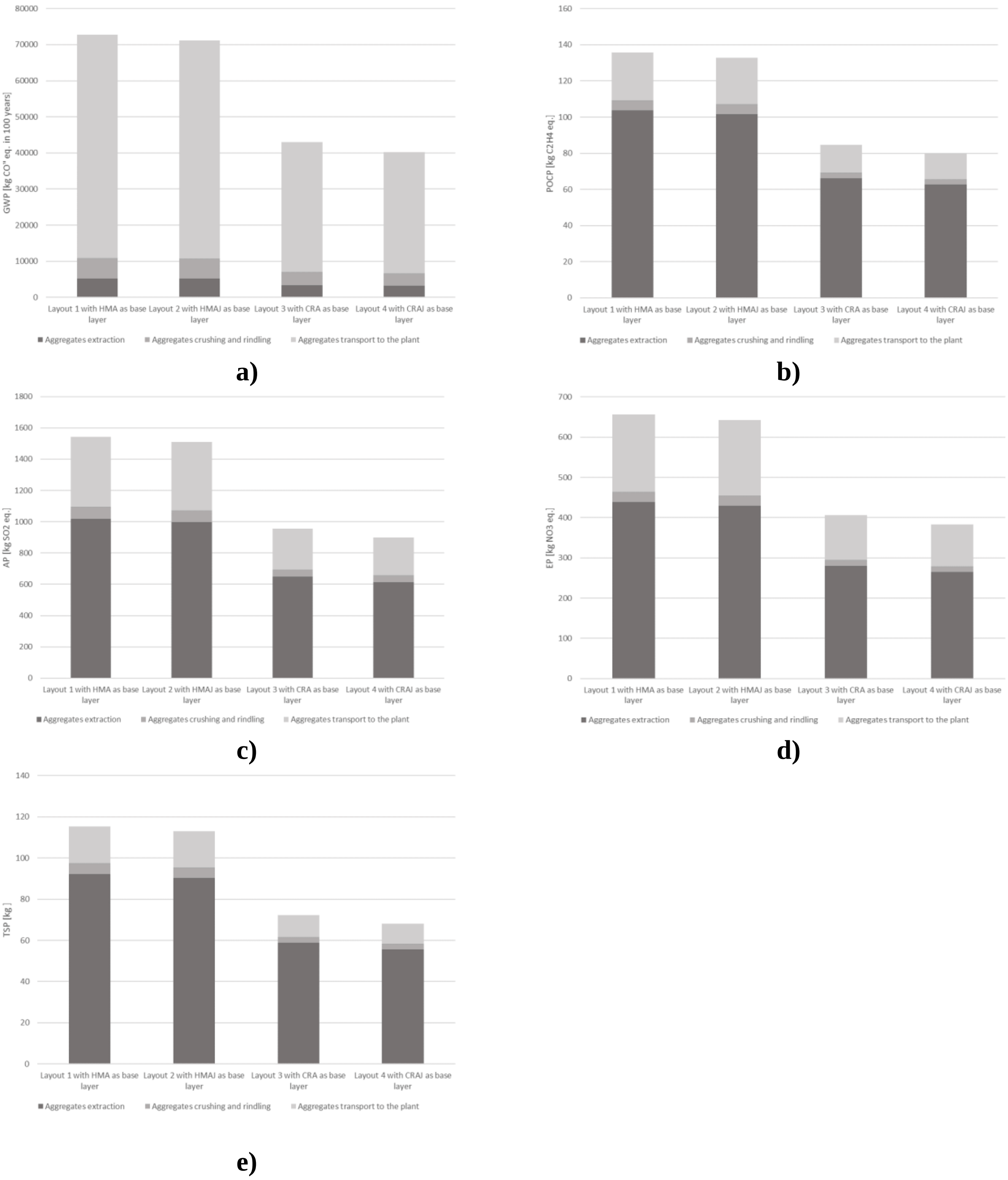


Figure 8.12 Pollution impact indicators results of aggregates production: a) GWP, b) POCP, c) AP, d) EP and e) TSP

Table 8.23 JW and RAP recovery: analysis of pollution impact indicators

Pollution impact indicators	Units	JW recovery		RAP recovery	
		Layout 2	Layout 4	Layout 3	Layout 4
GWP	kg CO_2eq. in 100 years	274.99	7.72	515.13	459.89
POCP	kg C_2H_4 eq.	0.30	0.15	10.14	9.05
AP	kg SO_2eq.	3.77	1.49	99.57	88.89
EP	kg NO_3 eq.	1.62	0.64	42.86	38.26
TSP	kg	0.24	0.13	9.01	8.05

Concerning the hot bituminous mixtures production, an average reduction of 29% in terms of GWP, POCP, AP, EP and TSP has been showed for Layout 3 and Layout 4 compared to to the Layout 1 and Layout 2 (see Figure 8.13), since the hot manufacturing process is related only to superficial layers and does not involve the base layer.

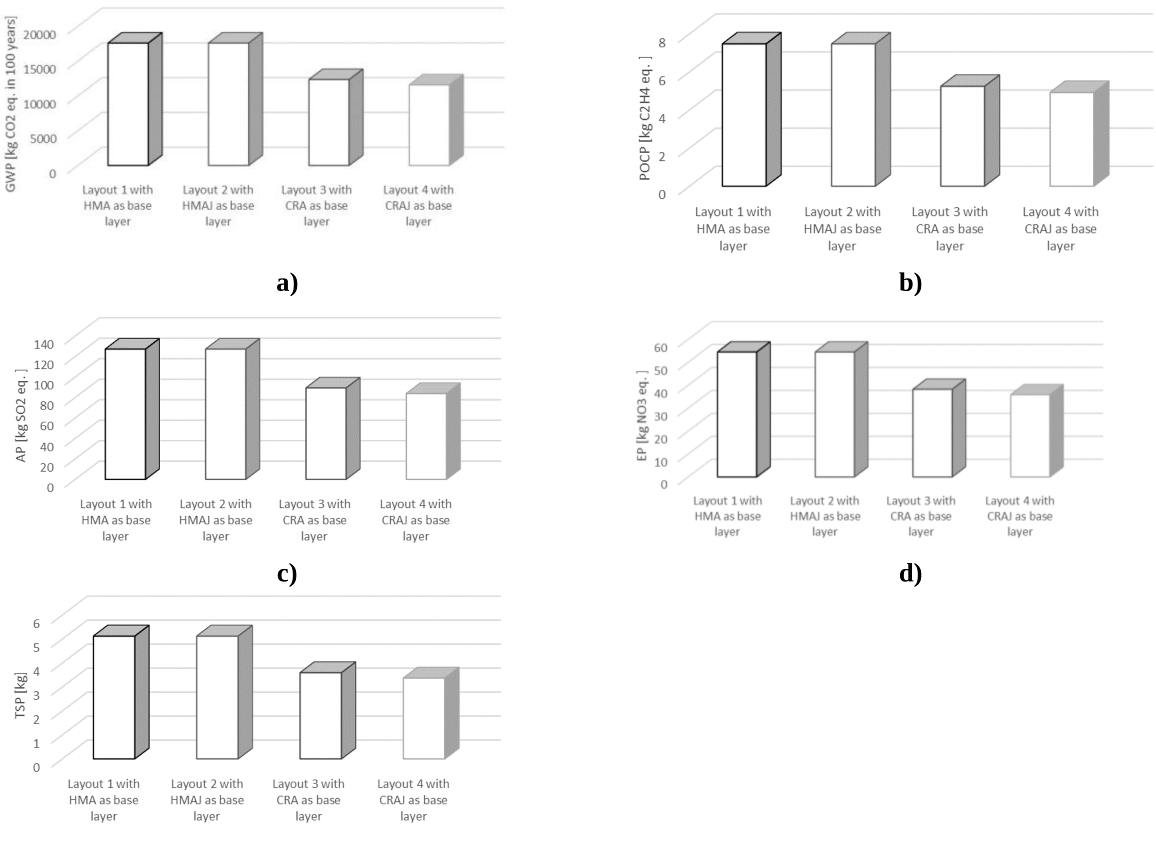


Figure 8.13 Impact indicators results of hot bituminous mixtures production process

Lastly, looking globally at LCIA results, which are reported as the sum of each activity in Table 8.24, it is possible to conclude that flexible pavements with cold in-place recycled asphalt as base layer, in particular adding both JW and RAP, offer an average reduction in terms of pollution impact indicators equal to almost 20.0% (average value of GWP, POCP, AP, EP and TSP), in terms of resources consumption equal to 14.2% (average value of NRER, water, bitumen, aggregates and SRM) and in terms of waste production equal to 99.0% (JW and RAP).

Table 8.24 LCIA global results

Category	Impac indicators	Units	Layout 1	Layout 2	Layout 3	Layout 4
Pollution	GWP	kg CO_2eq. in 100 years	402527.83	411938.73	324103.50	320997.62
	POCP	kg C_2H_4 eq.	342.56	351.93	295.34	293.71
	AP	kg SO_2eq.	3036.51	3077.43	2361.96	2331.00
	EP	kg NO_3 eq.	1109.62	1108.43	788.03	764.87
	TSP	kg	243.13	249.80	192.65	195.09
Resources consumption	NRER	MJ	5324493.41	5420675.50	4632089.69	4569041.77
	Water	l	75.51	83.58	698.64	660.17
	Bitumen	t	527.26	583.64	464.43	505.47
	Aggregates	t	11678.43	11346.11	7304.16	6805.68
	SRM	t	0.00	275.94	5818.38	5416.85
Waste production	RAP and JW	t	5465.06	5189.12	276.45	54.01

8.2 Investment cost analysis

To evaluate the economic feasibility for the alternatives designed, an investment cost analysis has been carried out. The results of the investment cost analysis (ICA) are reported in Table 8.26, with reference to cost items related to the manufacturing process of the bituminous solutions. The cost items related to the milling of the existing pavement have contributed in equal part to the investment costs of the four alternatives; as concerning the transport to the landfill, the first reductions are visible for the Layout 2 comparing to the Layout 1 due to recovery of JW for the base layer bituminous mixture. This difference in the case of Layout 3 and Layout 4 is higher, and it reaches respectively 97% and 99% when they are compared to Layout 1; this is due to the higher amount of waste reemployed into the two base layer cold in-situ bituminous mixtures. In the Layout 3 and Layout 4

RAP disposal charges are not present, since in both cases the total amount of RAP derived from the milling of existing pavement is totally reemployed. Concerning JW disposal, the item cost is equal to 0 in the case of Layout 2, where the total amount of JW is completely reemployed into the bituminous mixture of the base layer; in the case of Layout 4 with CRAJ as base layer, even if a small portion of JW (54.01 tonnes) is disposed of in landfill, the JW disposal cost has been resulted 2536.5 € lower than Layout 1 and 3's JW disposal cost.

