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Review

Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review ☆

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HIGHLIGHTS

- Introducing the Recycled Tyre Rubber (RTR) material as environmental problem as well as engineering resource.
- Introducing the wet process technology.
- Describing in details the existing products associated to the wet process high viscosity technology.
- Describing in details the wet process No Agitation technology.
- Comparing the described technologies and providing justifications and suggestions toward a widespread use of RTR-MBs.

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ABSTRACT

Nowadays, only a small percentage of waste tyres are being land-filled. The Recycled Tyre Rubber is being used in new tyres, in tyre-derived fuel, in civil engineering applications and products, in moulded rubber products, in agricultural uses, recreational and sports applications and in rubber modified asphalt applications. The benefits of using rubber modified asphalts are being more widely experienced and recognized, and the incorporation of tyres into asphalt is likely to increase. The technology with much different evidence of success demonstrated by roads built in the last 40 years is the rubberised asphalt mixture obtained through the so-called "wet process" which involves the utilisation of the Recycled Tyre Rubber Modified Bitumens (RTR-MBs). Since 1960s, asphalt mixtures produced with RTR-MBs have been used in different parts of the world as solutions for different quality problems and, despite some downsides, in the majority of the cases they have demonstrated to enhance performance of road's pavement. This study reports the results of a literature review upon the existing technologies and specifications related to the production, handling and storage of RTR-MBs and on their current applications within road asphalt mixtures. Furthermore, considering that RTR-MBs technologies are still struggling to be fully adopted worldwide, mainly because of poor information, lack of training of personnel and stakeholders and rare support of local policies, the present work aims to be an up-to-date reference to clarify benefits and issues associated to this family of technologies and to finally provide suggestions for their widespread use.

Contents

Abbreviations: CRM, Crumb Rubber Modifier; ELTs, end of life tyres; RTR-MB, Recycled Tyre Rubber Modified Bitumen; RTR, Recycled Tyre Rubber.

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1. Tyre rubber: environmental problem or engineering resource?

The increasing number of vehicles on the roads of industrialised and developing nations generates millions of used tyres every year. About 1.4 billion tyres are sold worldwide each year and subsequently as many eventually fall into the category of end of life tyres (ELTs) (Fig. 1). Moreover, the amount of ELTs in Europe, US and Japan are about to increase because of the projected growing number of vehicles and increasing traffic worldwide. These tyres are among the largest and most problematic sources of waste, due to the large volume produced and their durability. The US Environmental Protection Agency reports that 290 million scrap tyres were generated in 2003 (EPA, 2007). Of the 290 million, 45 million of these scrap tyres were used to make automotive and truck tyre re-treads. In Europe every year, 355 million tyres are produced in 90 plants, representing the 24% of world production [1]. In addition the EU has millions of used tyres that have been illegally dumped or stockpiled. The inadequate disposal of tyres may, in some cases, pose a potential threat to human health (fire risk, haven for rodents or other pests such as mosquitoes) and potentially increase environmental risks. Most countries, in Europe and worldwide, have relied on land filling to dispose of used tyres but the limited space and their potential for reuse has led to many countries imposing a ban on this practice. The current estimate for these historic stockpiles throughout the EU stands at 5.5 million tonnes (1.73 times the 2009 annual used tyres arising) and the estimated annual cost for the management of ELTs is estimated at € 600 million [2]. With landfills minimising their acceptance of whole tyres and the health and environmental risks of stockpiling tyres, many new markets have been created for scrap tyres.

In order to face this problem, in Europe in 1989, a used tyres group composed of experts from the main tyre manufacturers

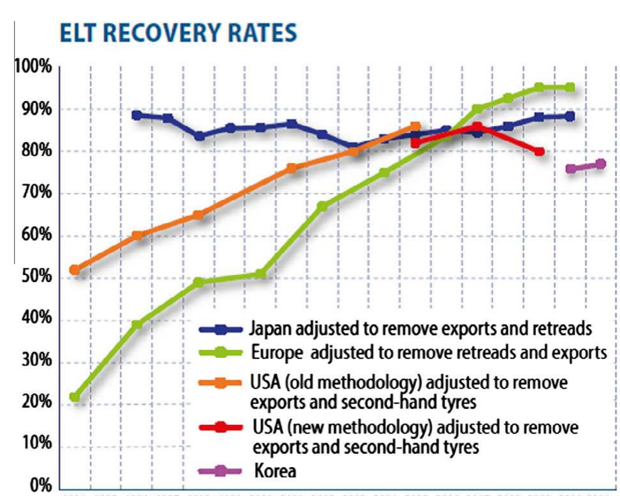

Fig. 1. Evolution of ELTs recovery rates in major tyre markets, adapted from [2].

producing in Europe, was set up under the strategic guidance of the European Tyre and Rubber Manufacturers Association (ETRMA). This Group was dedicated to the management of end of life tyres (ELTs). Also thanks to this group, since 1996, the collection rate has increased steadily while there has been a continuous decline in the land filling of used tyres (Table 1). In 2009 the European Union was faced with the challenge of managing, in an environmentally sound manner, more than 3.2 million tonnes of used tyres of which 95% were recovered. This confirms Europe as one of the most active areas in the world in the recovery of ELTs.

Country arise and recovery rates demonstrate that ELTs management in Europe is allowing the progressive elimination of land filling and raises the availability of Recycled Tyre Rubber (RTR) to be recycled for other purposes. In fact, the same characteristics that make waste tyres such a problem also make them one of the most re-used waste materials, as RTR is very resilient and can be reutilised in other products. These efforts should for example help to further develop the use of ELTs in rubberised asphalt in road construction, which has high growth potential in Europe and it is still relatively underutilised [2].

1.1. Recycled Tyre Rubber as engineering material

The tyre is a complex and high-tech safety product representing a century of manufacturing innovation, which is still on-going. From the material point of view the tyre is made up of three main components materials: (i) elastomeric compound, (ii) fabric and (iii) steel. The fabric and steel form the structural skeleton of the tyre with the rubber forming the "flesh" of the tyre in the tread, side wall, apexes, liner and shoulder wedge [3]. This engineering process is necessary to transform natural rubber in a product able to ensure performance, durability and safety. In fact, natural rubber is sticky in nature and can easily deform when heated up and it is brittle when cooled down (Table 2). In this state it cannot be used to make products with a good level of elasticity. The reason for inelastic deformation of not-vulcanised rubber can be found in the chemical nature as rubber is made of long polymer chains. These polymer chains can move independently relative to each other, and this will result in a change of shape. By the process of vulcanisation cross-links are formed between the polymer chains, so the chains cannot move independently anymore. As a result, when stress is applied the vulcanised rubber will deform, but upon release of the stress the rubber article will go back to its original shape. Compounding is finally used to improve the physical properties of rubber by incorporating the ingredients and ancillary substances necessary for vulcanisation, but also to adjust the hardness and modulus of the vulcanised product to meet the end requirement. Different substances can be added according to the different tyre mixtures; these include mineral oil and reinforcing fillers as carbon black and silica [4]. In general, truck TR contains larger percentages of natural rubber compared to that from car tyres [5]. Table 3 summarises the general tyre composition of tyres used in cars and trucks in the EU [2].

From the structural point of view, the main components of a tyre are the tread, the body, side walls and the beads (Fig. 2). The tread is the raised pattern in contact with the road. The body supports the tread and gives the tyre its specific shape. Beads are metal-wire bundles covered with rubber, which holds the tyre on the wheel. The inherent characteristics of the tyre are the same worldwide. They include: the resistance to mould, mildew, heat and humidity, retardation of bacterial development, resistance to sunlight, ultraviolet rays, some oils, many solvents, acids and other chemicals. Other physical characteristics include their non-biodegradability, non-toxicity, weight, shape and elasticity. However, many of the characteristics, which are beneficial during their on-road life as consumer products, are disadvantageous in their post-consumer life and can create problems for collection, storage and/or disposal [6].

Table 2
Effect of temperature on natural rubber, adapted from [2].

−10 °C	Brittle and opaque
20 °C	Soft, resilient and translucent
50 °C	Plastic and sticky
120 °C −160 °C	Vulcanised when agents e.g., sulphur are added
180 °C	Break down as in the masticator
200 °C	Decomposes

Table 3
Comparison of passenger car and truck tyres in the EV, adapted from [3].

Material (contents)	Car (%)	Truck/buses (%)
Rubber/elastomers	48	43
Carbon black	22	21
Metal	15	27
Textile	5	–
Zinc oxide	1	2
Sulphur	1	1
Additives	8	6

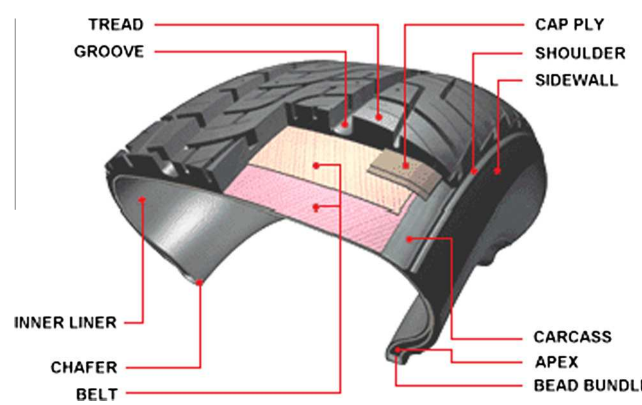

Fig. 2. Tyre structure, adapted from [7].

1.2. From ELTs to Crumb Rubber Modifier

The tyre life cycle traditionally comprises five main stages, which includes extraction, production, consumption, collection of

Table 1
ELTS management trends in the EU, adapted from [1].

	1994 (%)	1996 (%)	1998 (%)	2000 (%)	2002 (%)	2004 (%)	2006 (%)	2008 (%)	2008 (%)
Re-use/export	11	81	11	10	11	9	9	8	10
Reconstruction	10	12	11	11	11	12	11	10	8
Material recovery	6	11	18	19	25	28	34	38	40
Energy recovery	11	20	20	21	27	31	31	37	38
Landfill (disposal)	62	49	40	39	26	20	13	6	4

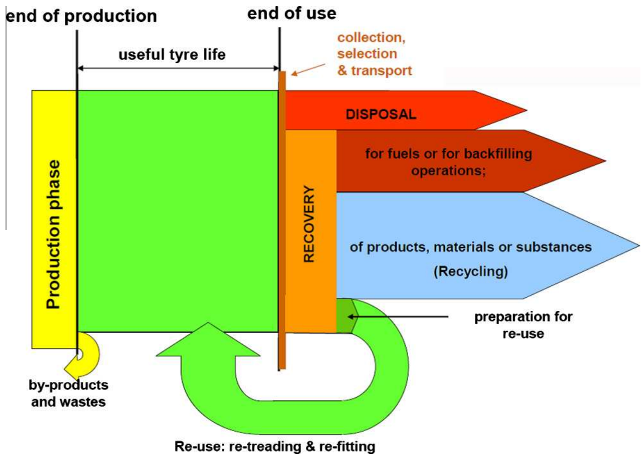

Fig. 3. Life cycle of end of life tyres, adapted from [8].

used tyres and waste management. A simplified version of the tyre cycle is illustrated in Fig. 3. After the collection of ELTs, the next stage includes landfilling and recovery. Worldwide there has been a continuous decline in landfilling used tyres, while the recovery routes include different options such as: "energy recovery" where ELTs having a calorific value equivalent to that of good quality coal are used as an alternative to fossil fuels, or "chemical processing" such as pyrolysis, thermolysis and gasification, (the economic viability of these options has yet to be proved) and finally "granulate recovery". The latter involves tyre shredding and chipping processes which is carried out by using large machinery that cuts up tyres into small pieces of different sizes. At this stage, after the removal of the steel and fabric components, the material RTR can be used for a variety of civil engineering projects: rubberised asphalt pavements, flooring for playgrounds and sports stadiums, as shock absorbing mats, paving blocks, roofing materials, etc.

