Chapter 12
Environmentally Friendly Disposal of End-Of-Life Plastics for Asphalt Production

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Abstract Polymers and plastics are main constituents of a variety of daily life products. Nevertheless, there is great public concern on these materials mainly due to waste and end-of-life management. This work reports an alternative for the recycle and reuse of End-of-Life Plastics (EOLP), as performance-enhancing additives of asphalt for road pavement. Physical–mechanical characteristics of Bitumen 50/70 mixtures containing different percentages of EOLP and other polyolefin waste (Secondary primary polymeric materials, SPPM) are compared to standard Bitumen. All mixtures where characterised to determine tensile strength, resistance by Marshall tests and Marshal quotation, density, air voids, indirect tensile strength (ITS), indirect traction coefficient (ITC). Data highlight that use of EOLP as bitumen modifier allows to improve Marshall Stability and ITS of road asphalts. Moreover, benign features of this process clearly appear due to the increase in plastic reuse and recycling, reduced plastic incineration, bitumen and additives consumption, waste management costs, CO_2 production.

Keywords "End-of-life" plastic (EOLP) recycling · Asphalt production · Circular economy · Eco-friendly manufacturing · Sustainability

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12.1 Introduction

Plastics are non-biodegradable materials that are believed to remain in the environment for over 4500 years, contributing, with their dispersion and accumulation, to environmental pollution (Nkanga et al. 2017). The main concern on plastic regards the waste and end-of-life management rather than its use, which is generally harmless. The recent apprehension arises due to marine plastic pollution and the "plastic islands", impacting heavily on marine life, since up to 12 million metric tons of plastic waste end up in the oceans every year (Jambeck et al. 2015). As a response to these observations, circular economy is pushing towards a radical change in production and waste management so that, for example, manufacturing processes should pursue water, waste and energy management solutions that contribute to the sustainable development of industries in order to achieve zero waste production and environmentally sustainable management cycles (Kirchherr et al. 2017).

Linear production according to the scheme "produce–use–dispose" is no longer possible in a logic of sustainability and circular economy (McKinsey Centre for Business and Environment 2016). As a matter of fact, circular economy is based onto the 4R principles (reduce, reuse, recover and recycle) that should be applied during the entire cycle of production, consumption and return of resources, involving the entire supply chain, from production to distribution, from use to recovery at the end-of-life (EllenMacArthurFoundation; Meherishi et al. 2019).

Within this framework, European countries have developed highly efficient systems for the management of plastic waste and recycling. The latest statistics by Corepla, the Italian National Consortium for the collection, recycling and recovery of plastic packaging, report that in 2018 in Italy, over 1.200.000 tons of plastic were collected separately (+13.6% compared to 2017). It is nevertheless true that of about 1 million tons of plastic thrown by the citizens, the incinerators burn almost 400 thousand tons.

In the above-mentioned situation, the present work reports a sustainable alternative for the reuse and revalorization of end-of-life plastic waste, currently sent to incinerators, as additives to produce enhanced high-quality asphalts. The use of end-of-life plastics (EOLP) for road asphalt offers an attractive solution for effective waste management. Various examples are known in literature in which secondary primary polymeric materials (SPPM) such as HDPE, LDPE, PE, PP, PS (Behnood 2019; Mosa 2017; Rajasekaran et al. 2013; Vasudevan et al. 2012), PET (Leng et al. 2018; Sojobi et al. 2016), PVC (Chhabra and Marik 2014; Cortavitarte et al. 2018; Hadidy and Tan 2009; Khan et al. 2016; Manju et al. 2017) and rubber powder (Bressi et al. 2019; Cao et al. 2019; Gupta et al. 2019; Tahami et al. 2019; Yu et al. 2019) are used as additives for asphalts. An interesting example regarding the use of plastic coming from electronic devises for making asphalt has recently been reported by Murugan (2018). Adversely to the literature reported above, the EOLP analysed in this work is a heterogeneous plastic mixture composed of any polymer having higher density than water such as PET, PC, PS, PMMA, PA and PP (see below).

The main objective of this study is to investigate the feasibility of applying EOLP as additives to improve overall characteristics of bituminous paving mixtures. To achieve this objective, physical–mechanical characteristics of asphalt formulations containing Bitumen 50/70 (B50) and different weight percentages of EOLP or a polyolefin waste similar to conventional plastic additives tested in the literature (SPPM), have been compared to virgin B50. Marshall stability and quotation, density, air voids, ITS and ITC of different mixtures have been measured. An evaluation of the main environmental and economic advantages of this end-of life waste recycling method is also reported. Advantages foreseen using EOLP are increased plastic recycling, reduction/avoidance of petrochemical derived plastic additives, improvement in fatigue life of road asphalt, together with reduced environmental impact and lower costs.

