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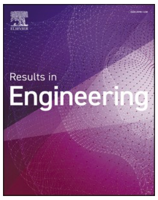

Multi-recyclability of asphalt mixtures modified with recycled plastic: Towards a circular economy

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ABSTRACT

Although asphalt pavements modified with recycled plastic have demonstrated enhanced performance, their recyclability remains under-explored, which is crucial under the scope of a circular economy. To address this, the present study investigates the multi-recyclability of asphalt mixtures, both with and without a recycled plastic modifier, at a recycling rate of 50 % over two cycles using an open-loop and a closed-loop model. The research utilised an innovative recycled plastic modifier made from hard waste plastics, incorporated into the mixture via the dry method. To ensure control over consistency and variables while also considering the novelty of the recycled plastic modifier, the reclaimed asphalt pavements (RAPs) were prepared using a loose asphalt mixture ageing protocol. Additionally, a rejuvenator made of vegetal derivatives was used as the recycling agent, considering the high recycling rate over each cycle. The comprehensive evaluation of volumetric and mechanical performance revealed that asphalt mixtures containing the recycled plastic modifier performed comparably to unmodified mixtures over two recycling cycles. Furthermore, all the recycled mixtures exhibited superior performance in resistance to rutting, moisture susceptibility, and fatigue compared to the conventional asphalt mixture. Overall, it can be inferred that the asphalt mixture modified with recycled plastic is capable of being recycled over multiple life cycles without compromising its mechanical and performance characteristics.

1. Introduction

The global shift towards a circular economy (CE) is driven by its regenerative growth model, aimed at addressing environmental, climatic, and economic challenges. Its goal is to expedite the transition from the traditional linear economic model to a CE that ensures resource availability while minimising waste generation through sustainable practices [1,2]. In particular, CE promotes the recirculation of materials and energy within the same (closed-loop) or alternative product system (open-loop) [3]. The significance of the CE in reflecting on society's development is also evidenced by the activities and outcomes of the technical committee of ISO/TC 323 "Circular Economy" [4].

Furthermore, the implementation of circular economy principles and sustainability in asphalt pavement construction has prompted exploring cost-effective and eco-friendly alternatives. Asphalt recycling is one such promising alternative, as the use of reclaimed asphalt pavement (RAP) in new asphalt production reduces the demand for non-renewable resources, energy consumption, environmental pollution, waste accumulation, and production costs [5,6]. However, technical issues concerning production, mechanical performance, and durability have restricted the high rate of RAP incorporation in asphalt mixtures, even though it is beneficial [7]. Besides, unpredictable weather conditions and increased traffic volume have influenced the service life and performance of asphalt pavements, leading to pavement deterioration such as rutting, fatigue cracking, and thermal cracking. Consequently, polymer modification has been adopted as a feasible approach to address these premature pavement distresses [8]. It involves the integration of various polymers into either asphalt binders or mixtures to enhance its properties, such as durability, elasticity, resistance to ageing and deformation, thus contributing to the overall quality and extended service life of the pavement structure [9,10]. In asphalt modification, polyethylene (PE), ethylene-vinyl acetate (EVA), polypropylene (PP), styrene-butadiene-styrene (SBS), styrene-isoprene-styrene (SIS), styrene-butadiene-rubber (SBR), and styrene-ethylene/butylene-styrene (SEBS) are the most widely employed polymers [11]. The application of these polymers has the potential to improve either the mechanical

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performance of the asphalt concrete or the rheological characteristics of the asphalt binder, depending on their type and method of application [12]. However, the cost of polymers and their modification methods can be a significant concern, as high-quality polymers and their modification processes tend to be more expensive, thereby contributing to the overall expenses of road construction [13].

Meanwhile, the increasing concern over plastic waste generation, estimated at approximately 300 million metric tonnes annually worldwide, along with its inherently low biodegradability, has prompted the exploration of innovative applications for effectively repurposing plastic waste [14–16]. The focus on managing plastic waste as an end-of-waste resource has led asphalt practitioners and researchers to shift their emphasis towards incorporating waste plastic into asphalt mixtures. This approach addresses the issue of plastic waste to some extent, while also enhancing the performance of asphalt concrete through plastic modification. The recycled plastics can be incorporated into asphalt mixtures via two methods: the wet method and the dry method [17]. In the wet method, recycled plastic is directly introduced to the bitumen and blended with the aid of a high-shear mixer, typically at high temperatures ranging from 160 to 180 °C. The rheological properties of the bitumen can be improved using a typical dosage of 1–8% recycled plastic, based on the weight of the bitumen, and thereby it could enhance the pavement performance at high, intermediate, and low temperatures [18,19]. Several studies indicated that the addition of recycled polyethylene terephthalate (PET) via wet method can increase the rutting resistance, bonding strength [20], moisture susceptibility, low temperature properties [21] and cracking resistance [22]. In addition, binder modification with low density-polyethylene (LDPE) has showed an enhanced impact on workability, resistance to rutting, anti-stripping and adhesive strength [23,24]. However, this approach of modification is limited to recycled plastics with a considerably low melting point. Some studies reported that although adding recycled plastics enhanced binder qualities, some, such as PVC, could emit harmful chloride emissions, making them unsuitable for binder modifications [25].