The size of the tyre shreds may range from as large as 460 mm to as small as 25 mm, with most particles within the 100 mm to 200 mm range, while the tyre chips range from 76 mm down to approximately 13 mm. By further reducing the size of shreds and chips, it is possible to produce Ground and Crumb Rubber, also known as size-reduced rubber, which are suitable to be re-used in the asphalt industry. Crumb Rubber Modifier (CRM) is the common name used to identify the RTR particles used to modify bitumen. It is important to recognize that today CRM is typically a highly controlled material. The process is no longer just grinding up a stockpile of ELTs and adding the rubber to hot asphalt. The handling and shredding process is carefully planned and monitored to produce a clean and highly consistent rubber material. During the process, the tyre's reinforcing wire and fiber is removed. The steel is removed by magnets and the fiber is removed by aspiration. The resulting rubber particles are consistently sized and very clean. Automated bagging systems help ensure proper bag weights and eliminate cross contamination [9].

There are several technologies to reduce ELTs in CRM.

1.2.1. Ambient grinding

This is a method of processing where scrap tyre is ground or processed at or above ordinary room temperature. Ambient processing is typically required to provide irregularly shaped, torn particles with relatively large surface areas to promote interaction with the paving bitumen. This is a mechanical grinding, performed by means of rotating blades and knives, in which the critical step is the separation of the fibers, amongst which are generally included steel fibers. Once separated from the metallic material, ambient grinding is able to produce rubber crumbs with grain size ranging from 5 to 0.5 mm. Ambient grinding is the most commonly used and probably the most cost effective method of processing end of life tyres. A schematic representation of ambient grinding is shown in Fig. 4.

1.2.2. Cryogenic grinding

As shown in Fig. 5, this process uses liquid nitrogen to freeze the RTR (typically between −87 to −198 °C) until it becomes brittle, and then uses a hammer mill to shatter the frozen rubber into smooth particles with relatively lower surface area (Fig. 6) than those obtained by ambient grinding (Figs. 7 and 5). Oliver [10] showed that several characteristics of the rubber granulate determine the elastic properties of the Crumb Rubber and those conferred on the final mix: they enhance with the decrease of specific gravity and particle size, and increase with the higher surface porosity of the granules. In fact, in wet process, rubber particles with a smooth surface, showed reduced reaction with the bitumen and worst the elastic properties of the mixture, if compared with those obtained by using granules with bigger porous surfaces and less specific weight. As a result, the use of CRM from cryogenic process in bituminous mixtures is discouraged [11]. A comparison between the properties of cryogenic and ambient ground rubber is summarised in Table 4.

1.2.3. Other processes

In addition to conventional ambient grinding techniques and the cryogenic process, there other less common proprietary processes currently in use to reduce RTR in crumbs or fine powder to be used as CRM:

- *Wet-grinding* is a patented grinding process in which tiny rubber particles are further size reduced by grinding into a liquid medium, usually water. Grinding is performed between two closely spaced grinding wheels. The obtained fine mesh RTR is mainly used as bitumen modifier [12].
- *Hydro jet size reduction*. This is a technique of processing RTR into finer particles with the help of pressurised water. Water jets at very high operating pressure (around 55.000 psi) rotate in high speed arrays producing clean, wire-free rubbers crumbs (Fig. 8). However, the process protocol is relatively new and still unknown to most in the industry. Nevertheless the high level of roughness of the resulting rubber crumbs makes this product very much attractive for bitumen modification. Fig. 8 shows an example of a microscopic analysis of crumbs obtained through a patented hydro jet size reduction process.

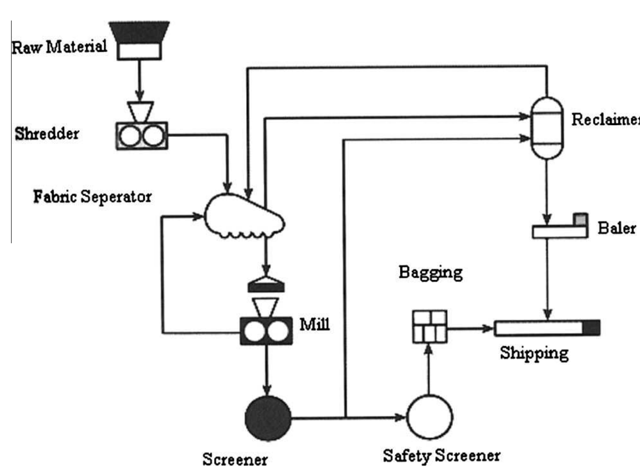

Fig. 4. Schematic representation of ambient grinding, adapted from [3].

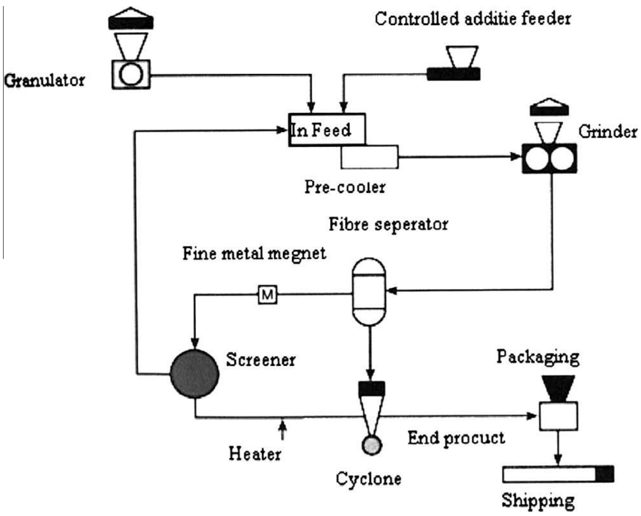

Fig. 5. Schematic representation of cryogenic grinding, adapted from [3].

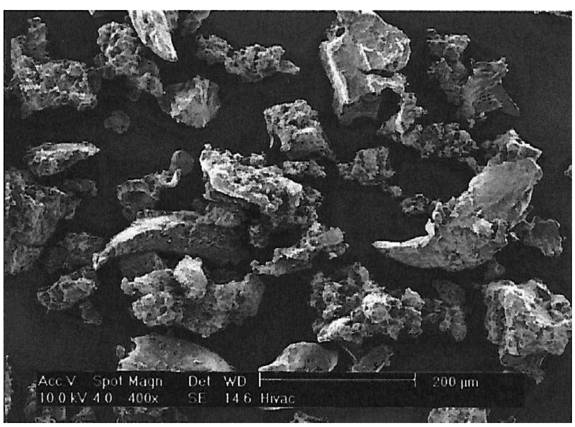

Fig. 6. Ambient rubber crumbs. SEM analysis at 200um and 400x magnification, adapted from [12].

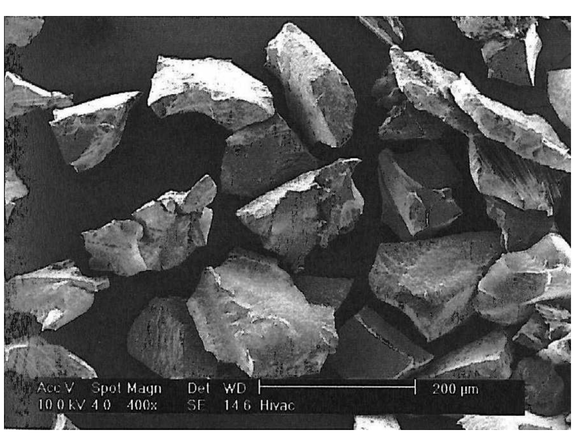

Fig. 7. Cryogenic rubber crumbs. SEM analysis at 200um and 400x magnification, adapted from [12].

1.3. History of RTR in road asphalt mixtures

The accumulation of ELTs and premature pavement failures are both interconnected and dependant of each other due to enormous increase in traffic density and axle loading respectively. The use of RTR in asphalt pavements started 170 years ago, with an experiment involving natural rubber with bitumen in the 1840s [13], attempting to capture the flexible nature of rubber in a longer lasting paving surface. In 1960s scrap tyres were processed and used as a secondary material in the pavement industry. One application was introduced by two Swedish companies which produced a surface asphalt mixture with the addition of a small quantity of ground rubber from discarded tyres as a substitute for a part of the mineral aggregate in the mixture, in order to obtain asphalt mixture with improved resistance to studded tyres as well as to snow chains, via a process known as "dry process" [14]. In the same period Charles McDonalds, a materials engineer of the city of Phoenix in Arizona (USA), was the first to find that after thoroughly mixing crumbs of RTR with bitumen (CRM) and allowing it to react for a period of 45 min to an hour, this material captured beneficial engineering characteristics of both base ingredients. He called it Asphalt Rubber and the technology is well known as the "wet process" (Fig. 9). By 1975, Crumb Rubber was successfully incorporated into asphalt mixtures and in 1988 a definition for rubberised bitumen was included in the American Society for Testing and Materials (ASTM) D8 and later specified in ASTM D6114-97. In 1992 the patent of the McDonald's process expired and the material is now considered a part of the public domain. Furthermore, in 1991, the United States federal law named "Intermodal Surface Transportation Efficiency Act" (then rescinded), mandated its widespread use, the Asphalt-Rubber technology concept started to make a "quiet come back" [15]. Since then, considerable research has been done worldwide to validate and improve technologies related to rubberised asphalt pavements.

Nowadays, these rubberised bitumen materials, obtained through the wet process, have spread worldwide as solutions for different quality problems (asphalt binders, pavements, stress absorbing lays and inlayers, roofing materials, etc.) with much different evidence of success demonstrated by roads built in the last 30 years.

Table 4
Comparison between ambient and cryogenic ground rubber.

Physical property	Ambient	Cryogenic
Specific gravity	Same	Same
Particle shape	Irregular	Regular
Fibre content	0.5%	Nil
Steel content	0.1%	Nil
Cost	Comparable	Comparable

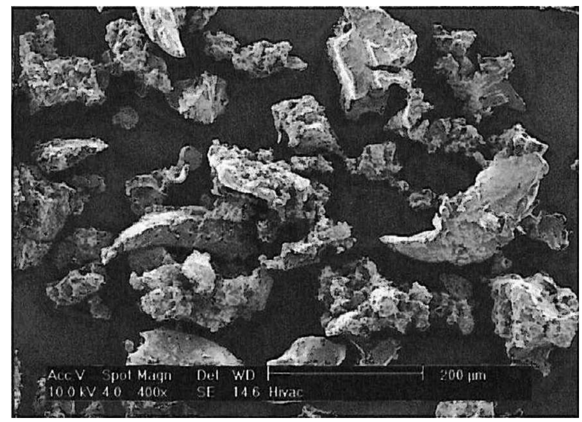

Fig. 8. Hydrojet rubber crumbs. SEM analysis at 200um and 400x magnification, adapted from [12].

