



LABORATORY AND ENVIRONMENTAL ASSESSMENT OF WARM ASPHALT MIXTURES MODIFIED WITH PLASTIC WASTE

Valentina Scaramucci, Gilda Ferrotti, Andrea Graziani, Andrea Grilli, Fabrizio Cardone
Università Politecnica delle Marche, Ancona 60131, Italy

Abstract

Nowadays, incorporating recycled plastic waste into asphalt pavements represents a sustainable approach to address environmental challenges related to waste disposal and the demand for limited natural resources. This practice can also improve the overall performance of road pavements. In this context, the present research reports the results of a laboratory characterization and environmental assessment of a warm mix asphalt (WMA) for binder course, modified with recycled plastic. Specifically, the plastic derived from waste generated during electrical wire manufacturing was added into the mixtures through the dry method at different contents (i.e. 0.5, 1 and 2%). The mixtures were qualified through workability and mechanical tests (compaction energy index, indirect tensile strength and indirect tensile stiffness modulus) and then compared with the corresponding reference mixture (without plastic) to assess the effect of recycled plastic modification. Test results show that the workability, strength and stiffness of WMA mixtures are enhanced with respect to the reference one. Finally, a comparative life cycle assessment was carried out to evaluate the potential environmental impact resulting from the incorporation of recycled plastic into the asphalt mixture compared to the conventional formulation.

Keywords: warm mix asphalt, plastic waste, mechanical testing, environmental assessment

1 Introduction

Plastic waste management has become one of the main environmental challenges worldwide. In recent decades, annual global plastic production has increased exponentially, reaching about 430 Mt in 2024 [1, 2], leading to an increase in plastic waste generation. According to the Organization for Economic Cooperation and Development projections [1], by 2060 the quantity of plastic waste is expected to almost triple, with recycling rate below 20% and about half disposed of in landfills. The non-biodegradability of plastics, combined with poor waste management lead to accumulation in the environment, with negative effects on the ecosystem and human life [3]. This scenario highlights the need to identify alternative and sustainable solutions for the management and recycling of plastic waste. Nowadays, a promising strategy is the reuse of plastic waste in the production of asphalt mixture, with the aim not only of reducing plastic waste but also of decreasing the consumption and costs related to virgin raw materials [4]. Moreover, several studies have reported satisfactory performance (e.g. fatigue performance and rutting resistance) of asphalt mixtures incorporating plastic waste. However, the type, amount, size and shape of plastic used, as well as the technology employed to introduce the plastic materials into the mixture (dry or wet method), affect the performance response of mixtures [5-7].

According to sustainability principles, it is essential, beyond the evaluation of mechanical performance, to analyze the environmental impact through a Life Cycle Assessment (LCA) [8], to comprehensively assess the potential benefits associated with the incorporation of plastic waste into asphalt mixtures. Indeed, LCA offers a comprehensive approach for evaluating the environmental impacts associated with a product throughout its entire life cycle, from raw material extraction to end-of-life management, encompassing different stages such as production, construction, and use [9-11]. Although the number of LCA studies on asphalt mixture with plastic waste is increasing, it remains difficult to identify studies aimed at evaluating the combined effect of WMA technology, reclaimed asphalt (RA) and plastic waste use. Moreover, in the field of mixtures with plastic waste, an additional challenge arises from the high sensitivity of LCA results to methodological assumptions, including the definition of system boundaries, the allocation rules applied to secondary materials, and the data sources employed [12, 13].

This paper aims to evaluate the mechanical response of asphalt mixtures incorporating different amounts of plastic waste through the adoption of a WMA technology. Furthermore, the study is complemented by an LCA analysis (from cradle to gate) which examines the combined use of WMA technology and plastic waste from an environmental point of view.

2 Experimental research

The experimental program of the present research was developed in two phases. The first phase involved the laboratory production of warm asphalt mixtures containing different amounts of recycled plastic. Subsequently, a compactability analysis and a mechanical characterization of these mixtures enabled to identify the effects of the recycled plastic on the mixture behavior, also verifying compliance with the technical specification for the Italian national road network [14]. A second phase was devoted to a comparative life cycle assessment (from cradle to gate) to compare the potential environmental impacts of incorporating recycled plastic into the WMA mixture with those of the conventional hot mix formulation.