While in the dry method, recycled plastic can be introduced directly to preheated mineral aggregates prior to being mixed it with bitumen in the production of asphalt concrete. On the basis of the characteristics and type of recycled plastic, such modifications can be served as either a partial substitute for aggregate or as a modifier for asphalt binder or mixture [26]. It has been stated that incorporating recycled plastic using the dry method could also effectively enhance the mechanical characteristics of asphalt concrete. There are several recycled plastics being incorporated using this approach despite of their melting point [27]. For instance, several studies indicated that the addition of recycled polyethylene (PE) via the dry method to the asphalt mixture showed improvements in compactability, rutting resistance, and fatigue cracking resistance [28–30]. In a study, two different recycled plastic modifiers were studied using the dry method. The findings of their study showed that the stiffness modulus, rutting resistance, and fatigue cracking properties of both the asphalt mixtures modified with recycled plastics were similar to those of the reference SBS-modified mixture [31]. From an environmental perspective, recycled plastic incorporation raised a concern over health and safety of the road workers. In response to this, Boom et al. conducted a study investigating the release of carcinogenic compounds from asphalt modified with recycled plastic additives. The findings of their study suggested that recycled plastic-modified asphalt reduces the non-carcinogenic and carcinogenic risk compared to the conventional asphalt [32].

The potential recyclability of plastic-modified asphalt is worth investigating from the perspective of a circular economy. In this regard, Lu et al. studied the recyclability of plastic-modified asphalt mixtures without a rejuvenator and found that asphalt mixtures containing 30 % RAP from plastic-modified asphalt exhibited no detrimental effects on rutting and cracking performances [33]. Similarly, the authors previously explored the feasibility of multi-recycling the asphalt mixtures that have been modified with recycled hard plastic using physical, chemical, and rheological characterization. The findings of their study reported that, from the perspective of binder-scale, asphalt mixtures containing recycled plastic modifiers can undergo multiple recycling cycles without causing any deterioration of their physical and mechanical characteristics [34]. However, the increasing prevalence of incorporating waste plastics into asphalt as modifiers necessitates further research to better comprehend the potential recyclability of pavements modified using such alternatives.

2. Scope and objectives

The literature extensively explored the efficiency of various recycled plastics in enhancing the rheological and mechanical performance of asphalt binders and mixtures. However, certain aspects, such as the characteristics of RAPs containing recycled plastics and their recyclability, are some of the missing information that needs to be addressed. It is crucial to gain a comprehensive understanding of RAP-containing recycled plastic modifiers, considering the increasing trend of incorporating recycled plastic as an asphalt modifier and the significance of RAP recycling. Currently, limited research exists on this topic; meanwhile, the multi-recyclability of asphalt mixtures has not been properly investigated. Therefore, the present study focuses on investigating the feasibility of multi-recycling the asphalt mixtures, with and without a recycled plastic modifier, at a 50 % recycling rate for two recycling cycles using a comprehensive volumetric and mechanical performance evaluation.

3. Materials and methods

3.1. Materials

3.1.1. Mineral aggregates

In this study, limestone aggregates in various fractions were used based on local availability. Moreover, it was observed that these aggregates are commonly utilised for highway construction in the southern region of Italy. The detailed information about the characteristics of the aggregates can be found in Table 1.

3.1.2. Bitumen

In this research, a paving grade bitumen with a penetration of 50/70 was utilised. Table 2 provides some of the physical properties of the bitumen.

3.1.3. Recycled plastic-modifier

The study used an innovative recycled plastic modifier, as shown in Fig. 1, to modify the asphalt mixture. The modifier, referred to as graphene-enhanced recycled plastic, hereafter GRP, is composed of recycled hard plastics and graphene nanoparticles. The GRP modifier comes in pellet form, typically ranging from 3 to 5 mm in size. Table 3 presents some of the technical characteristics of the GRP modifier.

3.1.4. Rejuvenator

A bio-based commercial rejuvenator, referred to as R, made up of vegetal derivatives was employed as the recycling agent in the study due to its proven performance in previous research [34]. Table 4 provides

Table 1
Characteristics of limestone aggregates.

Characteristics	Unit	Value	Standard
Apparent density of aggregates	g/cm^3	2.82	EN 1097-6
Resistance to fragmentation	%	20	EN 1097-2
Flakiness index	%	7	EN 933-3
Sand Equivalent	%	90	EN 933-8
Polished stone value	PSV	46	EN 1097-8

Table 2
Physical properties of the bitumen.

Properties	Unit	Value	Limit	Standard
Density at 25 °C	g/cm^3	1.03	1.01–1.06	EN 15326
Penetration	dmm	53	50–70	EN 1426
Softening point	°C	49.6	46–54	EN 1427
Dynamic viscosity at 160 °C	Pa.s	0.14	0.03–0.15	EN 13302
Fraass breaking point	°C	−6	≤ −6	EN 12593

Fig. 1. The recycled plastic modifier.

Table 3
Technical characteristics of the GRP modifier.

Parameters	Unit	Aspect/Value
Material State	–	Granules
Colour	–	Black
Apparent density at 25 °C	g/cm^3	0.4–0.6
Softening Point	°C	160–180

Table 4
Technical characteristics of the rejuvenator.