The strongest difference between the alternatives is in the cost of base layer laying, in particular, between Layout 1 with HMA as base layer and Layout 4 with CRAJ as base layer. Nowadays, the costs related to the production and laying of bituminous mixtures containing secondary raw materials are not included in the pricelists of public works. Therefore, in this study the definition of the unit prices of the bituminous mixtures for base layer has been performed by taking into account four cost items: a) Cost of materials (fresh aggregates and binders), b) Cost of labour (depending on the working hours and the skills of the workers), c) Cost of equipment (computing the cost of each equipment to carry out the production and laying of each bituminous mixture for the base layer) and d) the percentage costs of worksite safety charges and company's profits. The results in terms of unit prices are reported in Table 8.25, while the total cost of the base layer laying is shown in Table 8.26. Both results show a reduction almost of 4.4%, 19.3% and 18.2 % respectively for Layout 2, Layout 3 and Layout 4 compared to Layout 1.

Taking into account all cost items (see Table 8.26), the global ICA showed that the solution with CRAJ as base layer (Layout 4) is the most cost effective with a reduction of 20% compared to the Layout 1.

Table 8.25 Definition of new prices for 1 tonne of bituminous mixture for base layer

Cost items	Units	Unit cost	Price [€]			
			HMA	HMAJ	CRA	CRAJ
Materials						
Limestone 31.5-2 mm	€/t	14.00	12.52	12.12	3.21	2.93
Limestone filler	€/t	20.00	1.35	0.99	0.92	0.73
JW	€/t	0	-	0.00	-	0.00
RAP from existing pavement	€/t	0	-	-	0.00	0.00
RAP supply	€/t	11.00			0.76	-
Bitumen	€/t	400.00	20.00	18.50	-	-
Bituminous emulsion	€/t	550.00	-	-	19.88	26.19
Cement	€/t	108.4	-	-	1.07	1.07
Water	€/t	1.37	-	-	0.05	0.04
Total Cost of materials	€/t		33.87	31.62	25.89	30.97
Labour supply						
Master worker (nr. 3)	€/h	29.615	2.15	2.15	0.36	0.39
Skilled worker	€/h	27.511	0.00	0.00	0.00	0.00
Common worker (nr. 2)	€/h	24.812	1.20	1.20	0.20	0.22
Total Cost of labour supply	€/t		3.36	3.36	0.56	0.61
Equipment						
Truck (transportation of hot bituminous mixtures and fresh aggregates)	ton/km	1.50	30.00	30.00	6.89	6.29
Tanker (transportation of bituminous emulsion, cement and water)	h	51.51	-	-	21.02	21.02
Hot bituminous mixtures plant production	t	12.00	12.00	12.00	-	-
Paver	h	87.50	2.12	2.12	-	-
Roller compactor	h	37.50	0.91	0.91	-	-
Pulvimixer	h	75.92	-	-	0.31	0.31
Grader	h	75.92	-	-	0.31	0.31
Rubber roller, iron roller and iron-rubber roller	h	75.71	-	-	0.31	0.31
Total Cost of equipment	€/t		45.03	45.03	28.83	28.23
Subtotal			82.25	80.01	55.28	59.80
Worksite safety charges (0.9%)			0.74	0.72	0.50	0.54
Company's profits (26.5%)			21.80	21.20	14.65	15.85
Total	€/t		104.79	101.93	70.43	76.19

Table 8.26 Cost analysis results

Cost items	Units	Layout 1 with HMA as base layer	Layout 2 with HMAJ as base layer	Layout 3 with CRA as base layer	Layout 4 with CRAJ as base layer
Milling of existing bituminous layers until 3 cm of depth	€	32147.51	32147.51	32147.51	32147.51
Milling of the remaining depth of existing bituminous layers	€	67090.46	67090.46	67090.46	67090.46
Transport to landfill within 10 km of distance	€	30755.69	29750.47	1005.22	194.88
Transport to landfill beyond 10 km of distance	€	81473.32	78810.44	2662.88	516.24
Charges of RAP disposal	€	41512.24	41512.32	-	-
Charges of JW disposal	€	3146.40	-	3146.40	609.90
Laying of base layer	€	679198.08	649520.98	547897.93	555763.93
Laying of binder layer	€	253154.29	253154.29	253154.29	253154.29
Laying of wearing course	€	230140.26	230140.26	230140.26	230140.26
Total	€	1418618	1382127	1137245	1139617

8.3 Laying time of the designed bituminous solutions

Given the mentioned mix design solutions of four road pavement layouts (see Table 8.2), an accurate investigation in terms of laying time of blends has been carried out to deep ascertain differences. Additional machines, and even different for completing specific operations, are used into cold recycling of reclaimed asphalt pavement with eventual JW reusing rather than traditional HMA; consequently, hourly productivity (see Table 8.8) that have any impacts on final results (see Table 28). The results reported in Table 8.27 show how the pavement laying with CRA as base layer requires more days than the remaining investigated solutions. In particular, a total of 48 days is necessary for Layout 3, higher of 29%, 23% and 37% than Layout 1, Layout 2 and Layout 4, respectively; although the machines required for the laying of a base layer realized in cold bituminous mixture have a higher productivity with respect to the hot bituminous mixtures laying, more time for the laying of cold in-situ bituminous mixtures is required since the achievement of the maximum mechanical performances, through a curing time, is set at 28 days.

Table 8.27 Laying time of road pavement bituminous layers

Alternative pavements	JW recovery	Base layer laying	Wearing course + binder layer laying	Curing time	Total
Layout 1	-	22 days	15 days	-	37 days
Layout 2	2 days	22 days	15 days	-	39 days
Layout 3	-	5 days	15 days	28 days	48 days
Layout 4	-	5 days	15 days	14 days	35 days

8.4 Technological complexity of the designed bituminous solutions

The four bituminous pavement layouts require different sets of machinery to carry out the recovery procedures of JW and the cold in-place recycling of RAP. In order to take into account the different degrees of complexity, a new relative variable, named Technological Complexity, comprised in the range 0-1, has been estimated. In particular, Technological Complexity has been assessed as a function of a) the cost of the additional equipment (comparing to the traditional equipment needed for hot bituminous mixtures production and laying), which is considered to be already fully amortised and, therefore, is not included in the investment cost (ICA), b) the management complexity of the yard works, that increases with the number of construction equipment involved and c) the need of highly-skilled workmen, needed for the cold in-place recycling activity. The qualitative description of *TC* is reported in Table 8.28.

Table 8.28 Features definition of Technological Complexity

Range	Attribute	Description
0	none	No additional equipment with respect to the traditional hot bituminous mixtures production and laying
0-0.25	low	Low influence of additional equipment on costs, on the number of construction equipment and on the skills needed by the workers
0.25-0.50	medium	Medium influence of additional equipment on costs, on the number of construction equipment and on the skills needed by the workers
0.50-0.75	high	High influence of additional equipment on costs, on the number of construction equipment and on the skills needed by the workers
0.75-1	very high	Very high influence of additional equipment on costs, on the number of construction equipment and on the skills needed by the workers

Basing on the previous consideration, the Technological Complexity is set equal to:

- 0 in the case of Layout 1, since no additional equipment is required with respect to the traditional hot bituminous mixtures production and laying
- 0.12 in the case of Layout 2, considering that the recovery of JW to be reused in HMAJ requires the use of a jaw mill. TC value was not set equal to the maximum value in the range reported in Table 8.28 because the additional equipment does not influence neither the yard activities, since it is placed in the hot bituminous mixtures production plant, neither the skills of the workers
- 0.75 in the case of Layout 3, since the cold in-place recycling of RAP (CRA base layer) requires an additional set of machinery that influences not only the initial cost, but also the worksite organization, the safety rules (due to the higher number of equipment that coexist during the yard operations) and the need of training workers for new worksite practices
- 1 for Layout 4, which combines the technological complexities of Layout 2 and 3 with the further difficulty deriving from the necessity of having the jaw mill placed in the yard during the construction works

9 Multi-criteria decision analysis

The multi-criteria analysis for decision-making purposes or Multi-criteria decision analysis (MCDA) is a discipline aimed at supporting the decision maker if he/she finds himself/herself operating with numerous and conflicting assessments, allowing for a compromise solution to be obtained in a transparent manner. The multi-criteria analysis methods support the decision maker in the organization and synthesis phase of complex and often heterogeneous information. This methodology allows the decision maker to analyze and evaluate different alternatives, monitoring their impact on the different actors in the decision-making process. To support the MCDA to determine the robustness of evaluations by examining how much of the results can be influenced by changes in methods, models, values of unmeasured variables or hypotheses a sensitivity analysis is adopted.

In the present research four different alternatives have been designed, each one better than the other with respect to a specific dimension: for example the solutions with CRA or CRAJ as a base layer are better than the others in terms of Environmental dimension, water sensitivity, fatigue cracking, investment costs and laying time; the solution with HMAJ is better than the other in terms of stiffness, rutting resistance and technological complexity. To keep into account all the dimensions for the choice by decision-maker of “the best” solution between the range of feasible solutions for an extraordinary maintenance work on an existing road pavement and the laying of a new contiguous section located under a tunnel a MCDA has been adopted as comparative evaluation method (Utility, Multipol, EDIS and ELECTRE methods). In particular, the four different layouts have been analyzed according to 4 dimensions, which are reported in Table 9.1 along with their dimension and units.