12.2 Materials and Methods

Bitumen 50/70 (B50) was supplied by IFAF S.p.a. (VE, Italy). Dried and cleaned SPPM (PE/PP 88/12 wt% mixture) and end-of-life plastics (EOLP) supplied by Elite Ambiente (Grisignano di Zocco, VI, Italy), were used as asphalt modifiers in the presence of 4, 5 and 10 wt% of bitumen. A mechanical grinder was used to convert polymeric waste into powder form (between 1.5 and 4.0 mm). The characteristics of the standard bitumen 50/70 (wear 0/12) are: softening point 46.0 °C, penetration at 25 °C: 55 dmm, dynamic viscosity at 60 °C: 259 Pa × sec, dynamic viscosity at 160 °C: 0.145 Pa × sec.

12.2.1 Sample Preparation

SPPM were recovered from the sink-floating separation of renewable materials from waste plastics (Bauer et al. 2018), followed by different processes of refinement and grinding. SPPM were used as received or further grinded to small particles of 1.5–4.0 mm size. Residual plastic material left as end-of-life waste (EOLP) after the recovery of reusable plastics (SPPM), was recovered from the settling tank, washed twice with hot water and grinded to small particles of 1.5–4.0 mm size. Different tests were carried out employing SPPM or EOLP in 4, 5 and 10 wt% mixed with B50, using a laboratory mixer at 165 °C, then leaving the mixture in the oven for two hours. Three to four samples of B50 were prepared for each of the different polymers tested. The coarse aggregate, fine aggregate and filler were used in different wt% in accordance with requirements specified in relevant standards. Each aggregate was analysed, identifying the granulometric and physical characteristics according to UNI EN 933–1:2012 for particle size distribution, UNI EN 1097–6:2013 for the bulk density of the granules and UNI EN 933–8:2015 for testing of the equivalent in sand. The mixture of aggregates was prepared with 30 wt% of limestone 8/12, 24 wt% of limestone 4/8, 32 wt% sand, 10 wt% RAP (Recycled Asphalt Pavement), 4 wt% filler. To this mixture 5 wt% B50 for road use was added containing 4, 5 or 10 wt% SPPM or EOLP.

12.2.2 Density Values and Air Void Tests

Each mixture has been prepared at 160 ± 5 °C taking care to maintain a homogenous mixture before adding the bitumen. Filler has been added to the mixture as the last component. In order to mechanically characterise the mixtures, samples were packaged with a gyratory press and a Marshall impact pestle according to UNI EN 12,697–31:2019 and UNI EN 12,697–30:2019. Samples were then measured and weighed in order to determine their physical characteristics both through the geometric method, as is customary for specimens packaged with gyratory press, or with hydrostatic weighing (UNI EN 12697-5:2019; UNI EN 12697-6:2012; UNI EN 12697-8:2019) methodology typically used for samples prepared with impact pestle. Subsequently, they were subjected to tests of indirect traction, stability and Marshall stiffness in order to verify the possible variation in the mechanical performances produced by the addition of SPPM and EOLP.

12.2.3 Indirect Tensile Strength (ITS) and Indirect Traction Coefficient (ITC) Tests

The determination of the indirect tensile strength and its coefficient has been carried out according to the UNI EN 12,697–23:2018 standard. The samples made with a 100 mm diameter gyratory press and with 210 rotations are left to rest after their packaging for a time between 2 and 12 days in the air, after which they are measured and weighed, thermostated in a water bath at 25 °C for about 2–3 h before being broken by a pressure capable of determining the stress opposite to the load and its deformation until break.

12.2.4 Marshall Tests

The resistance of the prepared bituminous mixture was estimated using Marshall test following guidelines given in UNI EN 12,697–34:2012. The height and diameter of the bituminous mixture specimens were 63.5 mm and 101.6 mm, respectively. The bitumen was maintained at 160 °C, and the recycled plastic was added to aggregate at specified percentage. The modified bitumen mixture was poured in a mould and left to rest after 24 h; the specimens were removed from the mould. Then the samples were immersed in hot water at the temperature of 60 °C for 30 min, thus dried and analysed. The various samples were placed in the Marshall Testing machine to determine the stability and scrolling. The maximum force recorded during compression testing was registered as Marshall stability value (kN). The stiffness of the mixture was reported as Marshall Quotient (kN/mm).