Parameters	Unit	Aspect/Value
Material State	–	Liquid
Colour	–	Dark brown-purple
Density at 25 °C	g/cm^3	0.85–0.95
Viscosity at 25 °C	cP	50–150
Flash point	°C	≥200
Pour point	°C	≤0

the technical characteristics of the rejuvenator.

3.2. *Experimental plan*

The experimental plan aimed to assess the feasibility of multi-recycling the asphalt mixture modified with recycled plastic, as compared to the conventional mixture. Fig. 2 presents the experimental plan for this research, which included two sets of asphalt mixtures: unmodified and GRP-modified asphalt mix. The study focused on evaluating the recyclability of these mixtures, at a recycling rate of 50 % for two recycling cycles through comprehensive volumetric and mechanical performance characterization. The abbreviations used for the studied mixtures, along with their descriptions, are provided below.

- **CA-0:** unmodified asphalt mixture (conventional asphalt mix), consisting of 100 % virgin materials.
- **CA-1:** First-cycle recycled mixture of the conventional mix, consisting of 50 % RAP of CA-0 and 50 % virgin materials, along with a rejuvenator.
- **CA-2:** Second-cycle recycled mixture of the conventional mix, consisting of 50 % RAP of CA-1 and 50 % virgin materials, along with a rejuvenator.
- **GRPA-0:** asphalt mixture modified with recycled plastic, consisting of 100 % virgin materials and GRP modifier.
- **GRPA-1**: First-cycle recycled mixture of the recycled plastic-modified asphalt mix, consisting of 50 % RAP of GRPA-0 and 50 % virgin materials, along with a rejuvenator.
- **GRPA-2:** Second-cycle recycled mixture of the recycled plastic-modified asphalt mix, consisting of 50 % RAP of GRPA-1 and 50 % virgin materials, along with a rejuvenator.

3.3. *Mix design and specimen preparation*

The mix design for unmodified and GRP-modified asphalt mixtures was performed in accordance with the Italian technical specifications for highways [35]. In this study, both asphalt mixtures were prepared for a dense-graded surface course with a nominal maximum aggregate size of 12.5 mm. Fig. 3 presents the design gradation curve of the optimised mix. For the unmodified asphalt mixture, the binder content was optimised based on the Superpave volumetric method, which resulted in an identified binder content of 5 % by weight of the aggregates. The specimens prepared using the gyratory compactor demonstrated 4 ± 0.5 % air voids at 120 gyrations, adhering to the recommended limit prescribed by the technical specification.

Meanwhile, the recycled plastic-modified asphalt mixture was prepared using the same mix gradation as previously stated. The GRP modifier was incorporated into the asphalt mixture via the dry method; specifically, 6 % GRP modifier by weight of bitumen was added to the hot aggregates approximately 1 h prior to the mixing phase with bitumen. This process enables the recycled plastic granules to soften, enhancing the workability of the mixture. Furthermore, a total binder content of 5 % by weight of aggregates was used for producing the GRP-modified asphalt mixture, and a mixing temperature of 170 ± 5 °C was employed based on the softening point of the GRP granules.

3.4. *Artificial RAP production*

Considering the crucial aspect of this research regarding the recyclability of recycled plastic-modified asphalt mixtures, it is essential to study the characteristics of the RAP coming from plastic-modified asphalt pavements. In this study, an innovative recycled plastic, specifically the GRP modifier, was utilised for modifying the asphalt concrete. However, RAP sources from GRP-modified asphalt pavements were unavailable, so the study necessitated manufacturing such RAP within the laboratory. Moreover, this research utilised the dry method approach for incorporating the GRP modifier into the asphalt mixture, as there is no established standard protocol for ageing loose asphalt mixtures. The authors have previously conducted studies on the impact of thermo-oxidative ageing on loose asphalt mixtures using the same bitumen, and the results were consistent with the collected RAPs from the same region [36]. Although multiple variables contribute to the ageing process of asphalt concrete, thermo-oxidative ageing is one of the predominant factors among them. Therefore, this study employs a loose asphalt mixture ageing protocol to simulate the effects of ageing and the end-of-life scenarios on both the asphalt mixtures, unmodified and GRP-modified, to provide a comprehensive understanding of their characteristics.

In order to prepare the RAPs, the unmodified asphalt mixture and the GRP-modified asphalt mixture were produced according to their defined mix design. After the mixing process, these two asphalt mixtures were placed in separate trays with a maximum thickness of 25 mm. The trays were then kept in the oven at 135 °C for 4 h to simulate the short-term ageing. Afterwards, the trays were taken out to cool, and to simulate the long-term ageing effect, the trays were again kept at 95 °C for 5 days in the oven. The procedure was repeatedly applied to produce RAPs of both the recycled mixtures for their further recycling stages.