Table 9.1 Decision indicators, dimensions and units

Dimension	Indicators	Units
Environmental	GWP	kg CO_2 eq. In 100 years
	POCP	kg C_2H_4 eq.
	AP	kg SO_2 eq.
	EP	kg NO_3 eq.
	TSP	kg
	NRER	MJ
	Water	t
	Bitumen	t
	Aggregates	t
	SRM	t
	RAP and JW	t
Mechanical	Stiffness	MPa
	ITS	MPa
	ΔITS	%
Durability	Fatigue cracking	-
	Rutting resistance	cm
Complexity	Investment costs	€
	Laying time	days
	Technological Complexity	-

Let *J* be the set of adopted indicators, and *K* the set of considered layouts, with $J = \{1, \dots j, \dots n\}$ and $K = \{1, \dots k, \dots m\}$. In this case: $J = \{1, 2, \dots, 19\}$ and $K = \{1, 2, 3, 4\}$. Collecting all the indicators for each analysed layout, the *decision matrix* has been obtained and is reported in Table 9.2. The 19 rows indicate the indicators while the columns represent the alternatives. Moreover, the generic entry X_{jk} represents the *x*-th value of indicator *j*-th related to alternative *k*-th; it is also defined as a *'compliance measure'* of indicator *j* to alternative *k.*

Table 9.2 Decision matrix

Indicators	Units	Alternatives			
		Layout 1	Layout 2	Layout 3	Layout 4
GWP	kg CO_2 eq.	402527.83	411938.73	324103.50	320997.62
POCP	kg C_2H_4 eq.	342.56	351.93	295.34	293.71
AP	kg SO_2 eq.	3036.51	3077.43	2361.96	2331.00
EP	kg NO_3 eq.	1109.62	1108.43	788.03	764.87
TSP	kg	243.13	249.80	192.65	195.09
NRER	MJ	5324493.41	5420675.50	4632089.69	4569041.77
Water	t	75.51	83.58	698.64	660.17
Bitumen	t	527.26	583.64	464.43	505.47
Aggregates	t	11678.43	11346.11	7304.16	6805.68
SRM	t	0.00	275.94	5818.38	5416.85
RAP and JW	t	5465.06	5189.12	276.45	54.01
Stiffness	MPa	8086.79	9226.10	4821.18	5579.09
ITS	MPa	0.68	0.76	0.64	0.73
ΔITS	%	0.12	0.09	0.06	0.04
Fatigue cracking	-	0.24	0.25	0.08	0.13
Rutting resistance	cm	0.32	0.15	0.62	0.57
Investment costs	€	1418618.25	1382126.73	1144101.25	1139617.47
Laying time	days	37.00	39.00	48.00	35.00
Technological Complexity	-	0.00	0.12	0.75	1.00

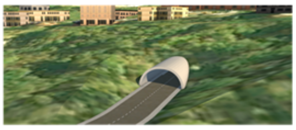
The next step consists in defining a proper weight vector. The assignment of the relative weights to the criteria establishes an order of relative importance among the latter. In fact, the weights measure, through numerical dimensionless values represents the properties that are assigned to the various aspects of the problem and for this reason they never have absolute value but only relative.

9.1 The Delphi method

The *Delphi method* is a group decision procedure, which involves a set of qualified experts with a deep understanding of the addressed issue, by combining the opinion of each expert interviewed attributing them equal decision making. The main focus of Delphi method is the study, the convergence of reliable opinion of the group of experts interviewed and the processing of useful information for decision-making: in this case, it enables to assess the feasibility of the alternatives designed contributing to the choice of the most appropriate solution on the basis of discretizing parameters to which everyone would match a different importance in accordance with field of work, know-how, sensitivity to a specific issue, boundary constraints, legal condition and scope.

The optimum of the solution change in function of the importance that each decision-making gives, creating a different combination between the indicators; therefore, the objectivity of the optimum solution is a combined synthesis of the indicators reported in Table 9.2.

Extraordinary maintenance work on an existing road pavement and the laying of a new contiguous section located under a tunnel



The case study provides for the design of flexible pavaments solutions for the extraordinary maintenance work on an existing road pavement and the laying of a new contiguous section located under a tunnel. Four layouts are shown whose fundamental characteristics have been enclosed in 19 indicators that briefly describe each solution.

It is required to identify an order of importance of the indicators for the layout selection on the bases of the identifiedmin and max value of each indicator given below

Indcators	Units	Max value	Min value
Global Warming Potential (GWP)	kg CO_2 eq.	411938.73	320997.62
Photochemical Ozone Depletion Potential (POCP)	kg C_2H_4 eq.	351.93	293.71
Acidification Potential (AP)	kg SO_2 eq.	3077.43	2331
Eutrophication Potential (EP)	kg NO_3 eq.	1109.62	764.87
Total Suspended Particle (TSP)	kg	249.8	192.65
Total consumption of non renewable energy resources (NRER)	MJ	5420675.5	4569041.77
Water consumption	t	698.64	75.51
Bitumen consumption	t	583.64	464.43
Aggregates consumption	t	11678.43	6805.68
Secondary raw materials consumption (SRM)	t	5818.38	0
Waste production	t	5465.06	54.01
Stiffness	MPa	9226.1	4821.18
ITS	MPa	0.76	0.64
ΔITS	%	0.12	0.04
Fatigue cracking	-	0.25	0.08
Rutting resistance	cm	0.62	0.15
Construction Costs	€	1418618.25	1139617.47
Construction Time	days	48	35

Layout 1

- ❑ **GWP**=402527.83kg CO2 eq.
- ❑ **POCP**=342.56kg C2H4 eq.
- ❑ **AP**=3036.51kg SO2 eq.
- ❑ **EP**=1109.62kg NO3 eq.
- ❑ **TSP**=243.13kg
- ❑ **NRER**=5324493.41 MJ
- ❑ **Water**=75.51 t
- ❑ **Bitumen**=527.26t
- ❑ **Aggregates**=11678.43 t
- ❑ **SRM**=0t
- ❑ **Waste production**=5465.06 t
- ❑ **Stiffness**=8086.79 MPa
- ❑ **ITS**=0.68 MPa
- ❑ **ΔITS**=12%
- ❑ **Fatigue cracking**=0.24
- ❑ **Rutting resistance**=0.32cm
- ❑ **Construction Costs**=1418618.25€
- ❑ **Construction Time**=37days
- ❑ **Technological Complexity**=0

Layout 2

- ❑ **GWP**=411938.73kg CO2 eq.
- ❑ **POCP**=351.93kg C2H4 eq.
- ❑ **AP**=3077.43kg SO2 eq.
- ❑ **EP**=1108.43kg NO3 eq.
- ❑ **TSP**=249.8kg
- ❑ **NRER**=5420675.5MJ
- ❑ **Water**=83.58t
- ❑ **Bitumen**=583.64t
- ❑ **Aggregates**=11346.11t
- ❑ **SRM**=275.94t
- ❑ **Waste production**=5189.12 t
- ❑ **Stiffness**=9226.1MPa
- ❑ **ITS**=0.76MPa
- ❑ **ΔITS**=9%
- ❑ **Fatigue cracking**=0.25
- ❑ **Rutting resistance**=0.15cm
- ❑ **Construction Costs**=1382126.73€
- ❑ **Construction Time**=39days
- ❑ **Technological Complexity**=0.12

Layout 3

- ❑ **GWP**=324103.5kgCO2 eq.
- ❑ **POCP**=295.34 kgC2H4 eq.
- ❑ **AP**=2361.96kg SO2 eq.
- ❑ **EP**=788.03NO3 eq.
- ❑ **TSP**=192.65kg
- ❑ **NRER**=4632089.69MJ
- ❑ **Water**=698.64t
- ❑ **Bitumen**=464.43t
- ❑ **Aggregates**=7304.16t
- ❑ **SRM**=5818.38t
- ❑ **Waste production**=276.45t
- ❑ **Stiffness**=4821.18MPa
- ❑ **ITS**=0.64MPa
- ❑ **ΔITS**=6%
- ❑ **Fatigue cracking**=0.08
- ❑ **Rutting resistance**=0.62cm
- ❑ **Construction Costs**=1144101.25€
- ❑ **Construction Time**=48 Days
- ❑ **Technological Complexity**=0.75

Layout 4

- ❑ **GWP**=320997.62kgCO2 eq.
- ❑ **POCP**=293.71kgC2H4 eq.
- ❑ **AP**=2331kg SO2 eq.
- ❑ **EP**=764.87NO3 eq.
- ❑ **TSP**=195.09kg
- ❑ **NRER**=4569041.77MJ
- ❑ **Water**=660.17t
- ❑ **Bitumen**=505.47t
- ❑ **Aggregates**=6805.68t
- ❑ **SRM**=5416.85t
- ❑ **Waste production**=54.01t
- ❑ **Stiffness**=5579.09MPa
- ❑ **ITS**=0.75MPa
- ❑ **ΔITS**=4%
- ❑ **Fatigue cracking**=0.13
- ❑ **Rutting resistance**=0.57cm
- ❑ **Construction Costs**=1139617.47€
- ❑ **Construction Time**=35Days
- ❑ **Technological Complexity**=1

Figure 9.1 Evaluation form for Delphi method

Figure 9.1 reported the evaluation form adopted to survey the experts. The form contains the instructions and the relevant information to evaluate each layout designed. A total of 50 experts have been invited to express their evaluation. This has been an iterative process: after each round of interviews, the data have been analysed and sent for the next round until a group consensus has been achieved.

Let W be the agreed weight vector and $w_{i,j,l}$ the generic entry, where a) i represents the decision-maker i-th, b) j represents the j-th indicator evaluated and c) l represents the area of the grater experience of the surveyed. Specifically, in this case, taking into account the choice of each expert, the values in Equation 81 have been identified according to Equation 80:

$$w_j^* = \frac{w_j}{\sum_{j=1}^{n} w_j} \tag{80}$$

where:

- w_j^* is the normalised weight value of the *j*-th indicator
- w_j is the weight of the *j*-th indicator

$$W = \{0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.06, 0.06, 0.06, 0.06, 0.10, 0.10, 0.10, 0.04, 0.04, 0.08, 0.08, 0.08\} \tag{81}$$

Therefore, the decision matrix (see Table 9.2) has been implemented with the normalization procedure, thus assuming a value between 0 (worst value of the indicator) and 1 (best value of the indicator), according the following Equation 82:

$$n_{jk} = \frac{\max a_{j,k} - a_{j,k}}{\max a_{j,k} - \min a_{j,k}} \tag{82}$$

where:

- $a_{j,k}$ is the value of the *j*-th indicators of the *k*-th alternative
- $\max a_{j,k}$ is the maximum value of the *j*-th indicators of the *k*-th alternative
- $\min a_{j,k}$ is the minimum value of the *j*-th indicators of the *k*-th alternative

The normalized values of each indicator for each alternative are reported in Table 9.3.