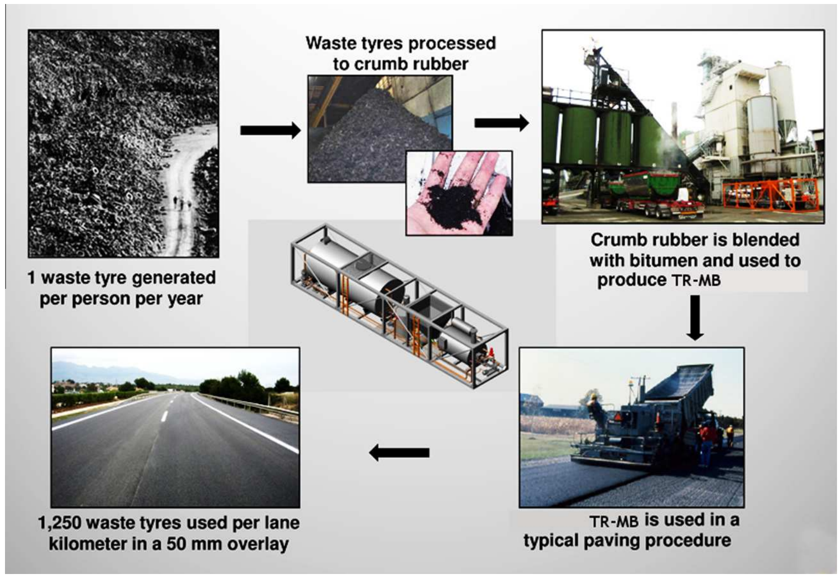

Fig. 9. Scheme of rubberised asphalt production through the "wet process".

2. Recycled Tyre Rubber Modified Bitumens (RTR-MBs)

2.1. Geography of RTR-MBs in road asphalt mixtures

Since the invention of McDonald, the wet process technology has been used and modified more widely in four states in the US: Arizona, California, Texas, and Florida. More recently wet process has been used also in South Carolina, Nevada and New Mexico. The preference for using this particular modifier was due to the fact that not only does the utilisation of ELTs solve environmental problems but it also offers other benefits such as increased skid resistance, improved flexibility and crack resistance, and reduced traffic noise [16].

South Africa and Australia started introducing bitumen–rubber as a binder for asphalt and for seals from the early 1980s and mid 1970s respectively. In South Africa, both wet and dry processes were reported to have been used successfully although the dry process was mainly used in asphalt [17]. Two states in Australia (New South Wales and Victoria) adopted the wet process for limited application of rubberised asphalt, mainly as a crack resisting layer, but otherwise its usage has been predominantly for sprayed seal applications [18].

In Europe wet rubberised asphalt has been successfully used in road pavements application since 1981 in Belgium, as well as in France, Austria, Netherlands, Poland and Germany [19], more recently also in Greece [20] and UK [21], but the countries with a higher numbers of applications are Portugal [22], Spain [23], Italy [24], Czech Republic [25] and Sweden [26].

Nowadays the rubberised asphalt technology is being adopted in many other parts of the world: As reported by Widyatmoko and Elliot [18], Taiwan was reported to have adopted the Arizona DOT gap-graded and open-graded rubberised asphalt mixtures for flexible pavement rehabilitation; furthermore, rubberised asphalt has been trialled in Beijing and for use in new and maintenance work as part of the preparation for the 2008 Olympics in China and it has also been used in EcoPark Project in Hong Kong. On the basis of first positive experiences also Brazil [27] and Sudan [28] are strongly investing in the application of this technology for road pavements.

2.2. Overview of the bitumen – RTR interaction process

The term "wet process" refers to a whole family of technologies which varies a lot with regards with the chosen processing

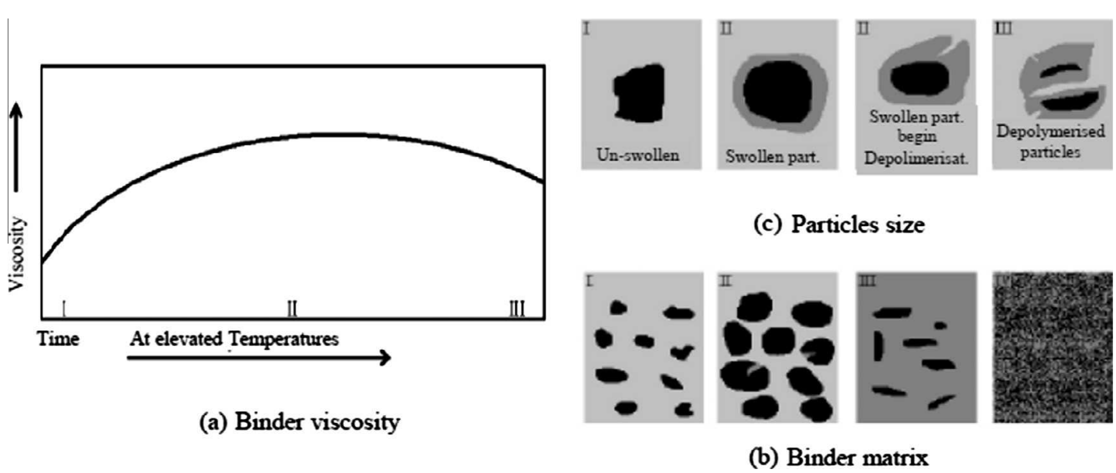

Fig. 10. Bitumen-RTR interaction phenomenon at elevated temperatures: change of properties over time. Adapted from [31].

conditions. The nature of the mechanism by which the interaction between bitumen and CRM takes place has not been fully characterised. Traditionally it is reported that bitumen–rubber interaction is not chemical in nature [13], but other studies claim that the increase in binder viscosity cannot be accounted for only by existence of the rubber swelling particles [29].

The reaction itself is made up of two simultaneous processes (Fig. 10): partial digestion of the rubber into the bitumen on one hand and, on the other, adsorption of the aromatic oils available in this latter within the polymeric chains that are the main components of the rubber, both natural and synthetic, contained in the RTR. The absorption of aromatic oils from the bitumen into the rubber's polymer chains causes the rubber to swell and soften [30].

Rubber particles are swollen by the absorption of the bitumen oily phase at high temperatures (160–220 °C) into the polymer chains, which are the key components of the RTR-MB to form a gel-like material. Therefore, during the reaction there is a contemporaneous reduction in the oily fraction and an increase of rubber particle sizes with a consequent reduction of the inter-particle distance. This implies the formation of gel structures that produce a viscosity increase up to a factor of 10 [13].

Rubber reacts in a time–temperature dependent manner. If the temperature is too high or the time is too long, the swelling will continue to the point where, due to long exposure to the high temperatures, swelling is replaced by depolymerisation/devulcanisation which causes dispersion of the rubber into the bitumen. Depolymerisation starts releasing rubber components back to the liquid phase causing a decrease in the complex modulus (G^*), which is related to the material stiffness, while the the phase angle (δ), related to the elastic properties, continue to modify (Fig. 10a and b). If temperature is high or time is long enough, depolymerisation will continue causing more destruction of the binder networking and so δ modification is lost [32]. The interaction between bitumen and rubber materials is material-specific and depends on a number of basic factors, including:

- Processing variables: temperature, time and device (applied shear stress).
- Base binder properties: bitumen source and eventual use of oil extenders.
- RTR properties: source, processing methods, particle size and content.

These variables represent the processing/interaction conditions that are necessary to monitor during the mixing of rubber within bitumen in order to govern the modification process. RTR-MBs are extremely dependent on the variability of these processing conditions, particularly to what concerns the temperature and time of reaction [33]. Moreover, RTR-MBs must be properly designed and, where necessary, produced to comply with specifications and provide a quality product suitable for the expected climate and traffic conditions. Depending on the adopted processing system, on the chosen processing conditions and on the selected materials, the wet process leads to different technologies as explained in the next sections.

2.3. Terminology associated with RTR-MBs

On the grounds of research done around the globe, rubberised bitumen is used as a general term to identify a group of concepts that incorporate RTR into bituminous binders for paving applications. These terms refer to the uses of RTR, in form of CRM as modifying agent in bitumen, that are different in their mix composition, method of production or preparation and in their physical and structural properties. The method of modifying bitumen with CRM produced from scrap tyres and other components as required before incorporating the binder into the bitumen paving materials, is referred to as the 'wet process'. Wet process is obtainable through two different processing systems.

2.3.1. McDonald process

This terminology is related to the system of producing RTR-MB with the original wet process proposed by Charles McDonald in the 1960s. The McDonald blend is a Bitumen Rubber blend produced in a blending tank by blending Crumb Rubber and bitumen. This modified binder is then passed to a holding tank, provided with augers to ensure circulation, to allow the reaction of the blend for a sufficient period (generally 45–60 min). The reacted binder is then used for mix production (Fig. 11).

2.3.2. Continuous blending-reaction systems

This system is similar to the McDonald process of blending, the difference is that CRM and bitumen are continuously blended during the mix production or prepared by hand and then stored in storage tanks for later use. Therefore, it consists of a unique unit with agitators, in which the reaction occurs during the blending [13].

2.3.3. Field blends

Bitumen-RTR blends are typically produced at the asphalt plant by incorporating some modifications to the existing asphalt plant, for this reason they can be identified as field-blends. The above mentioned modifications include the introduction/adaptation of heated blending tanks, heated reaction tanks, rubber feed and storage tanks [13]. Hence, it is already few years that field-blended RTR-MBs can also be blended through less drastic modification to

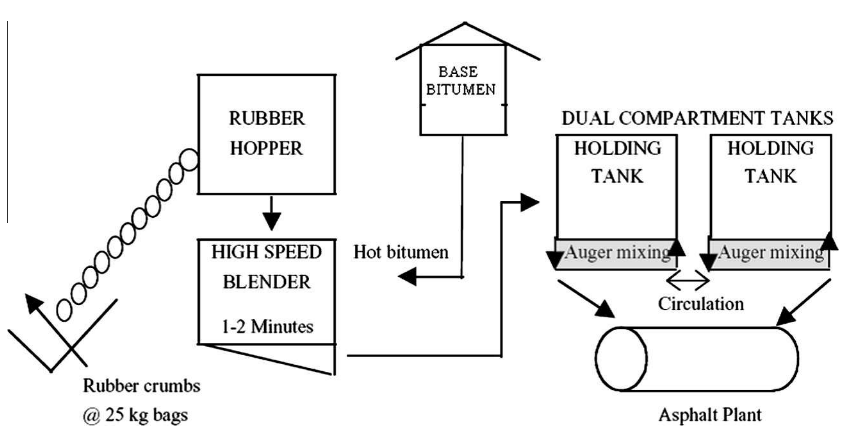

Fig. 11. Schematic diagram of McDonald's wet process.

a standard hot mix asphalt plant through the portable production unit based on the McDonald system. The equipment is typically trailer mounted and is transported into the asphalt plant site. The blending unit receives ground rubber in the hopper, the rubber then moves to the mixing chamber to be blended with virgin liquid bitumen (Fig. 12); the resulting rubberised bitumen is stored in the Portable Reaction Tank (Fig. 13). Once reacted, binder is moved to a second compartment where it is fed to the hot-mix plant to be included in the HMA production. At the end, conventional paving equipment without modifications is used to place the material.

2.3.4. Terminal blends

The terminal blended rubberised binder consists of bitumen with Crumb Rubber Modifier (CRM) binder which is digested into the bitumen at the refinery (Fig. 14) or at a bitumen terminal and then delivered to the plant. These binders are blended with various patented processes and they could present problems of phase separation.

2.3.5. Caltrans terminology

The most important distinction among the various rubberised bitumens seems to be related to the ability of obtaining a homogeneous RTR-MBs which do not present the issue of phase separation during storage periods. Based on this distinction, Caltrans [36] divides the wet process into two families linked to two very different types of RTR modification currently in use: the "wet process-high viscosity" and the "wet process-No-Agitation". To promote a clear understanding, a detailed description of these technologies is provided in the next paragraphs.