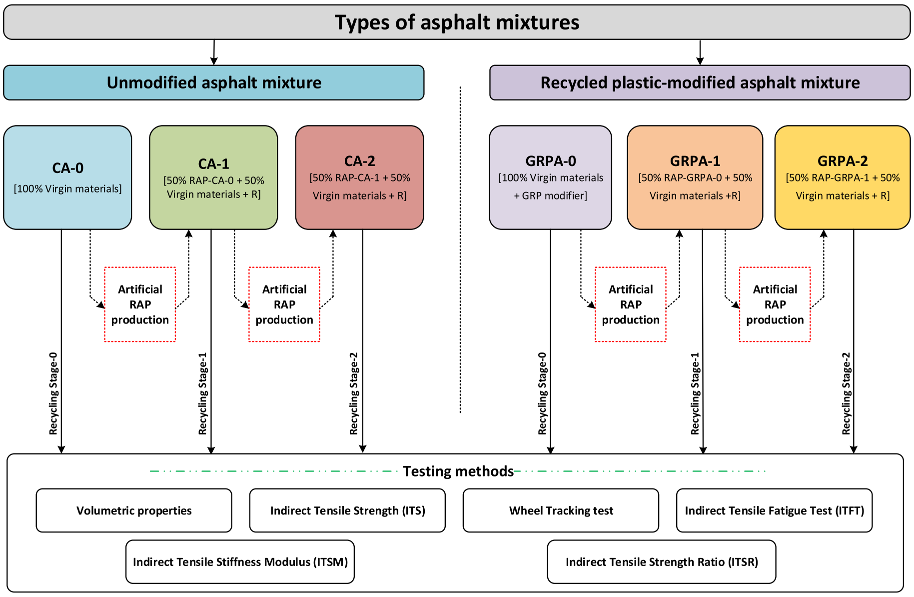

Fig. 2. Experimental plan.

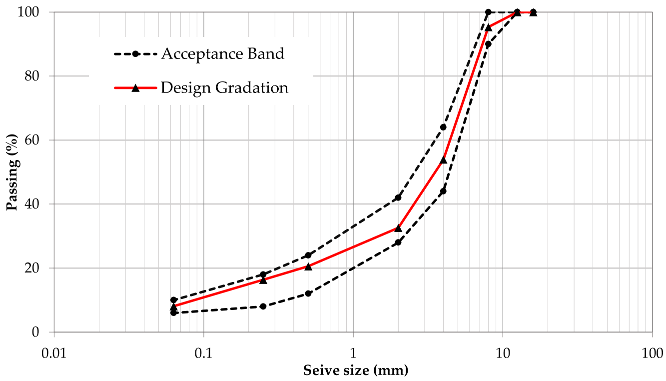

Fig. 3. Design gradation of the mix.

3.5. *Simulation of multiple recycling*

The research comprehensively evaluates the viability of recycling asphalt mixtures, with and without a recycled plastic modifier, to ascertain if these mixtures can be effectively recycled multiple times in a comparable manner. To achieve this goal, as shown in Fig. 2, a systematic approach was formulated to assess their recyclability, which involves multiple ageing and recycling phases with a consistent recycling rate of 50 % at each cycle. Initially, both asphalt mixtures were prepared according to their defined mix designs. Subsequently, the subsets of these mixtures were subjected to the accelerated ageing process explained in the former section to produce their respective RAPs. The recycling process involves systematically using 50 % manufactured RAP from the preceding cycle along with 50 % virgin materials (aggregates and bitumen) to produce their subsequent recycled mixtures. For instance, GRPA-1, the first recycling cycle for the plastic-modified asphalt mixture, was produced by combining 50 % virgin materials with 50 % RAP derived from the GRPA-0 mix, along with an optimised rejuvenator dosage. The process is repeated for its second recycling cycle, where, in this case, the recycled mixture is composed of 50 % virgin materials and 50 % RAP derived from the GRPA-1, along with an optimised dosage of rejuvenator. The same methodology was applied to recycle the conventional mixture as well.

The mix design for all the recycled mixtures, regardless of the recycling cycle, was kept similar to that of the conventional asphalt mix. This approach was chosen for comparative analysis with the conventional asphalt mix and to better understand the activation level of aged binders in the RAPs during recycling. Consequently, an optimal binder content of 5 % by weight of the aggregates was maintained for all recycled mixtures at both cycles. Considering a 50 % recyclability rate, 2.5 % virgin bitumen (based on the weight of the total mixture) along with an optimised dosage of rejuvenator was added at each stage of recycling under the assumption that the remaining portion of binder from RAP would fully activate upon the mixing phase and blend with bitumen. Furthermore, before the mixing phase, the optimised rejuvenator dosage was introduced to the pre-heated virgin bitumen at 160 °C. Subsequently, the bitumen-rejuvenator blend was manually stirred for about 1 min and then placed in an oven at the mixing temperature of 160 °C for 10 min to ensure consistency. Table 5 summarises the optimised dosages of rejuvenator used in the study to attain the targeted characteristics for the recycled mixtures at each cycle, based on the findings from a preliminary study conducted by the authors [34].

3.6. *Test methods*

The test methods used in the study were performed in accordance with the European standard testing methods and adhered to the Italian technical specification for highways. The following laboratory tests were conducted to achieve the goal of this study.

3.6.1. *Volumetric properties*

The volumetric properties of the asphalt mixtures were evaluated in accordance with EN 12697-8 guidelines [37]. To achieve this, three specimens with a diameter of 100 mm from each mixture were compacted using a gyratory compactor up to 210 gyrations, as stipulated by the Italian technical specification. As per the technical specifications, determining air voids content at specific gyration levels such as 10, 120,

Table 5
The dosage of rejuvenator at each recycling cycle.