2.1 Materials

The laboratory investigation involved the production of four dense-graded WMAs (coded as DGW_0, DGW_0.5, DGW_1 and DGW_2) for binder course, characterized by the same total bitumen content (i.e. 4.8% by aggregate mass) and modified with different contents of recycled plastic (0, 0.5, 1 and 2% by aggregate mass). The WMA without plastic (i.e. DGW_0) was selected as reference mixture for comparison purpose. The design aggregate gradation (table 1) adopted for all mixtures includes 20% RA (8/25 mm class), resulting exclusively from milled courses of motorway pavement, three different classes of virgin limestone 10/16, 5/11 and 0/4 mm (28, 15 and 33% respectively) and a limestone filler (4%).

Table 1 Design mixture grading curve along with the Italian technical specification limits for state road pavements [14]

	Cumulative passing (% by mass) for each sieve [mm]								
	20	16	12.5	8	4	2	0.5	0.25	0.063
Design mixture	100.0	99.2	83.1	63.9	44.5	34.8	15.7	10.7	6.2
Upper standard limit	100.0	100.0	86.0	72.0	54.0	40.0	22.0	16.0	8.0
Lower standard limit	100.0	90.0	66.0	52.0	34.0	25.0	10.0	6.0	4.0

A conventional 70/100 pen grade bitumen modified by adding 3% (by bitumen mass) of synthetic waxes blend was used to enable production at lower temperature. It is characterized by these index properties: Penetration @25°C of 55*0.1mm, Softening Point of 82°C, Dynamic Viscosity @160°C of 0.095 Pa·s. The recycled plastic, derived from waste generated during electrical wire manufacturing, was a white-colored polyolefin-based compound consisting of a polymeric matrix mainly made of ethylene–vinyl acetate (EVA) and polyethylene (PE). Recycled plastic was supplied in flexible flakes having size ranging between 2 and 4 mm (Density: 1.0-1.5 g/cm³, Melting Point: 90-200°C). The plastic granulates were dozed by aggregate weight according to the selected content and added into the mixtures through the dry process. A mixing temperature of 130°C was adopted to produce all the selected WMAs.

2.2 Testing methods

After production, the mixtures were compacted using a gyratory compactor (compliant with EN 12697-31) to obtain two series of specimens with 100 mm diameter compacted at 100 and 180 gyrations, respectively, according to the technical specifications for traditional hot dense-graded asphalt mixture [14]. The temperature selected for compaction was 120°C.

The compactability analysis of the mixtures was performed on the specimens compacted at 180 gyrations by calculating the air voids (AV) (EN 12697-8) and the Compaction Energy Index (CEI) from the gyratory data. CEI is a parameter used to assess the mixture workability and is related to the energy expended by the roller to compact the mixture to the required density before opening to traffic. It can be calculated as the area under the compaction curve starting from the 8th gyration up to a compaction level equal to 92% of the mixture maximum density [15]. Three replicates were performed for each mixture. The stiffness properties were evaluated on the specimens compacted at 100 gyrations through indirect tensile test configuration at 20°C, according to standard EN 12697-26 (Annex C). The test consisted in applying an impulsive loading with a rise-time of 124 ms along the vertical diameter of the specimen causing a target maximum horizontal deformation of 7 ± 2 mm. The Stiffness Modulus is then calculated as representative parameter of the mixture stiffness. Four replicates were performed for each mixture.

The strength behavior was evaluated through indirect tensile test configuration at 25°C according to standard EN 12697-23, on the specimens previously subjected to ITSM test. The test consisted in applying continuously a progressive load at a constant speed of 50 mm/min along the vertical plane until the specimen reached the failure. The data recorded during the test allowed to calculate the Indirect Tensile Strength (ITS) as representative parameter of the mixture strength properties. Four replicates were performed for each mixture.

2.3 Life cycle assessment

In this research, the main goal of the LCA analysis was to evaluate the environmental sustainability of incorporating different contents of recycled plastic (added by dry process) into the production of WMA mixtures and to compare these outcomes with those of a conventional dense-graded HMA (coded as DGH), which is currently used for the binder course in Italian secondary road pavements. To this end, the selection of the system boundaries was based on the stages defined in the standard EN 15804:2021 and included the raw material supply (module A1), the transportation to the asphalt plant (module A2) and the manufacturing of asphalt mixture (module A3) with the aim of evaluating LCA outcomes limited to the mixture production process (i.e. cradle to gate approach). To provide an accurate comparison among the different alternatives, the functional unit adopted was 1 t of asphalt mixture produced.