3. Wet process-high viscosity

The original wet process-high viscosity, invented by Charles McDonald, leads to a product with a series of benefits which are basically all linked to the binder's increase in elasticity and viscosity at high temperatures that allows greater film thickness in paving mixes without excessive drain down or bleeding. According to Caltrans [36], the RTR-MB that maintain or exceed the minimum rotational viscosity threshold of 1500 cPs at 177 °C (or 190 °C) over the interaction period should be described as "wet process-high viscosity". These materials require continue agitation, with special equipment, to keep the RTR particles uniformly distributed. They may be manufactured in large stationary tanks or in mobile blending units that pump into agitated stationary or mobile storage tanks to be used directly at the job site. Phase separation is a big issue of these binders that needs therefore to be produced directly on the job-site or rarely transported to the field within tanks equipped with special augers, For this reason, these blends are often well-known as *Field blends.*

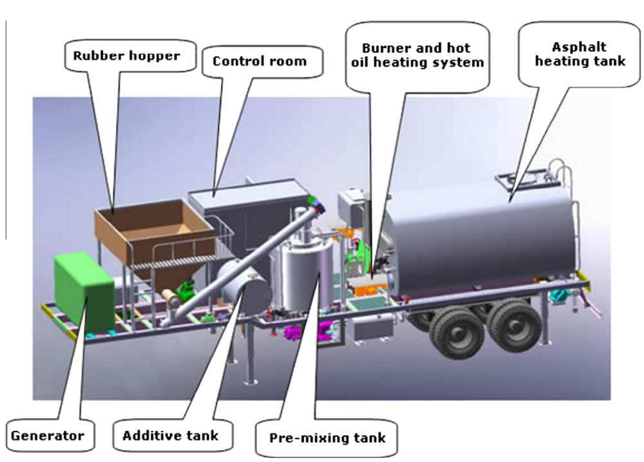

Fig. 12. Example of mobile Mixing unit for Asphalt-Rubber, adapted from [34].

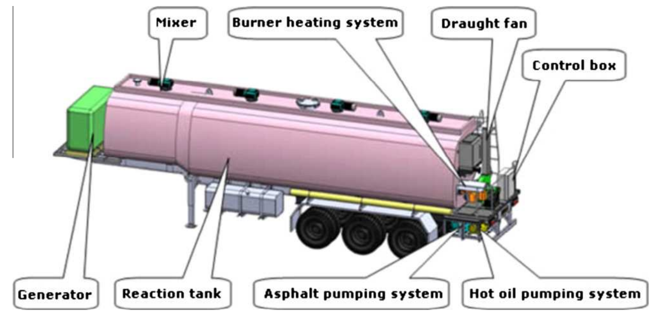

Fig. 13. Example of mobile reaction tank for Asphalt-Rubber, adapted from [34].

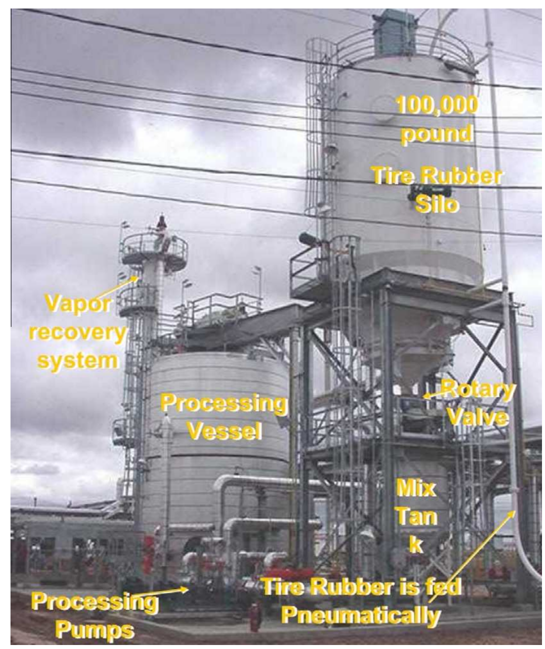

Fig. 14. Terminal blend binder system, adapted from [35].

Wet process-high viscosity binders typically require at least 15% CRM to achieve the threshold viscosity. However, for some specifications [36] the viscosity requirements are meet also with less than 15% of RTR content. A number of RTR-MBs and mix specifications have been developed based on this original idea and each of them is related to a specific technology. This section will describe each of these technologies listed in Table 5 by providing a step by step framework to operate an appropriate plan production and storage of these materials. At last, this paragraph will provide an overview of the benefits and limitations related to the wet process-high viscosity.

Table 5
Existing specifications for rubberised asphalt mixtures.

Technologies	Specifications	Country
Asphalt-Rubber binder	ASTM D6114/D6114 M, [4] Caltrans' Asphalt-Rubber user guide, [5]	USA
Bitumen Rubber binder	SABITA Manual 19, [6] AsAc Technical Guideline, [7]	RSA
Crumb Rubber binder	Austroads, [8]	AUS and NZ

3.1. Asphalt-Rubber binder (USA)

According to the ASTM D6114 [37], Asphalt-Rubber is "a blend of asphalt cement, CRM and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles".

3.1.1. CRM requirements

According to ASTM D6114, in order to produce Asphalt-Rubber, the rubber should have the following characteristics:

- Less than 0.75% moisture and free flowing.
- Specific gravity of 1.15 ± 0.05.
- No visible nonferrous metal particles.
- No more than 0.01% ferrous metal particles by weight.
- Fibre content shall not exceed 0.5% by weight (for hot mix binder applications).
- Recommends all rubber particles pass the No. 8 (2.36 mm) sieve.
- (Note that Rubber gradation may affect the physical properties and performance of Bitumen Rubber hot mix).

Caltrans (2006) specifies that CRM to be used as modifier must include 25 ± 2% by mass of high natural rubber and 75 ± 2% of CRM from scrap tyre. Both types of rubber must meet specific chemical and physical requirements including gradation and limits on fabric and wire contaminants. The RTR consists primarily of 2 mm to 600 μn sized particles (No. 10 to No. 30 sieve sizes). The high natural rubber CRM is somewhat finer, mostly 1.18 mm to 300 urn sieve sizes (Table 6).

3.1.2. Base binder requirements

ASTM D6114 specifies three different types of Asphalt-Rubber. Each of them is associated to a suitable bitumen to be used as base of modification

- Type-I binders typically include stiffer base bitumen and are generally recommended for hot climates, such as: AC-20, AR-8000 and PG64-16.
- Type-II binders typically include base bitumen softer than Type-I and are generally recommended for moderate climates, such as: AC-10, AR-4000 and PG58-22.
- Type-III binders typically include the softest grade base bitumen and are generally recommended for cold climates, such as: AC-5, AR-2000 and PG52-28.

where AC (asphalt cement) and AR (Aged Residue) are referred to the American grading systems based on viscosity. For example, an AC 20 asphalt has a viscosity of 2000 poise (+20%) at 60 °C, whilst an AR 4000 bitumen has a viscosity of 4000 poise (+25%) at 60 °C after aging. A rough comparison between penetration and viscosity (AC and AR) bitumen grades is shown in Fig. 15.

Table 6
Typical gradation of the RTR to be used in the Asphalt-Rubber binder, adapted from [38].

Sieve #	Nominal size (mm)	% Passing
10	2.36	100
16	1.18	75–100
30	600 μm	25–100
50	300 μm	0–45
100	150 μm	0–10
300	75 μm	0

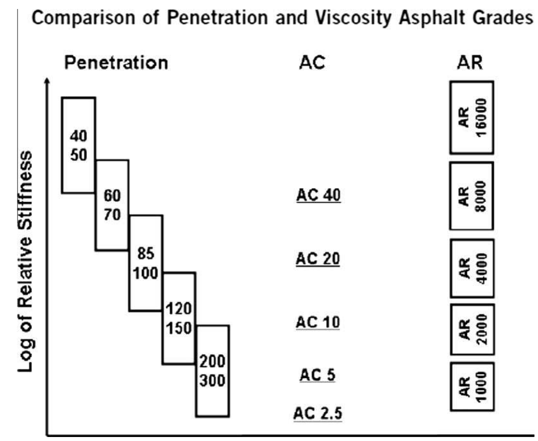

Fig. 15. Comparison of Penetration and Viscosity bitumen grades.

3.1.3. Asphalt-Rubber plant production

By definition, Asphalt-Rubber is prepared using the "wet process-high viscosity" system. Physical property requirements are listed in ASTM D 6114, "Standard Specification for Asphalt-Rubber binder" (Table 8). The Asphalt-Rubber is produced at elevated temperatures (⩾350 F, 177 °C) in low shear (Shatanawi, 2010) to promote the physical interaction of the asphalt binder and rubber constituents, and to keep the rubber particles suspended in the blend. Various petroleum distillates or extender oil may be added, at a rate of 2.5–6% by mass of the bitumen binder, to reduce viscosity, facilitate spray applications, and promote workability. Field production of high viscosity Asphalt-Rubber binders is a relatively straightforward process and it is still based on the McDonald process (Fig. 11). Equipment for feeding and blending may differ among Asphalt-Rubber types and manufacturers, but the processes are similar. The component materials are metered into high shear blending units to incorporate the correct proportions of extender oil and CRM into the paving grade asphalt. The blending units thoroughly mix the CRM into the hot asphalt cement and extender oil, and the blend is pumped into a heated tank where the Asphalt-Rubber interaction proceeds.

RTR is usually supplied in 1 ton (0.91 tonne) super sacks that are fed into a weigh hopper for proportioning. Augers are needed to agitate the Asphalt-Rubber inside the tanks to keep the CRM particles well dispersed, otherwise the particles tend either to settle to the bottom or float near the surface. Agitation can be verified by periodic observation through the top hatch or the port where the auger control is inserted. The Asphalt-Rubber binder must be interacted with agitation for a minimum of 45 min at temperatures from 190 to 218 °C to achieve the desired interaction between bitumen and rubber. In order to maintain the reaction temperature within the specified range, the bitumen must be hot, 204–224 °C before the design proportions of scrap tyre CRM and high natural rubber CRM are added. This is because the CRM is added at ambient temperature (not heated) and reduces the temperature of the blend. The component materials are metered into blending units to incorporate the correct proportions of CRM into the bitumen, and are thoroughly mixed. The Asphalt-Rubber producer is allowed to add the extender oil while adding the rubber, although in some cases the base binder may be supplied with the extender included. If the Asphalt-Rubber producer adds the extender oil, use of a second meter is recommended to best control the proportioning. The meter for the extender oil should be linked to that for the bitumen. An Asphalt-Rubber binder interacted at lower temperatures will never achieve the same physical properties as the laboratory design, although it may achieve the minimum specification values for use. Hand held rotational viscometers are used to monitor the

Table 7
Caltrans specification for rubberised bitumen [36].

Test parameter	Specification limits
Apparent viscosity, Haake, 190 °C: cp	1500–4000
Cone penetration at 25 °C (ASTM D217): dmm	25–70
Softening point (ASTM D36): °C	52–74
Resilience at 25 °C (ASTM D3407): %	Minimum 18

viscosity of the Asphalt-Rubber interaction over time for quality control and assurance. Before any Asphalt-Rubber binder can be used, compliance with the minimum viscosity requirement must be verified using an approved rotational viscometer (e.g. Brookfield). As long as the viscosity is in compliance and the interaction has proceeded for at least 45 min, the Asphalt-Rubber may be used [36].

Caltrans (2006) recognises that before starting the plant production, an appropriate Asphalt-Rubber binder design must be developed (Table 7). It also specifies that at least 2 weeks prior to start of construction the Contractor must supply to the Engineer, for approval, an Asphalt-Rubber binder formulation (design or "recipe") that includes results of specified physical property tests, along with samples of all of the component materials. Samples of the prepared Asphalt-Rubber binder must also be submitted to the Engineer at least 2 weeks before it is scheduled for use on the project.

3.1.4. Asphalt-Rubber storage

Caltrans requires heating to be discontinued if Asphalt-Rubber material is not used within 4 h after the 45-min reaction period. The rate of cooling in an insulated tank varies, but reheating is required if the temperature drops below 190 °C. A reheat cycle is defined as any time an Asphalt-Rubber binder cools below and is reheated to 190–218 °C. Caltrans allows two reheat cycles, but the Asphalt-Rubber binder must continue to meet all requirements, including the minimum viscosity.