Recycled mixture	Recycling cycle	Optimum dosage[a]	Recycled mixture	Recycling cycle	Optimum dosage[a]
CA-1	1	4.5 %	GRPA-1	1	5.5 %
CA-2	2	4.5 %	GRPA-2	2	4.5 %

[a] Rejuvenator dosage is based on the weight of the aged binder in RAP.

and 210 is crucial for approving mixtures intended for use on highways. Moreover, other volumetric parameter such as voids in mineral aggregates (VMA), voids filled with binder (VFB) and the bulk density (G_{mb}) of each mixture were also studied.

3.6.2. *Indirect tensile strength*

The purpose of this test was to determine the indirect tensile strength (ITS), which refers to the maximum tensile stress calculated from the peak load applied to a cylindrical specimen loaded diametrically at a rate of 50 mm/min until it fails. It clearly provides information on the cohesion and tensile strength of the asphalt mixtures. In accordance with EN 12697-23 [38], three specimens from each mixture compacted at 120 gyrations were tested after being conditioned at 25 °C for 4 h. The ITS can be calculated as follows:

$$ITS = \frac{2\ .P}{\pi\ .d\ .\ h}.1000 \tag{1}$$

In the equation, *ITS* in kPa, *P* is the peak load in N, *d* is the diameter of the specimen in mm, and h is the thickness of the specimen in mm.

3.6.3. *Indirect tensile stiffness modulus*

The indirect tensile stiffness modulus (ITSM) test was conducted to measure the resilient stiffness of the asphalt mixtures. The test was performed on a servo pneumatic load machine, which applies 5 load pulses on the cylindrical specimen at a rise time of 80 ms to achieve the specified target horizontal deformation according to the Annex C of EN 12697-26 [39]. In this study, in order to investigate the linear visco-elastic behaviour of the asphalt mixtures, three test temperatures of 10 °C, 20 °C and 30 °C were carried out. The stiffness modulus of each pulse can be calculated using the following equation.

$$E = F.(\nu + 0.27) / (z.h) \tag{2}$$

In Equation (2), *E* is the stiffness modulus in MPa, ν is the Poisson's ratio (assumed as 0.35), *F* is the applied load in N, *z* is the amplitude of the resilient horizontal deformation and *h* is the thickness of the specimen in mm.

3.6.4. *Indirect tensile strength ratio*

The moisture susceptibility of the asphalt mixtures was determined using the indirect tensile strength ratio (ITSR), defined as the ratio of the indirect tensile strength of wet specimens to dry specimens. In accordance with EN 12697-12 [40], three specimens from each asphalt mixture were conditioned in a water bath at 40 °C for 72 h, followed by conditioning in an air chamber at 25 °C for 4 h.

3.6.5. *Wheel tracking test*

The wheel tracking test was conducted to evaluate the rutting resistance of the asphalt mixtures under repetitive wheel loads. The samples were prepared in accordance with EN 12697-22 [41], which involved producing two slabs measuring 305 x 305 × 50 mm for each mixture using a roller compactor. To ensure consistency, all specimens from each mixture were compacted to achieve a targeted air void range of 4 ± 0.5 %. Prior to the test, the samples underwent conditioning at the test temperature of 60 °C for 4 h within the chamber of the wheel tracking device. The test involved applying a load of 700 N to the specimen using a solid rubber tyre that reciprocated over it, covering a distance of 230 ± 10 mm. The frequency of the wheel was maintained at 26.5 cycles per minute while traversing across the specimen. The test was conducted under the condition that it would terminate when it reached 20000 passes or a maximum rut depth of 20 mm. Additionally, the wheel tracking slope (*WTS*) and the proportional rut depth (*PRD*) can be calculated using the following equation to see the trend of rutting among the studied mixtures.

$$WTS_{Air} = (d_{10000} - d_{5000}) / 5 \tag{3}$$

$$PRD = 100.(d_n - d_0) / h \tag{4}$$

In equation (3), *WTS* is the wheel tracking slope in mm/10^3 load cycles, d_{10000} is the rut depth measured in mm after 10000 cycles and d_{5000} is the rut depth measured in mm at 5000 cycles. While in equation (4), *PRD* is the proportional rut depth in %, d_n is the rut depth in mm after n load cycles, d_0 is the initial rut depth in mm, and *h* is the thickness of the slab in mm.