Table 9.3 Normalized decision matrix

Indicators	Alternatives			
	Layout 1	Layout 2	Layout 3	Layout 4
GWP	0.10	0.00	0.97	1.00
POCP	0.16	0.00	0.97	1.00
AP	0.05	0.00	0.96	1.00
EP	0.00	0.00	0.93	1.00
TSP	0.12	0.00	1.00	0.96
NRER	0.11	0.00	0.93	1.00
Water	1.00	0.99	0.00	0.06
Bitumen	0.47	0.00	1.00	0.66
Aggregates	0.00	0.07	0.90	1.00
SRM	0.00	0.05	1.00	0.93
RAP and JW	0.00	0.05	0.96	1.00
Stiffness	0.74	1.00	0.00	0.17
ITS	0.33	1.00	0.00	0.75
ΔITS	0.00	0.33	0.72	1.00
Fatigue cracking	0.02	0.00	1.00	0.73
Rutting resistance	0.63	1.00	0.00	0.11
Investment costs	0.00	0.13	0.98	1.00
Construction Time	0.85	0.69	0.00	1.00
Technological Complexity	1.00	0.88	0.25	0.00

The next step has been focused on the utility evaluation of each alternative, U_k, as follows:

$$U_k = \sum_j w_j^* \cdot X_{jk}^* \tag{83}$$

where:

- w_j^* is the normalised weight value of the *j*-th indicator calculated according to Equation 29
- X_{jk}^* is the value of the *j*-th indicator belonging to *k*-th alternative

The best alternative has been the one with the higher value of utility *U**, with $U^* = max_k \{U_k\}, k \in K$. Results are shown in Figure 9.2, where the best solution is represented by the Layout 4 with CRAJ as base layer with the maximum utility value, greater than Layout 1, Layout 2 and Layout 3 respectively of 111%, 63% and 28%.

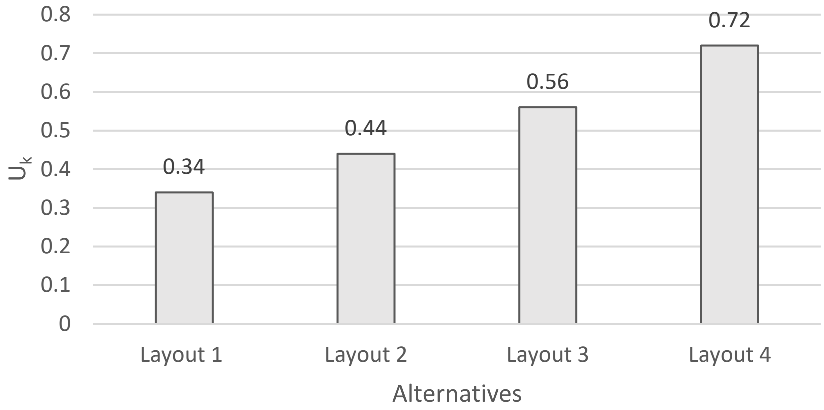


Figure 9.2 Utility method results

9.2 Sensitivity analysis

Since the aim of the research was to find a solution that can substitute a traditional solution in HMA, a new decision matrix was designed. The normalized indicators were grouped for each dimension belonging to each layout solution and the difference between the Layout 1 and the layouts containing the alternative materials (JW and RAP) (Layout 2, Layout 3 and Layout 4) were calculated. The new decision must is reported in Table 9.4.

Table 9.4 New decision matrix

	Layout 1 vs		
Dimension	**Layout 2**	**Layout 3**	**Layout 4**
LCA	1.42	17.98	24.16
Mechanical	16	-15	2.5
Service life	8	0.5	1.8
Costs	-3	-19	-20

Sensitivity analysis plays an important role in verifying the robustness of a study's conclusions. If the results remain robust under different assumptions, methods or scenarios, this can strengthen their credibility. Therefore, the purpose of the present study is providing a sensitivity analysis of the stability of the obtained outcome applying the Multi-weights methods by carrying out different MCDA methods as ELECTRE, EDIS and Utility with 5 weight vectors in addition to basic configuration; for each method the decision matrix has been changed by removing in turn the dimension for a total of 10 different configurations for each of the above-mentioned methods obtaining therefore a total of 50 weight vectors (a total of 11 different configuration and 55 weight vectors) In table 9.5 are reported all the weight vectors for all 11 configurations (from configuration 0 to 10).

Table 9.5 Weight vectors for each configuration

Configuration	Weight vectors					Configuration	Weight vectors				
	1	2	3	4	5		1	2	3	4	5
0	0.250	0.500	0.167	0.167	0.167	6	0	0	0	0	0
	0.250	0.167	0.500	0.167	0.167		0.500	0.500	0.750	0.500	0.250
	0.250	0.167	0.167	0.500	0.167		0	0	0	0	0
	0.250	0.167	0.167	0.167	0.500		0.500	0.500	0.250	0.500	0.750
1	0	0	0	0	0	7	0	0	0	0	0
	0.333	0.333	0.600	0.200	0.200		0.500	0.500	0.750	0.250	0.500
	0.333	0.333	0.200	0.600	0.200		0.500	0.500	0.250	0.750	0.500
	0.333	0.333	0.200	0.200	0.600		0	0	0	0	0
2	0.333	0.600	0.333	0.200	0.200	8	0.500	0.750	0.500	0.500	0.250
	0	0	0	0	0		0	0	0	0	0
	0.333	0.200	0.333	0.600	0.200		0	0	0	0	0
	0.333	0.200	0.333	0.200	0.600		0.500	0.250	0.500	0.500	0.750
3	0.333	0.600	0.200	0.333	0.200	9	0.500	0.750	0.500	0.250	0.500
	0.333	0.200	0.600	0.333	0.200		0	0	0	0	0
	0	0	0	0	0		0.5	0.25	0.5	0.75	0.5
	0.333	0.200	0.200	0.333	0.600		0	0	0	0	0
4	0.333	0.600	0.200	0.200	0.333	10	0.500	0.750	0.250	0.500	0.500
	0.333	0.200	0.600	0.200	0.333		0.500	0.250	0.750	0.500	0.500
	0.333	0.200	0.200	0.600	0.333		0	0	0	0	0
	0	0	0	0	0		0	0	0	0	0
5	0	0	0	0	0						
	0	0	0	0	0						
	0.500	0.500	0.500	0.750	0.250						
	0.500	0.500	0.500	0.250	0.750						

In this way it has been possible to take into account different evaluation procedures and different perspectives, as well as analysing the effect of the available data set on the optimal solution identified. The procedure aims to define how much the final selected solution can be defined as rugged problem solver in light of decisional criteria hypothesized here.

9.2.1 ELECTRE method

The first method analysed has been ELECTRE method. It is based on an *evaluation-in-pairs* procedure in which for each pair of alternatives two indexes, namely concordance index ($c_{kk'}$) and discordance index ($d_{kk'}$), has been determined. In detail, the concordance index and discordance index have been calculated respectively as reported in the Equation 84 and Equation 85.

$$c_{kk'} = \sum_j w_j^* : X_{jk}^* > X_{jk'}^* \qquad (84)$$

where:

- $c_{kk'}$ concordance index of the comparison between the *k*-th alternative and *k'*-th alternative
- w_j^* is the normalised weight value of the *j*-th indicator
- X_{jk}^* is the utility of *j*-th indicator of the *k*-th alternative
- $X_{jk'}^*$ is the utility of *j*-th indicator of the *k'*-th alternative

$$d_{kk'} = \max_j \{(X_{jk'}^* - X_{jk}^*) : X_{jk}^* < X_{jk'}^*\} \tag{85}$$

where:

- $d_{kk'}$ discordance index of the comparison between the *k*-th alternative and *k'*-th alternative
- $X_{jk'}^*$ is the utility of *j*-th indicator of the *k*-th alternative
- X_{jk}^* is the utility of *j*-th indicator of the *k'*-th alternative

Once defined the concordance and discordance indexes, $c^*$and d^* have been evaluated as mean value, respectively, of concordance indexes and discordance indexes of all indicators of each alternative. In particular, the analysis has been carried out comparing each concordance index and discordance index respectively with $c^*$and d^*, and the selection criteria has been set as follow: the alternative k was globally preferred to alternative *k'* if $c_{kk'} \geq c^*$ and $d_{kk'} \leq d^*$.

In order to carry out a sensitivity analysis also with respect to the available decision matrix, the proposed methodology has been applied to 10 different decision matrixes, in addition to the basic configuration, which are characterized by the lack of one and/or two dimension.

The following Table 9.9 provides examples of a calculation sheet of the concordances and discordances in the case of configuration 0 with the weight vector C0v1 where all the dimensions have the same weight. In Table 9.9a is reported the normalized matrix of the utilities and the weight vector take into account in the configuration 0, in Table 9.9b is reported the concordance and the discordance index belonging to each layout in comparison with the others, carried out according the Equation 84 and 85, respectively; in Table 9.9c is reported the comparison between the concordances and the discordances with c* and d*, evaluated in reference to the configuration 0 with the weight vector C0v1. The conditions required have been respected by Layout 4 in comparison with Layout 3 such that resulting the ideal solution for this configuration 0 with the weight vector C0v1.