Sometimes the binder must be held overnight. The bitumen and rubber will continue to interact at least as long as the Asphalt-Rubber remains liquid. The rubber breaks down (is digested) over time, which reduces viscosity. Up to 10% more CRM by binder mass can be added to restore the viscosity to specified levels. The resulting Asphalt-Rubber blend must be interacted at 190–218 °C for 45 min and must meet the minimum viscosity requirement before it can be used.

3.2. Bitumen Rubber binder (RSA)

Bitumen Rubber binder is a terminology used for the rubberised bitumen obtained by the wet process in South Africa. Bitumen Rubber binders combine rubber crumbs (Table 9) with bitumen at high temperatures to achieve a complex two phase product, named non-homogeneous binder. In the Technical Guideline of the South African Asphalt Acadamey [38], is also reported that properties of the modified binder used in hot mix asphalt will influence the engineering properties of the resultant mix, therefore the substitution of a conventional bitumen with a modified binder can result in higher air voids due to reduced workability of the higher viscosity modified binders. For this reason, it is important that split samples of the modified binder are sent to all the participating laboratories (e.g.: supplier, site and control laboratories) and tested before commencement of a project to ensure that the results are within the reproducible limits as prescribed by the test methods.

Table 9
Rubber crumbs requirements for bitumen–rubber, adapted from [38].

Property	Requirement	Test method
Sieve analysis (% mass)		MB-14
Passing screen (mm)		
1.180	100	
0.600	40–70	
0.075	0–5	
Poly-isoprene content (%m/m total hydrocarbon)	25 min	Thermo gravimetric Analysis
Fibre length (mm)	6 max	
Bulk density (g/cm^3)	1.10–1.25	MB-16

3.2.1. Rubber requirements

In South Africa, the Committee of Land Transport Officials (COLTO)'s specification requires the reclaimed rubber to have not less than 30% natural rubber by mass of hydrocarbon content [39], whilst the SABITA Manual [40] and the Technical Guideline of the South African Asphalt Acadamey [38] specify 60–75% natural rubber by mass of hydrocarbon content, with all rubber particles passing the 1.18 mm sieve. The CRM is produced by a mechanical size reduction process. CRM produced by cryogenic-mechanical techniques are not permitted in South Africa. The CRM must be pulverised, free of fabric, steel cords and other contaminants.

3.2.2. Base bitumen requirements

The binder used in the production of the bitumen–rubber must be SABITA B12 or B8 road-grade bitumen (60/70 or 80/100 penetration-grade bitumen respectively) or a blend of these grades to provide a product with a particular viscosity and other prescribed properties.

3.2.3. Bitumen Rubber production

The binder is manufactured from blending penetration grade bitumen (72–82% by mass), plus extender oil (0–4%) plus rubber crumbs (18–24%) in a patented high shear mixer with a speed of

Table 8
Specification for Asphalt-Rubber [37].

Binder specification	ASTM D6114 (2009)		
	Type I	Type II	Type III
Apparent viscosity 177.5 °C (ASTM D 2196): cp	1500–5000	1500–5000	1500–5000
Penetration at 25 °C (ASTM D5): dmm	25–75	25–75	50–100
Penetration at 4 °C (ASTM D5): dmm	Min 10	Min 15	Min 25
Softening point (ASTM D36): °C	Min 57.2	Min 54.4	Min 51.7
Resilience at 25 °C (ASTM D5329): %	Min 25	Min 20	Min 10
Flash point (ASTM D93): °C	Min 232.2	Min 232.2	Min 232.2
After TFOT (ASTM D1754), residual penetration at 4 °C (ASTM D5): %	Min 75	Min 75	Min 75
Climatic region	Hot	Moderate	Cold
Average minimum monthly temperature: °C	Min −1	Min −9	Min −9
Average maximum monthly temperature: °C	Min 43	Max 43	Max 27

3000 r.p.m, at a temperature in excess of 180 °C but not more than 220 °C and for short periods before the introduction of rubber. During the addition of the rubber component, the blend cools down considerably and has to be re-heated to a temperature of 190–200 °C to ensure proper digestion of the rubber in the bitumen. Special manufacturing equipment is required to manufacture this highly viscous material. The product has a limited useable life of 4–6 h and, therefore, manufacture usually takes place onsite, or very close to the construction site. Bitumen Rubber binder can be used for surface dressing operations, in which case it is applied with binder distributors specially designed to handle this highly viscous binder. For surface dressing applications, the bitumen–rubber binder is manufactured using the "wet process", which is also the most used for the manufacture of bitumen–rubber hot-mix asphalt. The blending unit consists of a small tank equipped with a high speed stirring device that ensures proper "wetting" of the rubber by the binder and prevents the formation of rubber lumps in the final product. From the blending tank the product is transferred to a digestion tank which could also be a specialised binder distributor. In the digestion tank the product is continually agitated while being heated to the final temperature.

The ratio of components varies depending on the bitumen source, the climatic conditions and the application. The more reliable manufacturers in South Africa nowadays prefer to standardise on 20% rubber content and also to preselect the type of tyres for the modification process. Following the addition of the rubber, a digestion period is required for the rubber to swell and partially dissolve in the bitumen/extender oil blend. The rubber never completely dissolves in the bitumen and the product is thus classed as a non-homogenous binder. The Bitumen Rubber blend is then circulated in a holding tank and heated at high temperatures (190–210 °C) to facilitate the chemical digestion process.

The extender oil could either be added to the penetration grade bitumen before delivery or to the bitumen on site. The requirements of the extender oil are such that it should have a flash point of greater than 180 °C and the percentage by mass of aromatic unsaturated hydrocarbons be greater than 55. To prevent sticking of rubber particles, also an addition of calcium carbonate or talc up to 4% by mass of rubber is permitted. On completion of the digestion period, a hand-held viscometer is used to perform a viscosity test on the product to confirm that sufficient digestion has taken place (Table 10). If approved, the product is ready for application [38].

3.2.4. Bitumen Rubber storage

Bitumen Rubber degrades rapidly at application temperatures which are in excess of 200 °C. Therefore the blending of Bitumen Rubber generally takes place in close proximity to the spray site or asphalt mixing plant. On completion of the digestion period, the product generally has a further useable life at the application temperature of approximately 4 h. The rate of degradation will vary depending mainly on the application temperature and can be monitored on-site with a hand held viscometer. The manufacturer of the Bitumen Rubber should supply temperature curves showing the changes in the properties over time.

Fig. 16 shows typical changes in the viscosity properties of a Bitumen Rubber at different temperatures over time. Only sufficient quantities of Bitumen Rubber should be blended at any time in accordance with what can be sprayed or mixed within the application viscosity window of the product. Allowance must be made for changing weather conditions and construction delays. Proper planning and close cooperation between the supplier and contractor is essential to limit the over production of Bitumen Rubber which may result in unnecessary degradation of the Bitumen Rubber over prolonged periods of heating. Product must not be superheated if it is not going to be used. This will enable the product to be superheated at a later stage for reuse if it is still within specification. If it happens to be out of specification then only 25% of the product can be re-blended with new bitumen and RTR. Table 11 shows the recommended temperatures and time limits for the short-term handling, storing, spraying, mixing and application binders modified with Bitumen Rubber. S-R1 is a Surface Seal, A-R1 is for hot mix while C-R1 is a Crack sealant and all of them are Bitumen Rubber binders.

Table 10
Properties of Bitumen Rubber surfacing seals and asphalt, adapted swfrom [38].

Property		Unit	Test method	Class	
			S-R1	A-R1	
Softening point[1]	°C	MB-17	55–62	55–65	
Dynamic viscosity @ 190 °C	dPa s	MB-13	20–40	20–50	
Compression and recovery	5 min		MB-11	>70	>80
	1 h	%		>70	>80
	4 days			>25	n/a
Resilience @ 25		%	MB-10	13–35	13–40
Flow		Min	MB-12	15–70	10–50

3.3. Crumb Rubber Modified binder (AUS & NZ)

Bitumen technologists in Australia have been looking into using rubber in bitumen since the early 1950s, when a surface dressing trial utilising 5% vulcanised reclaimed rubber in R90 bitumen (100 pen) with 10 mm aggregate was applied on the Prince Highway at St. Peters in New South Wales. However, there was not much development until the mid-1970s, when the Road authority of the state of Victoria (VicRoads) in conjunction with the Australian Road Research Board (ARRB) started using Crumb Rubber Modified bitumen in spray seal in urban and rural applications. It has been used extensively as a bitumen modifier in sprayed bituminous seals and occasionally in bitumen applications in Victoria. Thanks to this experience VicRoads, in collaboration with the Roads and Traffic Authority (RTA), New South Wales and the Main roads by Western Australia, have prepared the "Scrap rubber bitumen guide".

Since 1986, success has been reported using rubberised bitumen in Australia, mainly RTA and VicRoads, specifically when used as a crack resisting layer, e.g. thin bitumen overlay over concrete, Stress Absorbing Membranes or Stress Absorbing Membranes Interlayers. In 2006, Austroads published technical specifications framework AP-T41 coupled with a guide to the selection and use of Polymer Modified Binders: AP-T42 including the use of rubberised bitumen, identified as Crumb Rubber Modifed binder [41]. The reports suggest a wide usage of rubber into asphalt with both wet and dry process. The AP-T42 guide includes also a "Crumb Rubber Protocol" in which Constituent Specification, Binder Design, Field Blending, Binder Specification Limits and other restrictions regarding and Sampling and Testing to check requirements are indicated.

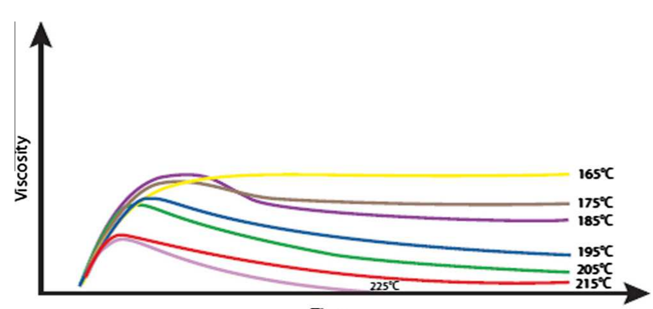

Fig. 16. Typical changes in viscosity values from Bitumen Rubber at different temperatures over time, adapted from [38].

Table 11
Typical temperature/time limits for Bitumen Rubber, adapted from [38].

Binder class	Short term handling		Storage		Spraying/asphalt mixing/application		
	Max temp (°C)	Max holding time (h)	Max temp (°C)	Max holding time (h)	Max temp (°C)	Min temp (°C)	Max holding time (h)
S-R1	165	24	150	240	210	195	Refer to time/viscosity curve
A-R1	165	24	150	240	210	190	
C-R1	165	24	–	–	190	180	–

Table 12
Austroads specification for Crumb Rubber for bitumen modification, adapted from [41].

Test	Methods	Size 16	Size 30
Grading			
Passing 2.36 mm	AG/PT 1:43	100	100
Passing 1.18 mm	AG/PT 1:43	80 (min)	100
Passing 0.60 mm	AG/PT 1:43	10 (max)	40 (max)
Passing 0.15 mm	AG/PT 1:43		5 (max)
Bulk density	AG/PT 1:44	350 kg/m^3	350 kg/m^3
Water content	AG/PT 1:43	<1%	<1%
Steel content	AG/PT 1:43	<0.1%	<0.1%

An important component of this Crumb Rubber specification is the role of laboratory testing as explained later.