3.6.6. *Indirect tensile fatigue test*

The indirect tensile fatigue test (ITFT) was performed to evaluate the fatigue life of asphalt mixtures by applying repeated load pulses in a constant stress-controlled mode using an indirect tensile method according to EN 12697-24 [42]. A servo-pneumatic loading machine applied repeated haversine compressive load pulses along the vertical diameter of the specimen with a 0.1 s load time and 0.4 s rest time, inducing uniform tensile stress perpendicular to the applied load and ultimately causing specimen failure. The study was performed at 20 °C, which included three stress levels (150, 250, and 350 KPa) for each mixture. A minimum of three cylindrical specimens were prepared for each stress level, resulting in a total of nine specimens tested per mixture to assess the fatigue life. The fatigue life refers to the total number of load cycles that lead to the failure of the specimen. According to the defined failure criteria, a specimen is considered to fail when the number of load cycles at which either the specimen completely splits, or the horizontal strain reaches 200 % of the initial strain value. The data obtained during the fatigue test can be used to obtain the least-squares regression lines, which represents the fatigue behaviour of the mixture, expressed by the following equation.

$$N_f = k_\varepsilon\ .\ (1/\varepsilon_0)^{n_\varepsilon} \tag{5}$$

In equation (5), N_f is the number of load cycles to failure, $\mathscr{E}_0$ is the initial strain in µm/m, and $k_{\mathscr{E}}$, $n_{\mathscr{E}}$ are the regression parameters.

4. Results and discussion

4.1. *Volumetric properties*

Table 6 provides a summary of the determined volumetric characteristics of the asphalt mixtures. The obtained results indicate that all the studied mixtures comply with recommended technical limits, affirming the validity of the mix design. It is worth noting that, at 120 gyrations, all mixtures exhibited an air voids content within a range of 4–5%. The data obtained from the compaction process was used to create the densification curves for the asphalt mixtures, depicted in Fig. 4, indicating the relationship between the applied number of gyrations and the relative density of the compacted specimen. In this analysis, a slightly higher air voids content was observed in the curve of the recycled plastic-modified mixture (GRPA-0) compared to the conventional one. However, this trend did not persist across subsequent cycles of recycling,

Table 6
Volumetric properties of the gyratory compacted specimens.

Mixture	Air voids content (%)			VMA (%)	VFB (%)	G_{mb} (kg/m^3)
	10 gyrations	120 gyrations	210 gyrations			
CA-0	13.3	4.4	2.6	15.8	72.0	2461
CA-1	13.5	4.2	2.2	16.2	74.0	2467
CA-2	13.1	3.9	2.1	15.9	75.1	2476
GRPA-0	13.7	5.1	3.3	17.8	71.4	2452
GRPA-1	13.6	4.3	2.4	16.2	73.7	2465
GRPA-2	13.0	4.1	2.1	16.0	74.4	2462

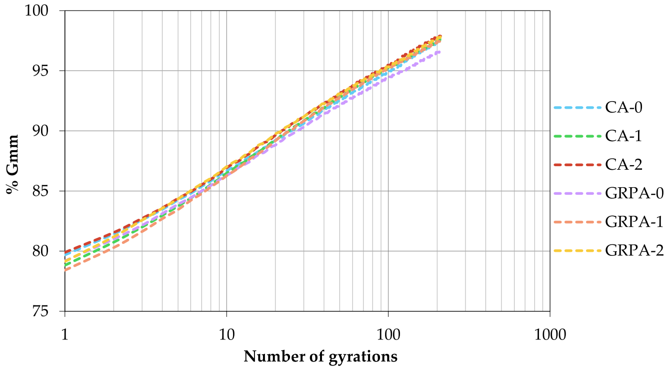

Fig. 4. Densification curve of the mixtures.

as evidenced by GRPA-1 and GRPA-2. The densification curve significantly illustrates the compaction trend of all the mixtures, and from that, it is clear that the dry method modification with recycled plastic did not adversely affect the compactability of the mixture. Notably, all the recycled mixtures at both recycling cycles demonstrated comparable densification curves with those of the conventional mix, indicating that the rejuvenator reactivates the aged binder during mixing phases and leads to workability comparable to that of a conventional mix. In addition, the mixture GRPA-0 showed a slightly lower bulk density among others, as the incorporation of the modifier lowers the density of the modified mixture. However, other volumetric parameters, such as VMA and VFB, of all the studied mixtures are within the acceptable threshold, ensuring good volumetric performance.

4.2. Indirect tensile strength

The results of the ITS test are shown in Fig. 5. The findings indicate that the ITS value of the recycled plastic-modified asphalt mixture is significantly higher than that of the unmodified mixture, with a 29 % increase. It signifies that the addition of the GRP modifier improved the cohesion and tensile strength of the mixture, which resulted in a high ITS value. In particular, in first-cycle recycled mixtures, CA-1 and GRPA-1 showed superior performance in ITS compared to the reference conventional mix (CA-0), consistent with previous studies suggesting that incorporating RAP into asphalt mixtures increases their tensile strength [43]. However, as anticipated, there was a slight decline in the ITS values for GRPA-1 (3.6 %) and GRPA-2 (7.3 %) compared to GRPA-0 because rejuvenator dosage was optimised to achieve comparable performance to conventional asphalt at each cycle; however, these recycled mixtures outperformed the reference mixture. Overall, all results for the recycled mixtures at both recycling stages comply with the technical limits (ITS = 0.90–2.2 MPa) suggested by the Italian highway authority. Based on this, it is obvious that modifying the asphalt mixture with recycled plastic did not have a negative impact on its tensile strength throughout the recycling cycles.