Table 9.6ELECTRE method: a)normalised matrix, b)Concordance and discordance indexes and c) comparison between alternatives in terms of concordance and discordance

a)

Dimension	**Layout 1 vs**			**Weight vector**
	Layout 2	**Layout 3**	**Layout 4**	**C0v1**
LCA	0	0.728	1	0.25
Mechanical	1	0	0.565	0.25
Service life	1	0	0.173	0.25
Cost	0	0.941	1	0.25

b)

Dimension	Alternative						
	Layout 2 vs		Layout 3 vs		Layout 4 vs		
	Layout 3	Layout 4	Layout 2	Layout 4	Layout 2	Layout 3	
LCA	0	0	0.250	0	0.250	0.250	
Mechanical	0.250	0.250	0	0	0	0.250	**c***
Service life	0.250	0.250	0	0	0	0.250	
Cost	0	0	0.250	0	0.250	0.250	
Concordance Index	0.500	0.500	0.500	0	0.500	1	**0.5**
LCA	0.728	1	0	0.272	0	0	
Mechanical	0	0	1	0.565	0.435	0	**d***
Service life	0	0	1	0.173	0.827	0	
Cost	0.941	1	0	0.059	0	0	
Discordance Index	1.669	2	2	1.068	1.262	0	**1.333**

c)

Alternative		ckk'>c*	dkk'<d*
Layout 2 vs	Layout 3	0	0
	Layout 4	0	0
Layout 3 vs	Layout 2	0	0
	Layout 4	0	1
Layout 4 vs	Layout 2	0	1
	Layout 3	1	1

The results of the 11 different configurations analysed are reported in Figure 9.3; it is possible to notice that in 11% of the cases the ideal solution occurs for the Layout 2, in particular for the weight vector 1 of the configuration 5 and for all weight vectors of the configuration 7 while the remaining 89% ideal solutions have been resulted in the Layout 4 (45% for the configurations from 1 to 4 for all weight vectors, 7% for the configuration 5 for the weight vectors from 2 to 5, 9% for the configuration 6 for all weight vectors and 27% for the configurations from 8 to 10 for all weight vectors).

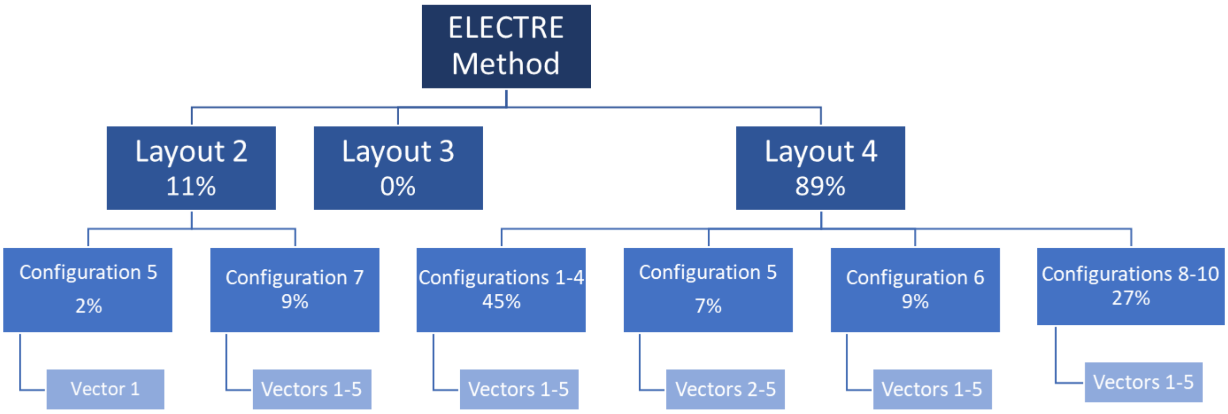


Figure 9.3 ELECTRE method final results with a concordance index equals to 1 and a discordance index equals to 0

9.2.2 EDIS method

Another method adopted in MCDA has been based on a measure of 'closeness' to a particular solution, which could be the average one (i.e. EDAS method [86]), the ideal one or the negative-ideal one (i.e. VIKOR [87] and TOPSIS [88] methods). In the present study, a technique aimed at choosing the best solution as that alternative closest to the ideal one has been adopted; similarly to the EDAS method, the utilized approach can be defined as EDIS method. The ideal solution A^* has been the alternative characterized by the maximum performance with respect to all indicators, as follow:

$$A^*: X^*_{jA^*} > X^*_{jk} \qquad \forall j \in J; \forall k \neq A^* \in K \tag{86}$$

where:

- $A^*$is the ideal solution
- $X^*_{jA^*}$is the maximum utility of j-th dimension identified as ideal solution $A*$
- X^*_{jk} is the utility of the j-th dimension of the k-th alternative

Whereas the implemented measure of closeness δ_k has been evaluated according to Equation 87.

$$\delta_k = \sqrt[q]{\textstyle\sum_j w^*_j \cdot \left|X^*_{jk} - X^*_{jA^*}\right|^q} \text{ with } q \geq 1 \tag{87}$$

where:

- δ_k is the distance from the ideal solution

- q is a coefficient $\in [1 \div +\infty]$, that identifies the type of distance calculated: i.e. q=1 Manhattan distance; q=2 Euclidean distance
- w_j^* is the normalized weight value of the *j*-th dimension
- $X_{jA^*}^*$ is the maximum utility of *j*-th dimension identified as ideal solution $A*$

In Table 9.7 are reported the distances from the ideal solution $X_{jA^*}^*$=1 for all weight vectors of the configuration 0 from q= 1 to 30.

After having computed the measure of δ for each alternative, related trends with respect to q, until a q equals to 30, have been plotted in a q-δ graph. Figure 9.4 shows the graph obtained for the configuration 0 that takes into account all indicators; in particular, in Figure 9.4 is possible to notice an upward trend of the distance calculated for each alternative until a q value is equal to 20, after that the values until q equals to 30 reach an asymptotic behavior. According to EDIS method, the best solution is represented by the shortest distance from the ideal solution that in this configuration is represented by Layout 4 with CRAJ as base layer.

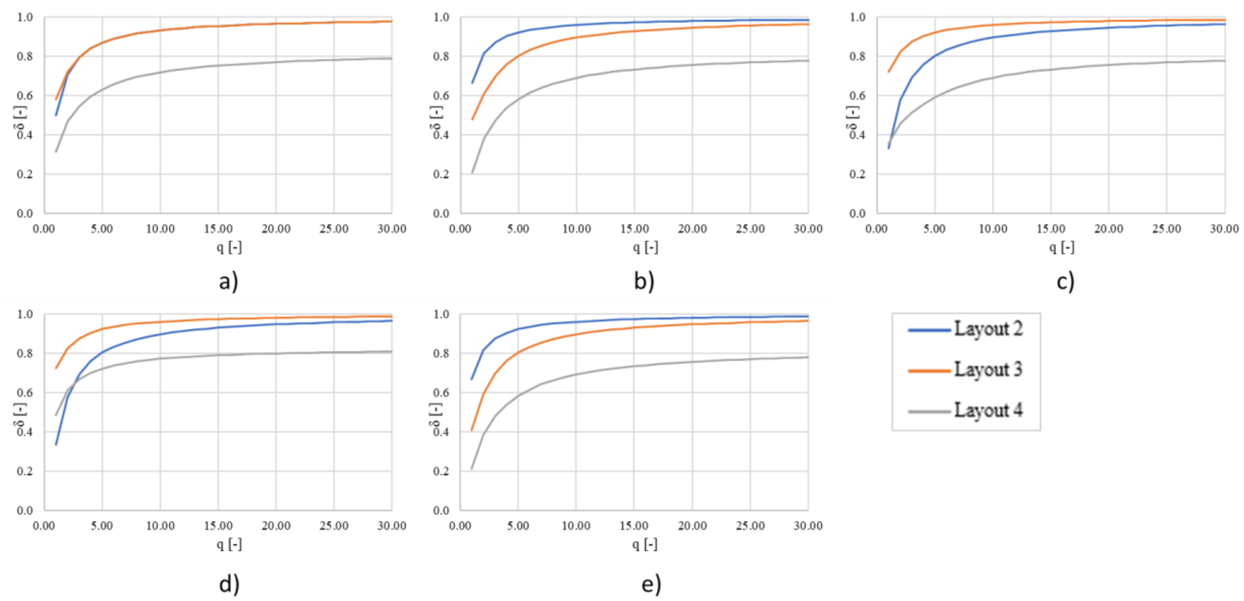


Figure 9.4 EDIS result for configuration 0: a) weight vector C0v1, b) weight vector C0v2, c) weight vector C0v3, d) weight vector C0v4 and e) weight vector C0v5

In Table 9.8 are reported the min δ of each *k*-th layout for each configuration from which it is possible to evaluate the most appropriate solution; in particular, in 82% of cases the Layout 4 has been resulted the suitable alternative, while for the 7% and 11% of cases respectively the Layout 2 and Layout 3 have been resulted the suitable alternative.