3.3.1. CRM requirements

In Austroads (2006), two levels of rubber content, nominally 15 and 18 are specified for Crumb Rubber Modified binder obtained through the wet process. Another level, from 25 to 30% , is designed for the dry process. Crumbs have only 2 sizes, namely 16 (coarse) and 30 (fine). Bulk density (max 350 kg/mc), grading, maximum particle size, steel content (<0.1%), moisture (<1%) and other properties must be specified by the contractor. All CRM shall be less than 3 mm in length and the rubber shall not contain any foreign material such as sand, fibre or aggregate. All this info is summarised in Table 12.

3.3.2. Base bitumen requirements

The only requirements related to the most suitable bitumen to be used as base for the Crumb Rubber Modified binders, is indicated in the "Crumb Rubber Protocol" of the technical guide of Austroads [41], which specifies to use Bitumen Class 170 corresponding to a Penetration grade of 85/100 (Table 13).

3.3.3. Crumb Rubber Modified binder production

As mentioned previously, the Austroads guide for Selection and use of Polymer Modified Binders AP-T42 [41], gives a major importance to the a priori laboratory testing. In fact, the design process requires a laboratory exercise to be undertaken using the following procedure:

1. A trial mix is prepared for each of an appropriate series of rubber concentrations such that the specification limits for the selected binder grade are met in at least one of the mixes (mixing temperature 195 °C, digestion period 45 min for size 16 rubber and 30 min for size 30).
2. The measured properties are plotted against rubber concentration and the concentration at which the specification limits are complied with is identified. This rubber concentration is deemed to be the design concentration.
3. A rubber extraction is performed on the design mix using AG:PT/T1 42 Laboratory method for determining Crumb Rubber concentration. The determined concentration of rubber is used as a check for the analysis of field collected samples.

The diagram in Fig. 17 illustrates the key steps. In the Austroads 2006 specifications, S40R, S45R/S50R and S55R were replaced by S15RF, S18RF, for asphalt application, and S55R was kept for sprayed sealing. Plant protocols may require different procedures to the field defined system and the contractor will be responsible for the binder design. Crumb Rubber Modified binders are produced with production routes: factory and field produced rubberised bitumen.

- *Factory produced Crumb Rubber Modified binders*: usually include combining oil and lower concentrations of rubber than their field produced counterpart. Factory produced Crumb Rubber Modified binder are used for hot mix asphalt by using the wet process. This has been shown to improve the mix properties but requires relatively high binder contents. Since the concentration of rubber is an important performance controlling factor, generally the higher the volumetric concentration, the more effective will be the binder in more demanding applications. Flux oil should only be added to the CRM classes and the manufacturer's recommendations should be followed. It is important to

Table 13
Summary of the most important specification requirements for RTR-MBs.

Properties	ASTM 2009			Caltrans 2006	AsAc 2007	Austroads 2007
	Type I	Type II	Type III			
Base bitumen requirements						
Penetration: dmm	85–100	120–150	200–300	120–150	60–100	85–100
Crumb Rubber requirements						
Passing sieve: mm	2.36			2.36	1.18	2.36
Rubber content: %	⩾15			18–22	18–24	15–18
Additives						
Extender oils: %	–			2.5–6	0–4	–
Caclium carbonate /Talc: %	0–4			–	0–4	–
Processing conditions						
Temperature: °C	177			190–220	180–220	195
Mixing speed: rpm	–			–	3000 rpm	–
Mixing time: min	45 + reaction			45–60	–	30–45

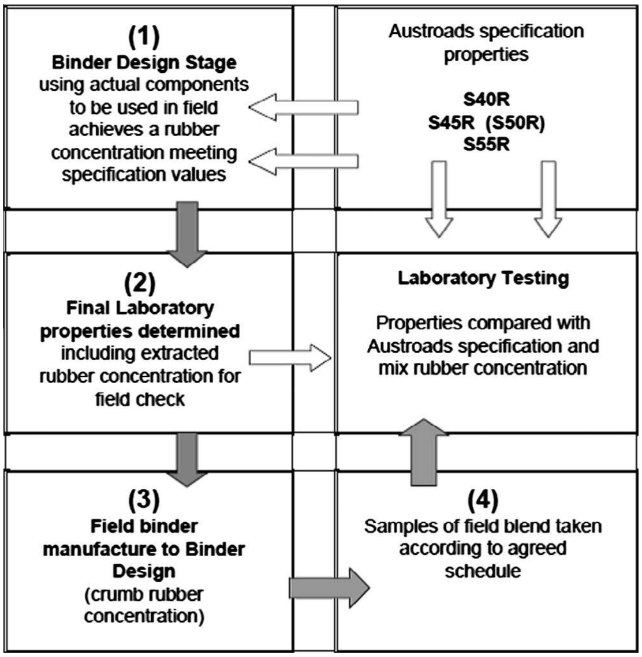

Fig. 17. Austroads laboratory procedure for Crumb Rubber modified binders, adapted from [41].

use the finer CRM in order to achieve a reasonable level of digestion in the binder in the short time that the material remains hot.

- *Field produced Crumb Rubber Modified binders*: are produced for sprayed sealing. They are a high temperature blend of bitumen and CRM without combining oils, and may contain up to 25% by mass of rubber; these formulations are not suitable for long distance transportation or extended storage but represent the highest performing materials within their class when optimally digested. The properties of the field produced rubberised bitumen are generally controlled by their softening point, elastic recovery and/or torsional recovery [41].

3.3.4. Crumb Rubber Modified binder storage

When field mixing Crumb Rubber binders, the material must be continually circulated to minimise settling out of any rubber particles. Failure to do this will most likely result in blockages of the spraying jets and/or pipework. Do not store field produced Crumb Rubber mixtures in bitumen sprayers, road tankers or bulk storage because of the potential problem of segregation and settling out of the rubber particles resulting in blocked pipework etc.

It is worth to highlight that current work in Australia is focussing on the use of Crumb Rubber as a substitute for other modified binders in more conventional applications while using similar design criteria, with particular interest in the use of pre-blended products which behave much more like other pre-blended modified binders. Laboratory investigations with pre-blended Crumb Rubber Modified binders indicate satisfactory performance but at higher binder contents (>8%).

Table 13 summarises some of the most important specifications requirements for the RTR-MB production around the world.

3.4. Wet process-high viscosity: benefits, issues and limitation

Extensive literature clearly shows the numerous successes obtained using rubberised bituminous mixtures produced with the wet process-high viscosity. However, this technology is not a panacea. This section was thought to explain the main benefits provided by the usage of this technology and the issues that still exist and, in some cases, limit its extensive application.

3.4.1. Benefits

The primary reason for using RTR-MBs is that it provides significantly improved engineering properties over conventional paving grade bitumen. As for Asphalt-Rubber binders, they can be engineered to perform in any type of climate as indicated in ASTM D 6114. At intermediate and high temperatures, the RTR-MB shows physical and rheological properties significantly different than those of neat paving grade bitumens. The rubber stiffens the binder and increases elasticity (proportion of deformation that is recoverable) over these pavement operating temperature ranges, which decreases pavement temperature susceptibility and improves resistance to permanent deformation (rutting) and fatigue with little effect on cold temperature properties [36].

As demonstrated by various researchers, RTR-MBs obtained through the wet process have reduced fatigue and reflection cracking, greater resistance to rutting, improved aging and oxidation resistance and better chip retention due to thicker binder films [42–45,39,46]. Also Asphalt-Rubber pavements have been demonstrated to have lower maintenance costs [47], lower noise generation [48–50] higher skid resistance and better night-time visibility due to contrast in the pavement and stripping [51]. A summary of the benefits of using High-viscosity RTR-MBs for road pavement applications is given below:

High Viscosity RTR-MBs have:

- Increased viscosity that allows greater film thickness in paving mixes without excessive drain down or bleeding.
- Increased elasticity and resilience at high temperatures.

High Viscosity RTR-MBs pavements have:

- Improved durability.
- Improved resistance to surface initiated and fatigue/reflection cracking due to higher binder contents and elasticity.
- Reduced temperature susceptibility.
- Improved aging and oxidation resistance due to higher binder contents, thicker binder films, and anti-oxidants in the RTR.
- Improved resistance to rutting (permanent deformation) due to higher viscosity, softening points and resilience (stiffer, more elastic binder at high temperatures).
- Lower pavement maintenance costs due to improved pavement durability and performance.

In addition, High Viscosity RTR-MBs pavements and binders can result in:

- Reduced construction times due to thinner lifts.
- Reduced traffic noise (primarily tyre noise).
- Improved safety due to better long-term colour contrast for pavement markings because carbon black in the rubber acts as a pigment that keeps the pavement blacker longer.
- Savings in energy and natural resources by using waste products and not contributing to the stockpiles.

3.4.2. Limitations

Wet process-high viscosity materials are useful, but they are not the solution to all pavement problems. The Asphalt-Rubber materials must be properly selected, designed, produced, and constructed to provide the desired improvements to pavement performance. Pavement structure and drainage must also be adequate. Limitations on the use of Asphalt-Rubber include [36]:

- High Viscosity RTR-MBs are not best suited for use in dense-graded HMA. There is not enough void space in the dense-graded aggregate matrix to accommodate sufficient rubberised binder content to enhance performance of dense-graded mixes enough to justify the added cost of the binder.
- Construction may be more challenging, as temperature requirements are more critical. Asphalt mixtures with High Viscosity RTR-MB must be compacted at higher temperatures than dense-graded HMA because, like polymers, rubber stiffens the binders at high temperatures. Also, coarse gap-graded mixtures may be more resistant to compaction due to the stone nature of the aggregate structure.
- Potential odour, also if it seems to not be harmful (see environmental issues).
- It is not possible to store High Viscosity RTR-MB at elevated temperatures without equipping storage tanks with augers or paddles. Furthermore,
- these binders cannot be stored for prolonged period. If work is delayed more than 48 h after blending the High Viscosity RTR-MB may not be usable. Takallou and Sainton [52], said "the rubberised binder must be used within hours of its production". The reason is that if over-processed the CRM will be digested to such an extent that it is not possible to achieve the minimum specified viscosity even if more CRM is added in accordance with specified limits [37].

Economic Issues related to the usage of RTR-MBs have been adequately addressed by a large number of research projects and reports and also through long standing construction evaluation. For the sake of brevity, the most notable are discussed below:

Higher initial costs. Costs are higher than conventional bitumen per unit ton until economies of scale are in place. From a study conducted in the USA by Hicks and Epps [53], it has been experienced that the Asphalt-Rubber hot mix could costs almost double than conventional mixes. Nevertheless, since the year 2000 a falling cost difference trend has been registered, also because costs of construction materials and petroleum products have increased (Fig. 18). Given this change in the cost structure it is easy to observe that High Viscosity RTR-MB is presently very attractive in cost when particularly examined in light of actual usage. With the RTR being a very cheap waste material the RTR-MBs technologies are increasing their appeal also from the economical point of view.

Lifecycle economics. As in any economical evaluation, cost effectiveness should be evaluated using Life Cycle Cost Analysis. Again, Hicks and Epps (2003) showed that evaluating different scenarios, in terms of pavement design, maintenance and rehabilitation strategies, the following was concluded:

- High Viscosity RTR-MB (Asphalt-Rubber) is a cost effective alternate for many highway pavement applications mainly due to the ability to reduce thickness when using rubberised asphalt. But also that,
- High Viscosity RTR-MB (Asphalt-Rubber) was not cost effective in all applications.
- When variability is considered in the inputs (cost, expected life, etc.), the Asphalt-Rubber alternates would be the best choice in most of the applications considered.