12.3 Results and Discussion

For this case study we employed two different plastic wastes produced at different stages of the disposal process adopted by Elite Ambiente. This treatment plant, ubicated in Grisignano di Zocco (VI), receives different sources of plastic waste coming both form household and industrial plants. Preliminary treatment is carried out to eliminate steal, paper and organic waste. Then, plastic waste is reduced to flakes and sink–float water density separation is used to recover PP and PE which is then reprocessed to give pellets of PE/PP with an average composition of 88/12 (Bauer et al. 2018). PE/PP mixtures are presently sold as secondary primary polymeric material (SPPM), whereas left over plastics (EOLP) after the recovery of SPPM are sent to incineration.

Polyolefins are known to give good stability and rotten resistance when employed as additives for road asphalt (Behnood 2019; Mosa 2017). Thus, we decided to employ SPPM as polyolefin additive reference standard for comparison with the EOLP complex polymers mixture. To overcome replicability problems using heterogeneous EOLP, tests were carried out on grinded material (mesh between 1.5 and 4.0 mm). The choice of granulometric selection employed and the definition of the control and comparison tests has been defined based on the Italian ANAS Technical Specification which mainly regulates bituminous conglomerates for road pavement production.

In order to define the interaction between the plastic and the bituminous conglomerate, the most requested mixture (Wear 0/12) for usual traffic load was used as reference standard and different formulations were prepared adding different percentages of SPPM or EOLP (see Table 12.1). The characteristics of bitumen 50/70 (B50) road asphalt concrete used, have been tested and classified according to the usual parameters (see materials and methods). Each mixture was prepared at 160 ± 5 °C taking care to heat and homogenize the aggregates, the granulate, before inserting the bitumen and the SPPM or EOLP (in different wt%, see material and method section). In this study we decided not to add any conventional additive to the conglomerate in order to define the real interaction between SPPM and EOLP with the bituminous conglomerate. Density, air voids, indirect traction stability (ITS), indirect traction coefficient (ITC) and Marshall stiffness of final asphalt samples was measured in order to verify the possible variation in the mechanical performances produced by the addition of SPPM or EOLP compared to standard B50 (see Tables 12.1 and 12.2).

The density values reported in Table 12.1 refer to bulk density which is generally influenced only by the packing ability of the aggregates and varies according to the

Table 12.1 Density and air void values of bitumen 50/70 and bitumen 50/70 plastic blends

Sample	Density (10 rot.) (g/cm^3)	Density (120 rot.) (g/cm^3)	Density (210 rot.) (g/cm^3)	Air void (10 rot)[a] (g/cm^3)	Air void (120 rot)[a] (g/cm^3)	Air void (210 rot)[a] (g/cm^3)
B50	2250	2472	2499	11.8	3.1	2.0
B50/5%SPPM	2173	2299	2318	12.3	7.3	6.5
B50/10%SPPM	2071	2134	2148	12.7	10.0	9.4
B50/4%SPPM[b]	2218	2459	2492	13.0	3.6	2.3
B50/4%EOLP[b]	2201	2443	2482	13.0	4.0	2.5

[a]Air voids values according to CSA ANAS should be between 11 and 13 after 10 rotations (rot.), 3–6 after 120 rotations and ≥2 after 210, with a rotation speed of 30 rpm. [b]Grinded plastic samples to 1.5–4.0 mm mesh

Table 12.2 Mechanical parameters—resistance to indirect traction

	ITS (kPa)	ITS (kPa) CSA ANAS	ITC (MPa)	Marshall value (kN)	Reference Marshall value (kN)	Marshall quotation (kN/mm)	Reference value Marshall quotation (kN/mm)
B50	1059	720/1400	91	15.13	>12	3.63	2.5–4.0
B50/5% SPPM	1875	720/1400	233	25.05	>12	5.58	2.5–4.0
B50/10% SPPM	1678	720/1400	133	29.63	>12	9.65	2.5–4.0
B50/4% SPPM[a]	1415	720/1400	165	16.03	>12	3.73	2.5–4.0
B50/4% EOLP[a]	1529	720/1400	180	15.35	>12	4.16	2.5–4.0

[a]Grinded plastic samples to 1.5–4.0 mm mesh

bitumen blend (Nkanga et al. 2017). Nevertheless, from these data it is possible to observe decreasing density values when higher concentrations of non-grinded SPPM are present. This is probably due to reduced homogeneity of the bitumen/plastic mixture which affects the density of the samples. In fact, in the presence of 4 wt% grinded SPPM, density values equivalent to the normal bitumen are restored. Similar results are obtained with the addition of 4 wt% EOLP.

The stability and durability of asphalt mixtures are known to be highly influenced by air voids which are correlated to the volumetric fractions and space distribution (Chen et al. 2013). Air voids generally require to be within an optimal range defined by standard methods (see Table 12.1), since low air void values cause rutting due to plastic flow, whereas an excess of air voids may lead to premature cracking or raveling due to oxidation and moisture (Chen et al. 2013).