Table 9.7 EDIS methods results for the configuration 0

			Weight vector														
			C0v1			C0v2			C0v3			C0v4			C0v5		
Distance	q	$X^*_{jA^*}$	Layout 2	Layout 3	Layout 4	Layout 2	Layout 3	Layout 4	Layout 2	Layout 3	Layout 4	Layout 2	Layout 3	Layout 4	Layout 2	Layout 3	Layout 4
δ1	1		0.500	0.583	0.316	0.667	0.479	0.210	0.333	0.722	0.356	0.333	0.722	0.486	0.667	0.408	0.210
δ2	2		0.707	0.721	0.467	0.816	0.609	0.381	0.577	0.824	0.457	0.577	0.824	0.611	0.816	0.589	0.381
δ3	3		0.794	0.796	0.545	0.874	0.700	0.476	0.693	0.875	0.514	0.693	0.875	0.667	0.874	0.696	0.476
δ4	4		0.841	0.841	0.595	0.904	0.761	0.538	0.760	0.904	0.556	0.760	0.904	0.700	0.904	0.760	0.538
δ5	5		0.871	0.871	0.631	0.922	0.803	0.582	0.803	0.922	0.591	0.803	0.922	0.722	0.922	0.803	0.582
δ6	6		0.891	0.891	0.658	0.935	0.833	0.615	0.833	0.935	0.620	0.833	0.935	0.737	0.935	0.833	0.615
δ7	7		0.906	0.906	0.679	0.944	0.855	0.641	0.855	0.944	0.643	0.855	0.944	0.749	0.944	0.855	0.641
δ8	8		0.917	0.917	0.696	0.951	0.872	0.661	0.872	0.951	0.662	0.872	0.951	0.758	0.951	0.872	0.661
δ9	9		0.926	0.926	0.709	0.956	0.885	0.678	0.885	0.956	0.678	0.885	0.956	0.765	0.956	0.885	0.678
δ10	10		0.933	0.933	0.720	0.960	0.896	0.691	0.896	0.960	0.691	0.896	0.960	0.771	0.960	0.896	0.691
δ11	11		0.939	0.939	0.729	0.964	0.905	0.702	0.905	0.964	0.703	0.905	0.964	0.776	0.964	0.905	0.702
δ12	12		0.944	0.944	0.737	0.967	0.913	0.712	0.913	0.967	0.712	0.913	0.967	0.780	0.967	0.913	0.712
δ13	13		0.948	0.948	0.743	0.969	0.919	0.720	0.919	0.969	0.720	0.919	0.969	0.784	0.969	0.919	0.720
δ14	14		0.952	0.952	0.749	0.971	0.925	0.727	0.925	0.971	0.727	0.925	0.971	0.787	0.971	0.925	0.727
δ15	15	1	0.955	0.955	0.754	0.973	0.929	0.734	0.929	0.973	0.734	0.929	0.973	0.789	0.973	0.929	0.734
δ16	16		0.958	0.958	0.758	0.975	0.934	0.739	0.934	0.975	0.739	0.934	0.975	0.792	0.975	0.934	0.739
δ17	17		0.960	0.960	0.762	0.976	0.937	0.744	0.937	0.976	0.744	0.937	0.976	0.794	0.976	0.937	0.744
δ18	18		0.962	0.962	0.765	0.978	0.941	0.748	0.941	0.978	0.748	0.941	0.978	0.795	0.978	0.941	0.748
δ19	19		0.964	0.964	0.768	0.979	0.944	0.752	0.944	0.979	0.752	0.944	0.979	0.797	0.979	0.944	0.752
δ20	20		0.966	0.966	0.771	0.980	0.947	0.756	0.947	0.980	0.756	0.947	0.980	0.799	0.980	0.947	0.756
δ21	21		0.968	0.968	0.774	0.981	0.949	0.759	0.949	0.981	0.759	0.949	0.981	0.800	0.981	0.949	0.759
δ22	22		0.969	0.969	0.776	0.982	0.951	0.762	0.951	0.982	0.762	0.951	0.982	0.801	0.982	0.951	0.762
δ23	23		0.970	0.970	0.778	0.983	0.953	0.765	0.953	0.983	0.765	0.953	0.983	0.802	0.983	0.953	0.765
δ24	24		0.972	0.972	0.780	0.983	0.955	0.767	0.955	0.983	0.767	0.955	0.983	0.803	0.983	0.955	0.767
δ25	25		0.973	0.973	0.782	0.984	0.957	0.769	0.957	0.984	0.769	0.957	0.984	0.804	0.984	0.957	0.769
δ26	26		0.974	0.974	0.784	0.985	0.959	0.772	0.959	0.985	0.772	0.959	0.985	0.805	0.985	0.959	0.772
δ27	27		0.975	0.975	0.785	0.985	0.960	0.774	0.960	0.985	0.774	0.960	0.985	0.806	0.985	0.960	0.774
δ28	28		0.976	0.976	0.787	0.986	0.962	0.775	0.962	0.986	0.775	0.962	0.986	0.806	0.986	0.962	0.775
δ29	29		0.976	0.976	0.788	0.986	0.963	0.777	0.963	0.986	0.777	0.963	0.986	0.807	0.986	0.963	0.777
δ30	30		0.977	0.977	**0.789**	0.987	0.964	**0.779**	0.964	0.987	**0.779**	0.964	0.987	**0.808**	0.987	0.964	**0.779**

Table 9.8 EDIS method results

Configuration	Vector	Distance	Suitable alternative	Configuration	Vector	Distance	Suitable alternative
	C0v1	0.779	Layout 4		C6v1	0.426	Layout 4
	C0v2	0.779	Layout 4		C6v2	0.426	Layout 4
0	C0v3	0.779	Layout 4	6	C6v3	0.431	Layout 4
	C0v4	0.808	Layout 4		C6v4	0.426	Layout 4
	C0v5	0.779	Layout 4		C6v5	0.416	Layout 4
	C1v1	0.723	Layout 3		C7v1	0	Layout 2
	C1v2	0.797	Layout 4		C7v2	0	Layout 2
1	C1v3	0.783	Layout 4	7	C7v3	0	Layout 2
	C1v4	0.813	Layout 4		C7v4	0	Layout 2
	C1v5	0.783	Layout 4		C7v5	0	Layout 2
	C2v1	0.390	Layout 3		C8v1	0	Layout 4
	C2v2	0.783	Layout 4		C8v2	0	Layout 4
2	C2v3	0.797	Layout 4	8	C8v3	0	Layout 4
	C2v4	0.813	Layout 4		C8v4	0	Layout 4
	C2v5	0.783	Layout 4		C8v5	0	Layout 4
	C3v1	0.390	Layout 3		C9v1	0.808	Layout 4
	C3v2	0.413	Layout 4		C9v2	0.789	Layout 4
3	C3v3	0.428	Layout 4	9	C9v3	0.808	Layout 4
	C3v4	0.420	Layout 4		C9v4	0.819	Layout 4
	C3v5	0.413	Layout 4		C9v5	0.808	Layout 4
	C4v1	0.333	Layout 2		C10v1	0.426	Layout 4
	C4v2	0.783	Layout 4		C10v2	0.416	Layout 4
4	C4v3	0.783	Layout 4	10	C10v3	0.431	Layout 4
	C4v4	0.813	Layout 4		C10v4	0.426	Layout 4
	C4v5	0.797	Layout 4		C10v5	0.426	Layout 4
	C5v1	0.557	Layout 3				
	C5v2	0.808	Layout 4				
5	C5v3	0.808	Layout 4				
	C5v4	0.819	Layout 4				
	C5v5	0.789	Layout 4				

9.2.3 Multi-utility evaluation method

At the end, a multi-utility evaluation method taking into account all weight vectors of each configuration at the same time has been performed, in particular to evaluate how changing the importance of each indicator can influence the outcome. The Utility matrix $\underset{k\times m}{NW}$ has been carried out according the following Equation 37

$$\underset{k\times j}{N} \times \underset{j\times m}{W} = \underset{k\times m}{NW} \tag{88}$$

where

- $\underset{k\times j}{N}$ is the normalised matrix of the utilities = $\underset{k\times j}{N} = \begin{pmatrix} n_{11} & \cdots & n_{1j} \\ \vdots & \ddots & \vdots \\ n_{k1} & \cdots & n_{kj} \end{pmatrix}$
- $$n_{kj} = \frac{\max a_{k,j} - a_{k,j}}{\max a_{k,j} - \min a_{k,j}} \tag{89}$$

  where:

  - $a_{k,j}$ is the value of the *k*-th alternative refers to *j*-th dimension belongs to the decision matrix $\underset{k\times j}{A} = \begin{pmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{k1} & \cdots & a_{kj} \end{pmatrix}$
- $\max a_{k,j}$ is the maximum value of the *k*-th alternative refers to *j*-th indicators
- $\min a_{k,j}$ is the minimum value *k*-th alternative refers to *j*-th indicators
- $\underset{j\times m}{W}$ is the weight vectors matrix= $\underset{j\times m}{W} = \begin{pmatrix} w_{11} & \cdots & w_{1m} \\ \vdots & \ddots & \vdots \\ w_{j1} & \cdots & w_{jm} \end{pmatrix}$

  where w_{jm} is the weight of the j-th dimension of the m-th configuration weight vectors.

In each configuration have been obtained 5 different values of utility U_k for each alternative *k* and to define the best ideal solution the mean μ and standard deviation σ have been calculated. In Table 9.9a is reported the normalized matrix $\underset{k\times j}{N}$, in Table 9.9b is reported the weight vectors matrix $\underset{j\times m}{W}$ and in Table 9.9c is reported the utility matrix $\underset{k\times m}{NW}$ related to the configuration 0 with the relative mean and standard deviation.

The mean and standard deviation of each alternative *k* have been plotted in a μ-σ graph where each alternative is represented by a point.

In particular, the μ-σ graph identifies four different regions:

- Region A where fall alternatives with highest mean and lowest variance
- Region B where fall alternatives with highest mean and highest variance
- Region C where fall alternatives with lowest mean and lowest variance
- Region D where fall alternatives with lowest mean and highest variance

The best solution has been the one fallen in the Region A. In Figure 9.5 are reported the μ-σ graphs of all configurations analysed; the Layout 4 has been resulted the best appropriate solution for all configuration except for the configuration 7 where the Layout 2 was found to be the best.

Table 9.9 Multi-utility method result for the configuration 0

a)

Dimension	Layout 1 vs Layout 2	Layout 3	Layout 4
LCA	0	0.728	1
Mechanical	1	0	0.565
Service life	1	0	0.173
Costs	0	0.941	1

b)

Dimension	Weight vector				
	C0v1	C0v2	C0v3	C0v4	C0v5
LCA	0.250	0.500	0.167	0.167	0.167
Mechanical	0.250	0.167	0.500	0.167	0.167
Service life	0.250	0.167	0.167	0.500	0.167
Costs	0.250	0.167	0.167	0.167	0.500

c)

	Utilities					Mean	Standard deviation
Alternatives	C0v1	C0v2	C0v3	C0v4	C0v5		
Layout 2	0.500	0.333	0.667	0.667	0.333	0.500	0.167
Layout 3	0.417	0.521	0.278	0.278	0.592	0.417	0.141
Layout 4	0.684	0.790	0.644	0.514	0.790	**0.684**	**0.115**