Other studies conducted at the Arizona State University [47] compared maintenance and user costs trends for the conventional bituminous pavements and Asphalt-Rubber pavements (Fig. 19). Results showed that after 5 years the maintenance and user costs are not much different, after 10 years the maintenance cost begins to substantially be different, as higher maintenance costs will be anticipated for the conventional pavement. This difference for user costs starts at about 15 years. Based on the data analysis presented for the two pavements, an Asphalt-Rubber pavement would be more cost-effective than a conventional pavement with respect to road authorities costs as well as user costs.

Plant modifications. Another issue that contribute to higher initial cost of the wet process-high viscosity are plant modifications. In case of the production of field blends it is necessary to adapt standard hot mix asphalt plant, for instance with portable units as illustrated in Section 2.3.3. Additionally, conventional paving equipment without modifications is used to place the material.

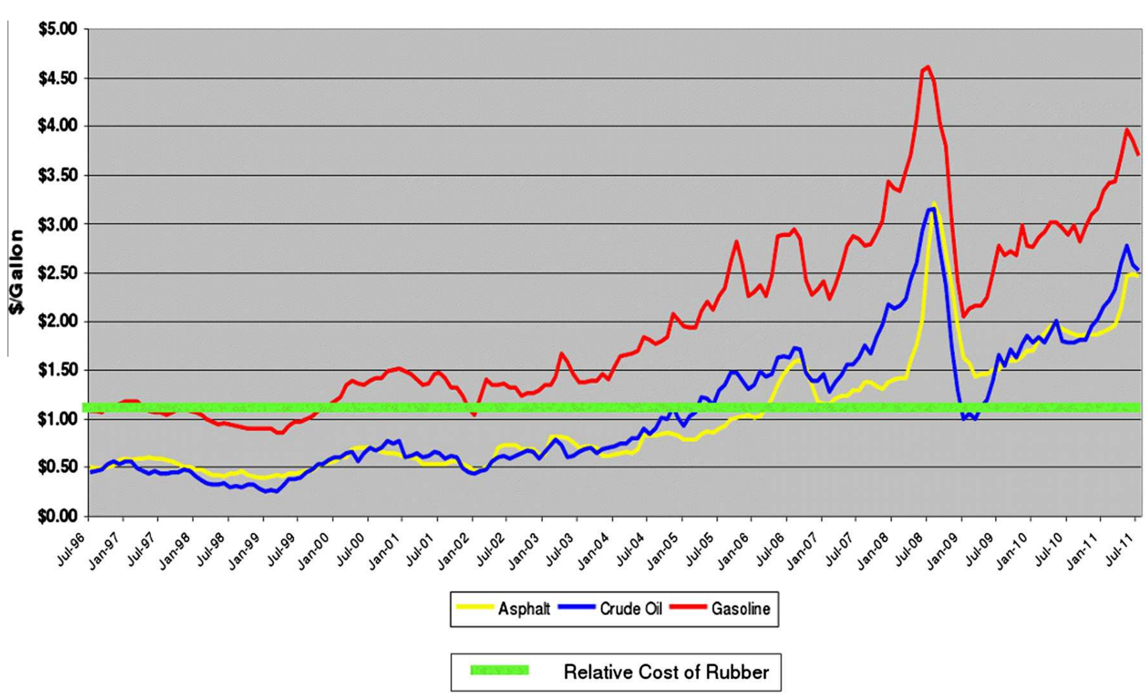

Fig. 18. Crude oil, Fuel, Bitumen and rubber cost's trends, adapted from [54].

From an investigation made in 2007 in UK by the Waste & Resources Action Programme [18] in order to study a possible adoption of this technology, resulted that the approximate cost for importing/hiring and running the blending plant for 5 to 7 days of rubberised bitumen production is estimated to be between £60,000 and £90,000 (70.000–105.000€). This is because none special mixing units described above is currently available in the UK, and therefore requires importing/hiring from either the US or mainland Europe. Moreover, for the installation of a Portable rubberised bitumen mixing plant, an area of not less than 150 m^2 will be required, depending upon the model and make of the mobile plant [18]. It is worth highlighting that mobilisation and set up of the field-blends binder production equipment cost as much for small jobs as for big ones, but large projects spread mobilisation costs over more asphalt tonnage. The memo suggests that smaller projects may not be cost effective with respect to initial cost. Although the break point for project size may have changed since then, unit costs of small projects (three days paving or less) should be evaluated by LCCA during the design phase [36].

3.4.3. Environmental Issues

High Viscosity RTR-MBs provides the obvious environmental benefit of using waste tyres. Nevertheless, their production and their applications in asphalt presents the following issues:

Hazardous Emissions. Fume emissions have been studied extensively in a number of Asphalt-Rubber projects in USA since 1989. Different studies, performed also by the National Institute for Occupational Safety and Health (NIOSH), Federal Highways Administration (FHWA), [55], determined that use of Asphalt-Rubber does not appear to increase health risks to paving personnel. In these studies the following is reported: "...risks associated with the use of Asphalt-Rubber products were negligible" and also "Emission exposures in Asphalt-Rubber operations did not differ from those of conventional asphalt operations" and also "...the effect of CRM on emissions may be relatively small in comparison to the effects of other variables" [36]. Those variables include the fueling rate of the dryer, mix temperature, asphalt throughput rate and asphalt binder content.

However, some agencies also concluded that the rubber modified mix had an objectionable odour [21]. Moreover, in Colorado while researching and developing specifications for the use of rubberised asphalt for the 2006 paving season, local contractors expressed concerns about using the "wet or dry methods", due to the excessive smoke and smell that would be expelled into the atmosphere during the manufacturing process of this material at their asphalt plants. The contractors were so concerned about losing their state environmental certifications that they indicated they would not use the wet or dry methods without some assurances that their operating permits would not be jeopardised [56]. Nevertheless, several recent studies coupling the RTR-MBs with the Warm mix technology have shown a significant reduction of emission during field operations due to an important decrease of the mixing and compaction temperatures [57,21]. Therefore, environmental concerns upon the widespread usage of the wet process still exist, but the development of these technologies is proving that also this issue can be significantly reduced.

Recyclability. Before 1992, in USA Asphalt-Rubber pavements had been performing well and the replacement/recycling of them was not necessary. As some sections of Asphalt-Rubber pavements have met their service life span, recyclability became an issue. Carlson and Zhu [58] report of two jobs occurred in the USA where Asphalt-Rubber mixes were successfully recycled. One example is the recycling job occurred in the City of Los Angeles, California [59], where the initial placement of the Asphalt-Rubber pavement occurred in 1982. In 1994 the pavement was milled and stockpiled at a nearby asphalt plant. The Asphalt-Rubber grindings were added to the virgin rock and oil so that the grindings composed 15% of the final mix. At another location, the grindings were put through a microwave process where nearly 100% of the output was composed of recycled Asphalt-Rubber. This project demonstrated that Asphalt-Rubber can be recycled using either microwave technology or conventional mix design technology. Air sampling during paving and recycling determined that employee exposures to air contaminates were well below the Occupational Safety and Health Administration permissible exposure limits, and in most cases below the detection limits.

4. Wet process-No-Agitation

No-Agitation Recycled Tyre Rubber Modified Bitumen (No-Agitation RTR-MB), technology was first used in Florida and Texas in the mid-1980s and till nowadays it seems to have been used only in some other states of the USA. This is a form of the wet process where CRM is blended with hot bitumen at the refinery or at a bitumen storage and distribution terminal and transported to the asphalt plant/job site for use. In fact the main intuition behind this technology is to take advantage of the engineered properties of the RTR by using the CRM as an alternative modifier to produce storage stable modified bitumen. These binders are often labeled as terminal blends, although nowadays they may also be field-blended at the asphalt plant. Furthermore, this terminology could sound restrictive also because some of the terminal-blended RTR-MBs, with or without addition of polymers, still present the issue of phase separation and need agitation by special augers or paddles. For this reason someone labeled the storage stable terminal blends as terminal blend-hybrid [60]. Therefore a preferred description for this type of binders is "wet process-No-Agitation" blends [36], which clearly indicates the ability of this material of not requiring special equipment to keep the CRM particles evenly dispersed in the modified binder even during the storage process.

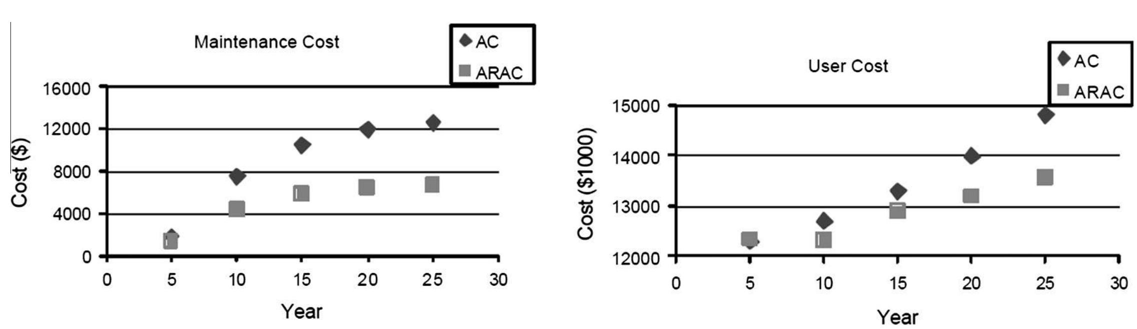

Fig. 19. Maintenance cost (left) and User cost comparison between conventional bituminous mixes (AC) and Asphalt-Rubber mixes (ARAC).

4.1. Production

In this process, no modifications to the asphalt plants are required because the No-Agitation RTR-MBs are manufactured with specific pressure, temperature, time and agitation requirements similarly to polymer modified bitumen. In the wet process-No-Agitation CRM and bitumen are blended through the continuous blending-reaction systems. No reaction tanks are provided. The bitumen is heated under a controlled environment in a tank to an elevated temperature and high shear stress. The CRM is then introduced into the tank and digested into the bitumen. The characteristic swelling process of the RTR-MB technologies is replaced by the depolymerisation/devulcanisation and optimised dispersion of the rubber into the bitumen by using high processing conditions (temperatures between 200 and 300 °C, shear stresses in the order of few thousands RPM and eventually with pressure higher than 1 atm), resulting in a smooth, homogeneous product. In the past, rubber contents for such blends have generally been ⩽10% by weight of bitumen or total binder, but some products now include even 25% CRM [61].

There are some proprietary and other non-proprietary processes. Some of them also include small percentage of other polymers (e.g. SBS), or other additives, to produce a combined homogeneous material that exhibits excellent storage stability and compatibility with the finished binder formulation. Such binders are typically modified with CRM particles finer than the 300 μm (No. 50) sieve size that can be digested (broken down and melted in) relatively quickly and/or can be kept dispersed by normal circulation within the storage. During this process, the operator takes samples and runs a solubility test to ensure the rubber is completely digested. Most manufacturers used a high shear process to make sure the CRM is completed digested. The solubility of the finished product is generally above 97.5%. The binder is then delivered to the hot mix plant by truck as a finished product with no additional handling or processing. After mixing with aggregate material is shipped to the job and no special equipment is required for paving, or odour/fume control. Moreover, the RTR mix is compacted like regular hot mix asphalt [62].

4.2. Storage stability

The wet process-No-Agitation aims to produce bitumen-Recycled Tyre Rubber blends which do not occur in eventual phase separation of the CRM from the binder during storage or transportation. The mechanism of phase separation is related to the differences in the properties, mainly physical, of the material constituents in the blends. After production of the blend, the presence of non-dissolved CRM particles in bitumen leads to phase separation, particularly when the blends are stored at high temperatures. As a result, the swollen CRM particles are considered to settle down quickly due to initial higher density than the bitumen phase [63]. On the other hand, migration of the CRM particles to the top of the storage container due to a reduced density after swelling has also been reported in some research studies [64,65]. These different mechanisms lead to an unstable condition which results in a rubberised blend with varied properties after the storage.