Examining the data in Table 12.1, it emerges that good results are achieved when 4 wt% of grinded SPPM or 4 wt% of EOLP is added. Less satisfactory data obtained with non-grinded SPPM are probably to be attributed to low homogeneity of the plastic material within the bitumen.

The results obtained for indirect tensile strength (ITS), indirect traction coefficient (ITC) and Marshall tests for the different mixtures containing SPPM and EOLP are reported in Table 12.2. Data achieved have been compared to those obtained by the standard control sample.

The mixtures produced with coarsly grinded SPPM show an increase in resistance of the asphalt mixture as shown by the values of ITS, ITC and Marshall value compared to B50 indicating an increase in asphalt resistance. Nevertheless, this positive effect is accompanied by a significant increase of Marshall quotation reaching values far beyond the reference value in the presence of 10 wt% of SPPM (9.65 kN/mm vesus a maximum value of 4.0 kN), which indicate a high stiffness of the material leading to premature cracking and severe damage. On the contrary, very good results are measured for specimens containing 4 wt% of grinded SPPM and EOLP allowing to achieve ITS values higher than standard B50 alone, which is reasonably higher than the CSA ANAS requirements, together with very satisfactory Marshall values and quotations. It is important to underline that both SPPM and EOLP mixtures achieved a good compromise between resistance ITS, ITC and Marshall value versus elasticity (Marshall Quotation), which are good requisites to produce long lasting road asphalt.

From the data above it clearly emerges that the size of the plastic particles added to the mixture play a crucial role in affecting the characteristics of the final manufact. This behavior is probably related to the reinforcing role of the polymeric mixtures added, which is maximized when smaller particles are used.

From an economical point of view, it must be stressed that EOLP is presently sent to incineration with considerable economical (about 110 €/ton) and environmental burden. SPPM instead is already sold to produce recycled plastic materials and is thus an expensive source of polymeric additives for asphalt production.

Based on the experimental evidences, an estimate of the economic and environmental advantages foreseen using B50/4 wt% EOLP for the layout of a 25–30 mm height top layer, 4 m wide and 1 km long road, are reported in Table 12.3. Economical data, shown in Table 12.3, clearly highlight the EOLP advantages in asphalt production.

Main results are: (i) reduction of fossil derived products (bitumen and additives); (ii) reduction of end-of-life incineration which is known to produce about 1 ton of CO_2 for ton of plastic burned; (iii) reduction in waste management and disposal; (iv) increase in optimization of EOLP recycling and reuse.

Prudentially we have not taken into consideration the CO_2 savings derived from the reduced consumption of bitumen, additives and reduced road maintenance, to counterbalance possible CO_2 burden (charge/load) coming from the exploitation of EOLP.

Table 12.3 Economic and environmental comparison between standard B50 and B50/4% EOLP

Materials	Standard bitumen process	EOLP bitumen process	Savings (€)
Bitumen 50/70 (400 €/ton)	111.330 kg	106.880 kg	1.780
EOLP	–	4.450 kg	
Additives (4 €/kg)	4.450 kg	–	17.800
Carbon credit achieved avoiding burning plastics		4.5 ton	
EOLP waste management (110 €/ton)			490

12.4 Conclusions

In this study, End-of-life Plastics were demonstrated to be suitable as bitumen modifiers, despite their complex and variable composition.

Two different plastic waste, SPPM and EOLP, have been used as bitumen modifier and their performance compared to standard bitumen 50/70 (wear 0/12) used for road asphalt. SPPM is a PP/PE mixture similar to conventional plastic additives tested in the literature, while EOLP has a very complex and heterogeneous composition. Data clearly show that grinding of the plastic waste used (<4 mm) is crucial to insure high performances.

Mixing bitumen with 4 wt% grinded EOLP allows to improve overall characteristics of road asphalt: higher resistance to permanent rutting and higher stability are achieved as evidenced by ITS/ITC and Marshall Stability values (respectively 1529 kPa/180 MPa and 15.35 kN). Moreover, decreasing bulk density, from 2250 to 2201 g/cm^3, and increasing air voids ensure resistance to premature cracking and ravelling of the plastic asphalt. EOLP, despite its complexity, allows to obtain a good balance between the resistance and the elasticity of the asphalt superior to B50 and to SPPM.

Moreover, the use of EOLP as bitumen modifier allows the reduction of plastic incineration, additives and bitumen consumption, waste management costs and CO_2 production. Scale-up studies are ongoing to verify important parameters such as the time stability, recyclability of the asphalt and to collect data for Life Cycle Assessment and Life Cycle Cost.

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