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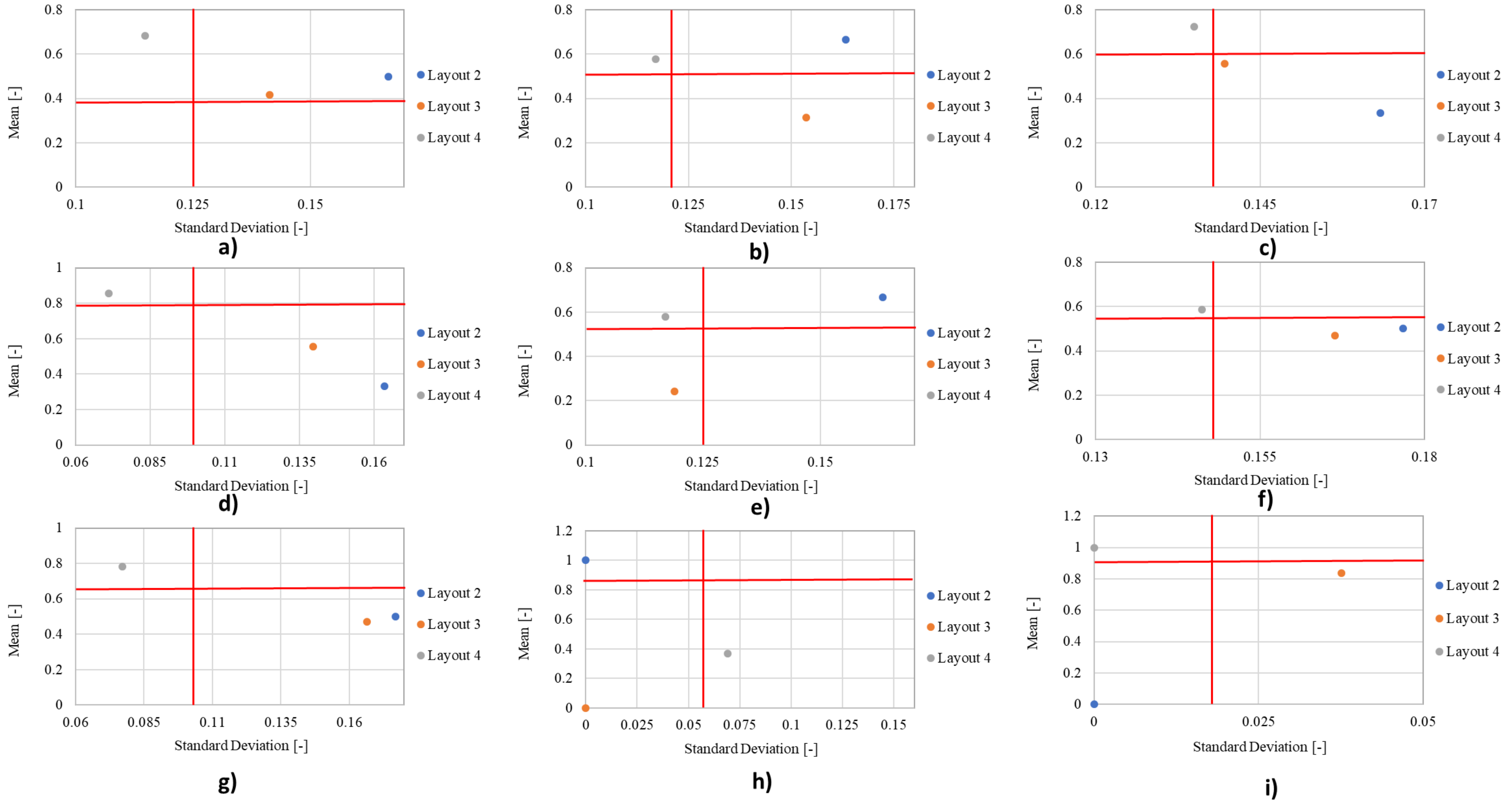

Figure 9.5 Multi-utility μ-σ graphs

9.3 Choice of the most suitable alternative

A first comparison of the methods analysed has been carried out in the case of Multi-utility where the solutions for each configuration have been sorted by mean decreasing (seeTable 9.10a) and by standard deviation increasing (see Table 9.10b); in both cases the configuration 7, 8, 3, 6 and 10 have been resulted in the same position and in particular the configuration 7 and 8 have been presented the same mean and standard deviation values (mean equals to 1 and standard deviation equals to 0); the difference between the two best configurations has arisen in the suitable alternative where the configuration 7 exhibit the Layout 2 while the configuration 8 exhibit the Layout 4. A further confirmation of Layout 2 and the Layout 4 as suitable alternative respectively for the configuration 7 and 8 has been resulted in the sorting by distance increasing of the EDIS method both with a same value of distance equals to 0. The difference between the EDIS and Multi-utility methods involves the worst suitable alternative position in the case of EDIS method sorting by mean decreasing since in the latter the configuration 4 resulted to be the worst between the best alternative on the contrary of Multi-utility method where the vector 4 of the configuration 9 with Layout 4 as suitable alternative is in the last position. This position is in compliant with the last position of Multi-utility method sorting by standard deviation increasing. Although the last position between the two sorting of the multi-utility method are different, the configuration 9 is however among the last three for the sorting by mean decreasing with Layout 4 as suitable alternative; therefore, based on these considerations the configuration 9 results the worst between all configuration in terms of suitable alternatives.

Table 9.10 Sorting of suitable alternative: a) Multi-utility by mean decreasing, b) Multi-utility by standard deviation increasing and c) EDIS by distance increasing

a)				b)			
Configuration	Mean	Standard deviation	Suitable alternative	Configuration	Mean	Standard deviation	Suitable alternative
7	1	0	Layout 2	7	1	0	Layout 2
8	1	0	Layout 4	8	1	0	Layout 4
3	0.855	0.071	Layout 4	3	0.855	0.071	Layout 4
6	0.782	0.077	Layout 4	6	0.782	0.077	Layout 4
10	0.782	0.077	Layout 4	10	0.782	0.077	Layout 4
2	0.724	0.135	Layout 4	0	0.684	0.115	Layout 4
0	0.684	0.115	Layout 4	1	0.579	0.117	Layout 4
5	0.587	0.146	Layout 4	4	0.579	0.117	Layout 4
9	0.587	0.146	Layout 4	2	0.724	0.135	Layout 4
1	0.579	0.117	Layout 4	5	0.587	0.146	Layout 4
4	0.579	0.117	Layout 4	9	0.587	0.146	Layout 4

c)

Position	Configuration	Vector	Distance	Suitable alternative	Position	Configuration	Vector	Distance	Suitable alternative
1	7	1	0	Layout 2	**29**	1	1	0.723	Layout 3
2	7	2	0	Layout 2	**30**	0	2	0.779	Layout 3
3	7	3	0	Layout 2	**31**	0	5	0.779	Layout 4
4	7	4	0	Layout 2	**32**	0	1	0.779	Layout 4
5	7	5	0	Layout 2	**33**	0	3	0.779	Layout 4
6	8	1	0	Layout 4	**34**	2	2	0.783	Layout 4
7	8	2	0	Layout 4	**35**	2	5	0.783	Layout 4
8	8	3	0	Layout 4	**36**	1	5	0.783	Layout 4
9	8	4	0	Layout 4	**37**	4	2	0.783	Layout 4
10	8	5	0	Layout 4	**38**	1	3	0.783	Layout 4
11	4	1	0.333	Layout 2	**39**	4	3	0.783	Layout 4
12	2	1	0.390	Layout 3	**40**	5	5	0.789	Layout 4
13	3	1	0.390	Layout 3	**41**	9	2	0.789	Layout 4
14	3	2	0.413	Layout 4	**42**	2	3	0.797	Layout 4
15	3	5	0.413	Layout 4	**43**	1	2	0.797	Layout 4
16	6	5	0.416	Layout 4	**44**	4	5	0.797	Layout 4
17	10	2	0.416	Layout 4	**45**	5	2	0.808	Layout 4
18	3	4	0.420	Layout 4	**46**	5	3	0.808	Layout 4
19	6	1	0.426	Layout 4	**47**	9	1	0.808	Layout 4
20	6	2	0.426	Layout 4	**48**	9	3	0.808	Layout 4
21	6	4	0.426	Layout 4	**49**	9	5	0.808	Layout 4
22	10	1	0.426	Layout 4	**50**	0	4	0.808	Layout 4
23	10	4	0.426	Layout 4	**51**	2	4	0.813	Layout 4
24	10	5	0.426	Layout 4	**52**	1	4	0.813	Layout 4
25	3	3	0.428	Layout 4	**53**	4	4	0.813	Layout 4
26	6	3	0.431	Layout 4	**54**	5	4	0.819	Layout 4
27	10	3	0.431	Layout 4	**55**	9	4	0.819	Layout 4
28	5	1	0.557	Layout 3					

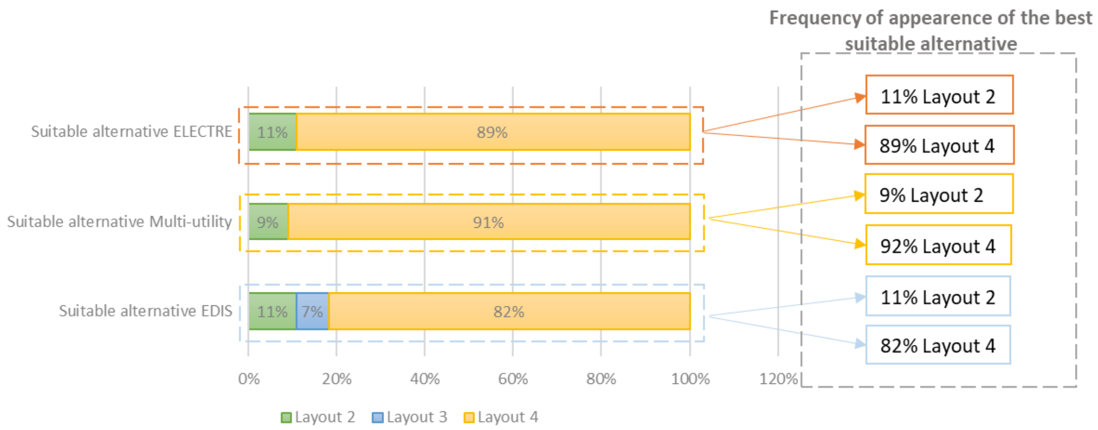

Figure 9.6 Frequency of appearance of the suitable alternative for ELECTRE, EDIS and Multi-utility methods

Figure 9.6 shows the frequency of appearance of the suitable alternative for each method; it is possible notice that although the Layout 4 has a major frequency related to the other two alternatives, the Multi-utility method shows an increment of 2% of Layout 4 as suitable alternative than ELECTRE method and an increment of 8% in comparison with EDIS method. The Layout 2 have the same frequency of appearance of 11% in both ELECTRE and EDIS method, increased by 2% respect to Multi-utility method. It is important highlighted that in the ELECTRE method it not was possible sorting the suitable alternative to identify the best suitable alternative for the reference method and therefore evaluate the frequency of appearance of the best suitable alternative as in the case of the EDIS and ELECTRE methods; both EDIS and ELECTRE methods show the same frequency of appearance of the best suitable solution of the 9% for both Layout 2 and Layout 4.