To run the LCA analysis, SimaPro software v10.2 was used and the Ecoinvent database v3.11 was selected to collect the life cycle inventory data on material supplies, resources and mixture production, in combination with primary data. The Life Cycle Impact Assessment (LCIA) approach applied was EN 15804+A2 (adapted) v1.03 method, which is aligned with the Environmental Footprint method, except for the biogenic carbon approach [16]). The impact categories considered were Acidification (AP), Climate change (GWP-total), Particulate matter (PM), Photochemical ozone formation (POCP) and Resource use, fossils (ADP-fossil).

3 Results and discussion

3.1 Compactability and mechanical characterization of mixture

Figure 1 shows the results of compactability in terms of average AV and CEI for all the investigated WMA mixtures. Specifically, the AV contents measured at three gyration levels (i.e. 10, 100 and 180) are reported in accordance with the technical specification [14], which require AV value of 11-15%, 3-6% and $\geq 2\%$ at each gyration level, respectively. Results highlight that for all mixtures modified with recycled plastic the air voids requirements are satisfied, although the plastic content causes a different effect on the residual AVs. Specifically, the mixtures containing 0.5 and 1% plastic show residual AVs slightly higher than the reference mixture (0% plastic), however an excess in plastic content (i.e. 2%) results in the lowest AVs. Similar outcomes can be noted in terms of CEI (right plot), highlighting an improved workability (lower CEI value) for the WMA mixture containing 2% plastic compared to the reference mixture DGW_0. These results point out that the presence of recycled plastic does not hinder the compactability of the mixtures.

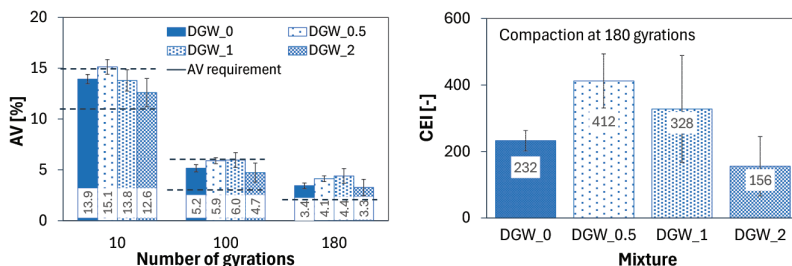


Figure 1 Compactability results, along with standard deviation (error bars): air voids AV (left plot), compaction energy index CEI (right plot)

Figure 2 (left plot) shows the average ITSM values. Results show that the mixture containing plastic are characterized by a higher stiffness modulus than the reference DGW_0 mix, with an increase in ITSM values as the recycled plastic content increases. However, the significant increase in stiffness of the mixtures DGW_2 (containing 2% of plastic) could be attributable to the lower residual AVs.

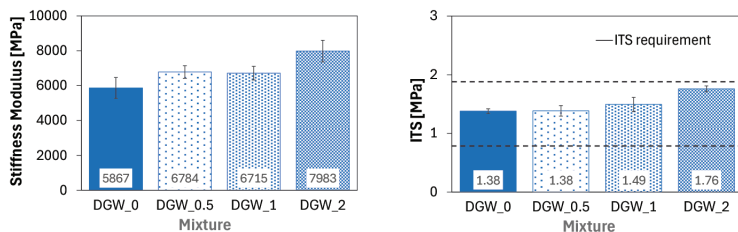


Figure 2 Mechanical results, along with standard deviation (error bars): Stiffness Modulus (left plot), Indirect Tensile Strength ITS (right plot)

Figure 2 (right plot) shows the average ITS values. Results show that all the WMAs meet satisfactorily the national road technical specification requirements for binder course ($0.80 < ITS < 1.90$ MPa). Specifically, the ITS trend highlights that the mixtures containing 0.5 and 1% plastic show comparable strength response to the reference DGW_0 mix, whereas the mixture with 2% plastic (DGW_2) guarantees an improved strength. This finding is consistent with the ITSM results, confirming that the lower AVs of the mixtures DGW_2 could contribute to the significant improvement of the strength response.