The improvement of the settling properties of the No-Agitation RTR-MBs is often linked to the careful selection of the blend's components usage of high-curing conditions [66] which ensures a high level of solubilisation of the CRM within the bitumen matrix. Some patented procedure states that as long as the CRM is fully digested into the binder (solubility is above 97%) it is possible to store them without phase separation [62]. However, at this stage the effect of the modification is significantly reduced. In fact, CRM is shown to a number of studies to effectively modifying the bitumen when it is still in the swollen state and not completely devulcanised/depolymerised (Fig. 10c). In order to maintain a convenient level of modification, recent studies have shown that is possible to improve the storage stability of RTR-MBs also by adding substances to operate a chemical stabilisation of the blends [67], by mixing rubberised bitumen blends in presence of a low percentage of polymers [68], with compatibiliser to activate the CRM [69], or with sulphur to improve crosslinking [64]. Another study [70] shows that hot storage stability of rubberised bitumens could be improved by blowing oxygen gases through these blends. In addition, pre-treatment of CRM particles with hydrogen peroxide has also resulted in a more stable RTR-MBs [71,72]. Furthermore, Attia and Abdelrahman [68] suggest improving the stability of modified binders also by lowering the storage temperatures. In any case, the stability of No-Agitation RTR-MBs during prolonged storage seems to be similar to other blended PMBs and the man role in improving the settling properties of bitumen-RTR blends is covered by an accurate selection of the processing conditions (Lo Presti et al. 2012).

4.3. Properties (Like a PMB)

Although such binders may develop a considerable level of rubber modification, rotational viscosity values rarely approach the minimum threshold of 1500 cPs at 177 °C, that is necessary to significantly increase binder contents above those of conventional asphalt mixes without excessive drain down [36]. Recently in the United States the specifications used for terminal blend (PCCAS, 2008) have utilised the PG grading system, named PG-TR system, similar to the ones used for polymer modified bitumen (Fig. 4.33). In California, PG-TR grades are specifically targeted for use in the same applications for which PG-PMB binders are used, including dense-graded mixes for thick structural sections. The terminal blends now meet the ASTM definition for minimum CRM content [73].

Within the No-Agitation RTR-MBs production, two main properties are of concern: first, the development of performance-related properties and, second, binder compatibility or storage stability. The literature indicates that performance-related properties develop early in the process while compatibility requires few hours to stabilise [74]. Few investigators have conducted studies on the rheological properties of these binders. For example, Thodesen et al. [75] evaluated several binders using the multiple creep recovery tests. Among the binders studied were an Asphalt-Rubber binder and a No-Agitation RTR-MB that uses 10% CRM and 1% SBS polymer. The results showed that the analysed RTR-MB exhibited the least creep and the highest percentage recoveries under various loading and temperature ranges. Another example is given by Attia and Abdelrahman [68], which investigating the possibility of producing high-performance terminal blends, suitable for SuperPave applications, found that by accurately regulating the processing conditions it is possible to balance the development of performance-related properties and storage stability. The same researchers proposed a procedure consisting in blending bitumen with 5% of CRM and 2% of SBS at elevated shear stress (30–50 Hz) and with the processing conditions shown in Fig. 4.38. They found that the final products have performance and binder stability (increasing shearing speed to 50 Hz) comparable to those of patent or proprietary products. Hence, interaction temperature on binder stability was not evaluated. Moreover the authors suggest enhancing the stability of binder by reducing the storage temperature at the plant.

4.4. Applications

No-Agitation RTR-MBs can be used with rubber contents as low as 5% and as high as 25%, depending on the application and the project's requirements. These products can be used in all paving and maintenance applications as a replacement of the polymer modified bitumens: [60]:

- Recycled Tyre Rubber Modified Paving Grade Bitumens.
- Standard PG grades – dense graded mixes.
- PG plus grades – high performance mixes.
- Warm mix standard grades – dense and open/gap graded mixes.
- Warm mix polymer modified grades – dense and open/gap graded mixes.
- Hot applied chip seal binders – neat and polymer modified.
- Recycled Tyre Rubber Modified Cutback Bitumens.
- (MC) Medium Cure Graded.
- (SC) Slow Cure Graded.
- Recycled Tyre Rubber Modified Bitumen emulsions.
- Rapid set chip seal.
- Micro surfacing slurry seals.
- Standard slurry seals.
- Cold in-place recycling.
- Cold Mix.
- Recycled Tyre Rubber Modified Seal Coats.
- Recycled Tyre Rubber Modified Surface Sealer.
- Recycled Tyre Rubber Modified Fog Seals.

5. Discussion and conclusion

High Viscosity RTR-MBs and No-Agitation RTR-MBs are different products and should not be interchanged (Fig. 20). However, both provide superior cracking performance at reduced thickness, when compared to conventional dense graded hot mix asphalt pavement. Only when there are construction issues the products are not be expected to perform in a superior manner.

In terms of binder properties, the main differences between these products are the viscosity and their storage stability. Viscosity for No-Agitation RTR-MB can range between 500 and 1000 centipoises at 135 °C, much lower than the viscosity for High Viscosity RTR-MB which is in the range of 1500–5000 centipoises at 177.5 °C (Table 8). With regards to the storage stability, No-Agitation RTR-MB born with the idea of obtaining a RTR modified binder comparable to the normal PMBs, therefore on contrary to High Viscosity RTR-MB, it is usually possible to store it as conventional PMBs. Furthermore, a recent study [76] highlights that the storage temperature of the No-Agitation RTR-MB could be significantly decreased (i.e. 15 °C) if compared to the field blended High Viscosity RTR-MB. Considering also the need of the field blends to be stored in agitated tanks, from this point of view the terminal blends leads to significant energy and money savings.

On the other hand, asphalts obtained by using High Viscosity RTR-MBs have more performance history since this process started over in 1960s and they have been used successfully with many applications. With regards to asphalt mixtures, High Viscosity RTR-MB technology is very successful when used with Open-Graded surface courses, where the high air void content of the mix allows an aggregate coating with a much thicker film (36 μm) of high RTR content modified bitumens (about 20%) which leads to an asphalt mix with significantly high binder content (about 7–9%) and with widely proven reduced oxidation, increased durability and increased resistance to reflective cracking. All these benefits are reduced when High Viscosity RTR-MBs is used for Dense-Graded hot mix projects since the dense gradation cannot adequately accommodate the rubber particle size, film thickness is reduced (9 micron) as well as acceptable binder content (about 5%) and the RTR-MBs needs to be produced with much lower rubber content (about 10%). The use of special equipment is not anymore justified by the significant benefits of a thicker coating, therefore in the case of Dense-Graded asphalt mixes the No-Agitation RTR-MBs are the most suitable. On this regard, they are more likely to compete with polymer modified bitumen rather than High Viscosity RTR-MB.

No-Agitation RTR-MBs have been successfully used for a much wider range of products as for instance chips seal applications, open graded and gap graded mixes and emulsions. Basically, No-Agitation RTR-MBs can be used wherever conventional asphalt mixes or asphalt surface treatments are needed. The lower viscosity of No-Agitation RTR-MB implies the usage of less binder per unit area (5–6% binder content) indicating less performance life than if High-Viscosity RTR-MB is used (8–10% binder content). In fact, the ability to inject more binder in the mix translates to better fatigue and reflective cracking performance.

In conclusion, the main advantages of the usage in asphalt mixture of the wet process-No-Agitation in lieu of the wet process – High Viscosity method at the contractor's plant include:

- No need for costly specialised equipment at the asphalt plant.
- No portable plants required for blending of Crumb Rubber with asphalts.
- No additional holding areas for storing the Crumb Rubber product.
- Easiest for the contractor to incorporate into their traditional manufacturing process.
- Mixing, laying and compaction temperatures are comparable to standard mix applications with PMBs.
- Works with all mix designs; does not require any special adjustments to gradation or mix design parameters.
- Being prepared at the refinery, completely eliminates potential problems with heating and blending of Crumb Rubber and asphalt products and
- Eliminates smoke and particulates from entering the atmosphere.
- The binder can be Performance Graded and emulsified
- The few available analyses on the sustainability of the product show that No-Agitation leads to economical saving and environmental benefits.

The aspects that make the wet process-High Viscosity preferable to the wet process-No-Agitation are:

- Evidence of great long term performance, while the long-term performance of existing projects using wet process-No-Agitation are still under evaluation.

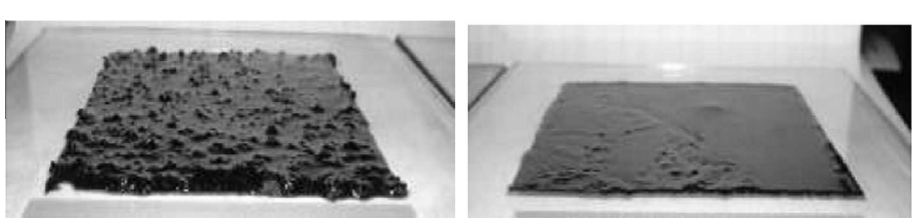

Fig. 20. RTR-MB from Wet process (left) and Wet Process-No-Agitation (right), adapted from [73].

- Some have expressed concern that there is no way to verify the amount of CRM used in No-Agitation RTR-MBs.
- Moisture susceptibility of asphalt mixture containing No-Agitation RTR-MB is still not clear.

5.1. Conclusions

The author believes that the widespread use of the RTR-MBs technologies within the road pavement industry is advisable. In fact the several benefits provided to the asphalt pavement performance, and to the overall sustainability of the infrastructure, are so evident that it is strongly advised to consider RTR-MBs technologies as a first option to the binders currently used in road pavements. Companies, road authorities, etc. have to evaluate if it is convenient to use the High Viscosity wet process technology, which proved widely to provide several benefits, in particular it allows highway designers to reduce pavement layer thickness due to the proven properties of rubberised bitumen, but presents some challenges as: the need for suitable blending and mixing equipment, the cost of such equipment and the degree of difficulty in preparing asphalt mix design. The other option is to choose the wet process-No-Agitation technology which solves several issues but leads to asphalts pavements with, so far, uncertain long term performance. In both cases the implementation of these technologies still presents issues as: the lack of availability of suitable RTR processing facilities in the vicinity and the cost of such facilities, the lack of rubberised bitumen binder and mix standards, the uncertainty on the environmental performance of these products and the lack of trained personnel particularly for accurate laboratory analyses, of raw materials and final blends, which are necessary to optimise the modification process and the performance of the final product. Education and training are indeed another key aspect for a successful application of RTR-MBs in road asphalt mixtures also because new procedures are being developed to perform an enhanced laboratory design of these technologies [77] as well as reducing limitations to their applicability in the field. Examples are given by the increasing number of rubberised asphalt applications with additives able to reduce paving temperatures (i.e. warm mix technologies) [21,57], but also from the invention of a new form of product delivery as the case of the rubberised pellets [78]. Another important aspect to clarify is the cost of this technology: it is true that initial costs are still an issue but the rapid cost increase of bitumen and results of lifecycle cost analyses indicate that RTR-MBs are in many cases an economically convenient option. At last, there is evidence that a closer involvement of local and national governments with policies supporting the RTR industries and the major investments on training and research could definitely help to decrease the costs of implementing RTR-MB technologies as well as solving the several issues indicated within this manuscript. A proof of this statement is given by the state of California (USA) where since 2005 a government mandate [79] supports the increasing adoption of these technologies in asphalt mixture and from the January 2013 the usage of rubberised asphalt pavements needs to reach at level of at least 35% of the total weight of asphalt paving materials produced in the country. The main reason of this mandate is the prediction of substantial savings in the long term.

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