In finally, from the comparison between the methods adopted it is possible state that the most appropriate method to carried out for the definition of the best suitable alternative is the multi-utility method since, unlike the others,1) has simple data processing, 2) takes into account simultaneously all weight vectors providing a global solution for each configuration, hence a high degree of stability with respect to the adopted weight vectors and in particular 3) the definition of the suitable alternative is given on basis of the no-distortion of the utility value of each dimension of each alternative but good values of the dimensions.

10 Conclusions

The complexity of the current socio-economic system even today benefits from a linear economy model since companies, not very responsive to market stimuli, act independently of each other, making it difficult for them to enter a virtuous and economic sustainable loop of recovery and recycling waste. To guarantee these requisites, the Italian legislator implemented Article 18, on the "Application of minimum environmental criteria in public procurement of supplies and the provision of services" of Legislative Decree no. 6/2016 on "Environmental provisions to promote green economy measures and contain the excessive use of natural resources" and, subsequently, Article 34 of the "Energy and environmental sustainability criteria" of Legislative Decree no. 50/2016 of the "Procurement Code", introducing Minimum Environmental Criteria (MEC). At this time, the use of alternative materials to replace limestone in road paving construction represents an extremely innovative process that fully meets LCA requirements.

The study described in this research focuses first of all on the construction of a laboratory mixing protocol for cold bituminous mastics and on the examination of their rheological performance and main differences in terms of shear modulus G* and non-recoverable creep compliance J_{nr} when compared to hot mastics. Specifically, the addition of jet grouting waste as a filler for bitumen with and without additional LF led to the best response in cold mastics. The achievement are as follows:

- Cold mastics mixing jet grouting waste, limestone filler and bituminous emulsion were made at 60°C using a filler-to-bitumen weight ratio of 0.3; the separation of bitumen from water into bituminous emulsion took place without the addition of cement as traditionally happens with cold bituminous mixtures; this is due to the role and contribution of jet grouting waste comprising water, cement and soil available in site.
- It was observed that cold mastics after 3 days of curing time at 60°C shows a worse G* performance than neat bitumen 50/70 contained in bituminous emulsion.
- The contribution in terms of G* of the jet grouting waste alone is greater into the hot mastics, while into the cold mastics G* increases and reaches highest value when JW is added with

limestone filler to bitumen; the combination of this two fillers gives more elasticity to the binder leading to a reduction of phase angle.

- The combination of jet grouting waste and limestone filler in cold mastics increases the stiffness response, returning a higher G* modulus, confirmed also by a reduction of the accumulated deformation obtained from a Multi-Stress Creep and Recovery test.

The second objective of the research was to investigate an optimal solution for making hot bituminous mastic with plastic waste, with the goal of saving natural resources without negatively affecting performance. Indeed, the research was designed to investigate, on the one hand, solutions that could return the same rheological performance as traditional limestone mastics by using PW as the sole filler type and keeping the weight ratios constant; on the other hand, the study aimed to find solutions where two types of filler were combined whose highest percentage was reached by plastic waste materials in order to exceed the performance of a hard modified bitumen selected here as top reference. From the result obtained, it was found that:

- The effects deriving from increasing the blending time from 10 to 60 minutes for making the mastics demonstrated that 10 minutes can be set as the optimal mixing time since no-significant differences have been returned by the ring and ball and viscosity at 100°C results for each prepared mastic
- As for G* analysis, slight increases were shown for limestone mastics in comparison to B5070 within all ranges of the test temperatures, while mastics containing PW (HP01, HP015, HP02) showed a distinct G* increase compared to B5070; in particular, the gap becomes more marked moving towards 50°C, where the best performance of HP02 is given. Looking into the phase angle variations, it can be observed that HP02 returns a reduction of 30% compared with B5070 50°C, while HL02 shows a reduction of 14% between 40°C and 50°C when compared with B5070. A different situation was observed when comparisons are made with modified bitumen (HMB); it can be observed that all alternative mastics containing PW plus LF as fillers have a higher G* value than HMB within a range of temperatures between 0 and 30°C, at which the lowest values of the phase angles are returned by HMB. Overall, it was observed that the HLP02 solution performs best in terms of the elastic behaviour since, keeping constant a G* value which tends to be higher and higher, it always returns the lowest phase angle.
- Moving on to illustrate the main results of the MSCR analysis, it was observed both for mastics with PW filler (HP01, HP015, HP02) and mastics with PW plus LF filler (HLP01, HLP015, HLP02) that there was a mean decrease of 73% in the Jnr and Jtot parameters at two

test temperatures (40°C and 50°C) in comparison with the whole dataset involving mastics prepared using LF (HL01, HL015 and HL02 show Jnr mean value of 0.1335 kPa-1 and Jtot mean value of 0.1349 kPa-1). The best performance in terms of the Jnr and Jtot parameters, which overlap each other for all mastics, takes place at two test temperatures by HP02 and HLP02 solutions; so this means that the stiffness contribution brought by PW and/or by adding a small amount of LF over the total weight of the bitumen was seen at two test temperatures, and above all the similarity of Jnr and Jtot helps the assertion that good recoverable deformation exists already from the end of the loading phase without waiting for the last step of the unloading cycles.

- Moving forward to illustrate the MSCR results, in terms of the Jnrratio(B5070) and Jtotratio(B5070) parameters, it was observed that a) all mastics with PW as sole filler type (HP01, HP015, HP02) return much lower values than mastics made up with LF filler, b) the HP01, HP015, HP02 solutions show 1) low loss-cumulated deformation compared with B5070 (Jnrratio(B5070)), but 2) excellent elastic recovery of the total deformation already at the end of the creep phase (i.e. 75% cumulated deformation in HP01, 89% in HP015, 93% in HP02).
- Jnrratio(HLP) and Jtotratio(HLP) were further assessed to test whether combining two types of filler, of which PW covers the highest percentage as a filler, and LF the lowest, the final rheological properties of the mastics can be an improvement in comparison to a) traditional limestone mastics (HL01, HL015, HL02) and b) alternative mastics using PW as a filler (HP01, HP015, HP02). The deformation values resulted lower for mastics containing both PW and LF filler than those observed for limestone mastics; the best solution is HLP02.

The use of materials alternative to natural ones plays an important and strategic role in the mix design process of road bituminous pavements for both hot and cold solutions, because they help to reduce a) virgin resources involved in the process without negative affects on the final mechanical performance of the mixtures and b) negative environmental impacts associated, first of all, with the activities related to mining materials (aggregates and bitumen, mostly) and then to laying and maintenance activities. The paper aims to promote an integrated experimental-methodological approach reflecting the requirements of Italian Law no. 128 of 2 November 2019 concerning the so-called “end-of-waste”.

The alternative mixtures suggested here (HMAJ and CRAJ) have been designed to keep constant the percentage of jet grouting waste as a filler by the total weight of the aggregates, seeking to establish the best configuration for the relative grading curves fully overlapping each other and that relate to study traditional HMA, following technical Standards at the same time. SUPERPAVE procedure was implemented for two hot solutions; for CRA and CRAJ solution an internal laboratory protocol was followed, in line with some existing procedures available in the literature, focusing on the achieving a desired compaction level by varying curing time.

The designed solution HMAJ was the most appropriate in terms of the parameters mentioned above. Good performance was also observed for the cold mixture asphalt prepared with RAP and JW, particularly in terms of ITS and creep resistance when compared with HMA

In any case, although the HMAJ solution gives the overall best physical and mechanical traits compared to the remaining mixtures examined, the other alternative mixture (CRAJ) also promotes the reuse of two types of waste, as they fully meet the reference Italian Technical Standard, and they favour saving natural resources as well as allowing good mixture performance.

Referring to the European and international regulatory standards that outline the guidelines for the execution of this procedure, and secondly by comparing the more authoritative and innovative application studies of LCA to the road paving sector this research aims to provide a perspective on the methodological approach to LCA analysis.

Using the specific data of the territory provided by the partner company of the study and the data concerning the materials tested at the La.Stra., the aforementioned methodology was applied, gradually disaggregating the fundamental phases of the life of a pavement in a series of simple “unitary” processes. These processes have been associated with the environmental impacts deriving from the main flows into and out of the processes themselves, determined in turn by the authoritative sources of the sector.

In this research, four different layouts of flexible pavement have been proposed where the additional value has been created by reusing, in the base layer mix design, reclaimed asphalt pavement, deriving from the milling of an existing pavement, and jet grouting waste, deriving from the soil consolidation during tunnel construction. The purpose was to identify the solution with the best compromise between the mechanical performances, as predictor of the best performance, the environmental impact indicators in terms of LCA, the cost of manufacturing, the technological complexity of the manufacturing process of the alternatives and the laying time of bituminous mixtures. A sensitivity analysis has been the support of the choice by decision-maker of the “best” solution between the range of feasible solutions. A key role has been played by the transport that is the major factor that has reduced the impact indicators of the LCIA in the case of a cold in-place recycled mixture, in particular reducing the GWP emission in terms of CO_2 and the waste production with the reuse of JW and RAP. The reduction of the cost for the manufacturing of a layout with CRAJ as base layer has been influenced by the reduction of the fresh aggregates supply.

The results highlight as best compromise the solution with a base layer made with a cold in-place recycling asphalt and the addition of JW.

Differently from other studies the results here presented are very promising since the data collected as primary data are real values derived from the real activities that comes from the aggregates excavation to the laying of the bituminous mixture both in plant and in site. Besides, developed methodology for using LCA for comparison of different structures, and then using multi-criteria analysis for selection of optimal solution is important contribution of this work that can be used in the future in the context of analyzing use of alternative and recycled materials in pavement structures.

Further studies to assess the effects of different plastic waste types on optimal mastics blending time determination, fatigue characterization of asphalt binders and mastics with the Linear Amplitude Sweep and Four-point Bending Beam test will be carried out, as well as mixing cold bituminous mastics with plastic waste to achieve, for example, the same performance as a traditional hot bituminous mastic, and, furthermore, improving procedures to select the most appropriate alternative, referring, for example, to the LCA and LCCA will be investigated.

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