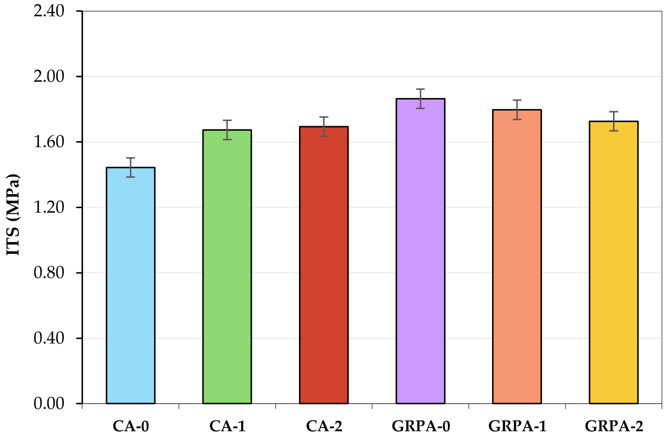

Fig. 5. ITS results of the mixtures.

4.3. Indirect tensile stiffness modulus

Fig. 6 illustrates the average ITSM values for the tested mixtures at three different temperatures. The asphalt mixture modified with recycled plastic, GRPA-0, consistently exhibited a significantly higher stiffness modulus compared to the unmodified mix, CA-0 across all the test temperatures, confirming the substantial impact of the GRP modifier on mixture stiffness. In the first recycling phase, both CA-1 and GRPA-1 demonstrated a marginal reduction in ITSM values compared to the conventional mix. This minor decline in stiffness modulus could be attributed to the effects of rejuvenation and aggregate distribution within the recycled mixtures. Despite the varying dosages of the rejuvenator in CA-1 and GRPA-1, both exhibited comparable ITSM values throughout all tested temperatures, affirming that recycling asphalt mixtures containing recycled plastic performs similarly to that of the conventional asphalt. Furthermore, this trend of a slight decrease in stiffness modulus was also observed in subsequent recycling phases. CA-2 and GRPA-2 showed comparable ITSM values among themselves and with their prior cycles. It is worth noting that the rejuvenated mixtures did not undergo severe ageing compared to their predecessors during multiple ageing cycles, which can be identified by the similar dosage of rejuvenation used for both CA-2 and GRPA-2 compared to the first-cycled recycled mixtures. It is obvious that if severe ageing occurred, it would have substantially influenced the stiffness modulus of the recycled mixtures and could be identified with a higher magnitude; however, this trend was not observed in this study. This suggests that, with the right selection and dosage of rejuvenators, recycled mixtures exhibit less severity of ageing compared to non-recycled mixtures. Besides, the Italian technical specification requires the ITSM value at 20 °C to be within the range of 3000–8000 MPa for a conventional asphalt mix. The obtained results showed that all the recycled mixtures at both recycling cycles are within these recommended limits, indicating that the recycled plastic modifier has no detrimental effect on recycling asphalt mixtures containing such a modifier.

4.4. Indirect tensile strength ratio

The average ITSR results are presented in Fig. 7. The results showed that all mixtures demonstrated significantly high ITSR values, exceeding the recommended threshold limit of 75 % suggested by the Italian technical specification. In this assessment, it was observed that the conventional mix performed better than the recycled plastic-modified asphalt mixture. The effect of recycled plastic in GRPA-0 mixture slightly reduced the ITSR value, which is 16 % less than that of CA-0.

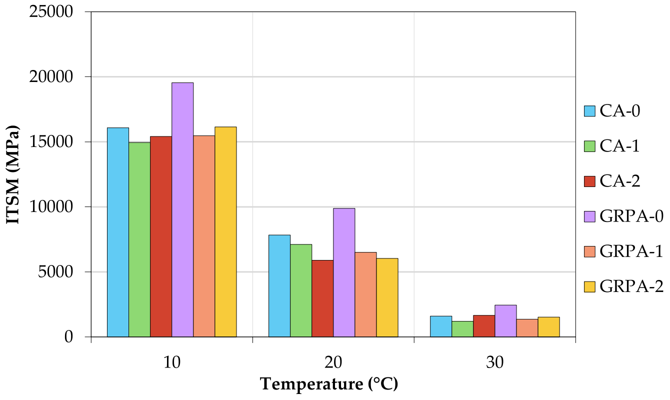

Fig. 6. ITSM results of the mixtures.

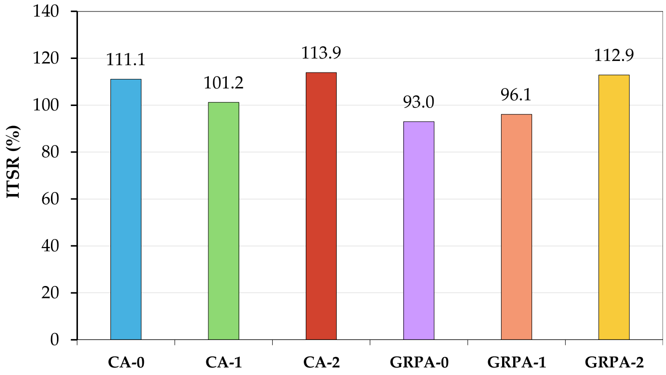

Fig. 7. ITSR results of the mixtures.