Analysis of the overall results shows that the stiffness and strength of the DGW_2 mixture are attributable to the higher plastic content, which in turn leads to a more significant reduction in voids.

3.2 Life cycle assessment

This section reports the results of the LCA, which considers both the WMA technology adopted and the use of recycled plastic waste. Plastic waste was modelled considering the burdens associated with the grinding process and related transports, as well as the environmental credits resulting from the elimination of landfill disposal, including avoided transportation. Figure 3 shows the percentage of variation in environmental impact indicators compared to a hot reference mixture DGH (solid columns) and compared to the warm mixture DGW_0 (dashed columns), both without plastic.

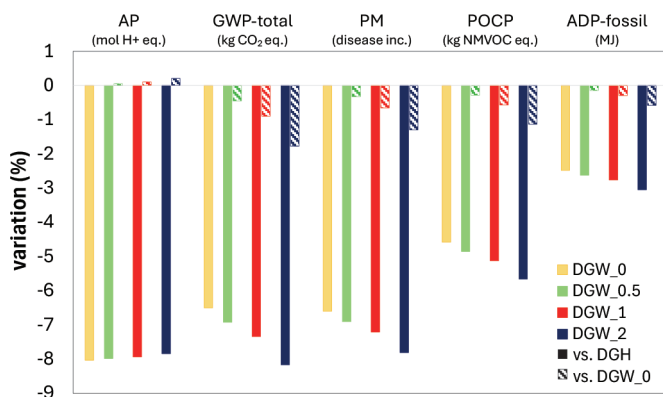


Figure 3 Variation of indicators for the selected impact categories

The comparison with the DGH (solid columns) shows that the process associated with the production of all WMA mixtures causes a decrease in all the selected impact indicators, highlighting that the highest contribution to the impact reduction comes from WMA technology rather than the incorporation of recycled plastic. Among the WMA mixtures (dashed columns), the use of recycled plastic shows benefits in terms of GWP-total, PM, POCP and ADP-fossil, which show a higher reduction as the plastic content increases, while AP shows the opposite trend. Despite the impact indicator variation due to plastic use can be considered not significant (likely because of small plastic amount), it can be highlighted that the incorporation of plastic does not penalize the environmental benefits associated to WMA technology.

Regarding climate change, figure 4 illustrates the contribution of each production-stage module (A1-A3) to the GWP-total indicator. Among the different mixtures, larger reductions in GWP-total were observed for module A3, confirming that the lower production temperature associated to WMA technology is the aspect exerting the strongest influence. On the contrary, the incorporation of recycled plastic into the mixtures provides slight benefits mainly observed in module A1.

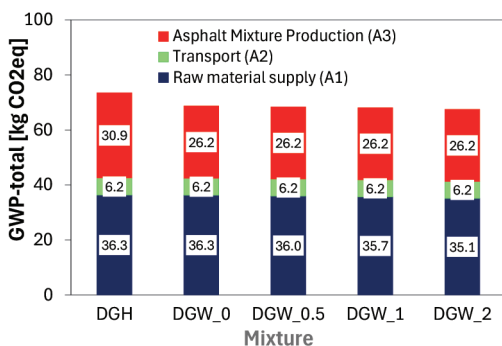


Figure 4 GWP-total indicator for the climate change category

4 Conclusion

Based on the laboratory characterization and environmental assessment of the selected mixtures, the following main conclusion can be drawn:

- the highest recycled plastic content (2%) studied seemed to promote the compactability of WMA mixture, leading to lower air void content and higher workability
- the increase in plastic content resulted in an increase in Stiffness Modulus and Strength values among all the mixtures analyzed; moreover, the stiffness and strength response of the mixture with 2% of plastic waste were controlled by the combined effect of volumetric properties and plastic content
- from an environmental perspective, and within the limits of a cradle-to-gate assessment, the combination of WMA technology and recycled plastic yielded environmental benefits compared with a conventional HMA. Despite the highest reduction in all impact categories coming mainly from WMA technology, the incorporation of recycled plastic guaranteed slight additional environmental benefits. It is important to clarify that the LCA results are strongly influenced by the type, amount and recycling process of plastic selected, as well as by the methodological approach adopted (e.g. system boundaries, allocation method for secondary materials and so on).

Future studies will consider an LCA analysis including additional life-cycle stages considering the influence of mixture performance (e.g. fatigue behavior) throughout service life of pavement as well.

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