Furthermore, the first-cycle recycled mixtures, CA-1 and GRPA-1, demonstrated a slight decline in ITSR values, i.e. 8.9 % and 13.5 % respectively, compared to CA-0, while the second-cycle recycled mixtures outperformed among all other mixtures. However, an increasing trend of resistance to moisture susceptibility was observed in the recycled plastic-modified mix over two recycling cycles. It is important to note that limestone aggregates, which are known for being less susceptible to moisture impact, were utilised in this study. Consequently, the adhesive bonding strength between the aggregates and the binder remains unaffected by moisture, and wet conditioning may contribute to increased stiffness, ultimately resulting in a higher ITS of the wet subsets. This could potentially contribute to the overall superior performance observed during the moisture susceptibility evaluation.

4.5. *Wheel tracking test*

Fig. 8 shows the evolution of rut depth obtained from the wheel tracking test over the load cycles, while Table 7 provides a summary of rutting parameters such as rut depth, WTS, and PRD for all mixtures. The results indicate significant differences in these parameters between the asphalt mixtures containing recycled plastic and the conventional mixture. Specifically, the recycled plastic-modified mixture (GRPA-0) exhibited a reduced rut depth of 2.9 mm compared to the reference unmodified mixture (CA-0), which had a substantially higher rut depth of 5.2 mm. Furthermore, comparing other rutting parameters between these two mixtures reveals that GRPA-0 showed an 82.6 % reduction in wheel tracking slope and a 44.8 % reduction in proportional rut depth compared to CA-0. The improved resistance to rutting observed with the recycled plastic-modified mix demonstrates its efficacy for high-temperature performance, which aligns with existing literature [44]. Furthermore, improved resistance to rutting was also evident in all the recycled mixtures during two recycling cycles when compared to the conventional mix. It is worth noting that during wheel tracking slope evaluation, GRPA-1 showed a marginally steeper slope compared to that of CA-1; this could be attributed to different rejuvenator dosages (1 % more) used during the recycling stage of the GRPA-1 mix. However, this variation in wheel tracking slope did not affect their final rut depth, which was identical. Some previous studies have reported that a higher dosage of rejuvenation can lead to increased rutting depth due to excessive softening of the binder [45]. Among all the evaluated mixtures, GRPA-2 exhibited the highest resistance to rutting, with a minimal rut depth of 2.3 mm and a proportional rut depth of 4.6 %. The higher resistance to moisture susceptibility identified in the ITSR test for the second-cycle recycled mixtures is consistent with the results of the rutting test, indicating their improved high-temperature performance.

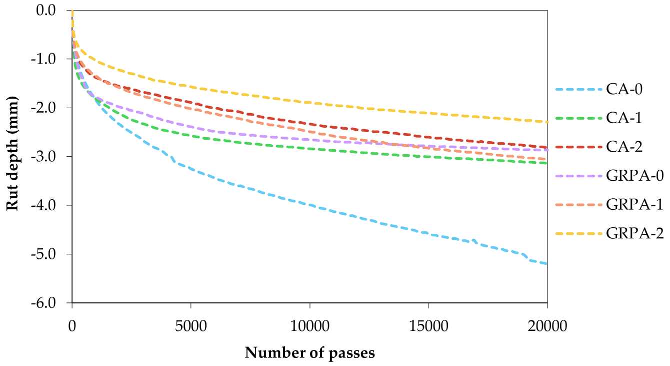

Fig. 8. Rut depth versus number of passes.

Table 7
Evaluated rutting parameters.

	CA-0	CA-1	CA-2	GRPA-0	GRPA-1	GRPA-2
Rut depth (mm)	5.2	3.2	2.8	2.9	3.1	2.3
WTS$_{Air}$ (mm/10^3 cycles)	0.24	0.07	0.10	0.04	0.11	0.08
PRD$_{Air}$ (%)	10.4	6.3	5.6	5.7	6.1	4.6

4.6. *Indirect tensile fatigue test*

Fig. 9 illustrates the fatigue life of asphalt mixtures in relation to their initial tensile strain and the total number of load cycles until failure. The fatigue life equations along with the co-efficient of determination are included in the figure. It is significant that that all the fatigue lines have co-efficient of determination higher than that of 0.90, which indicate a good statistical correlation within the obtained results to predict the fatigue behaviour. The results indicate that incorporating recycled plastic via dry method improved the fatigue life of the modified asphalt mix, potentially extending its service life compared to conventional pavements, aligning with previous research. The enhancement in fatigue life can be identified by the lower slope of the fatigue line. Conversely, the conventional mix (CA-0) exhibited higher initial strain at all stress levels compared to other mixtures, leading to inferior fatigue performance. In contrast, GRPA-0 showed lower initial strain across all stress levels than other mixes, although it showed higher stiffness modulus at the test temperature. Notably, the recycled mixtures from both plastic-modified and conventional mixtures showed higher fatigue performance at each recycling cycle compared to the conventional mix, which can be observed from the fatigue model. This could be attributed to the influence of rejuvenation, which altered the viscoelastic behaviour of these mixtures, which was also evident by the lower stiffness modulus obtained in the ITSM test at 20 °C. The same enhanced trend was also observed in the second-cycle recycled mixtures (CA-2 and GRPA-2). Furthermore, in order to compare the fatigue life within the investigated mixtures, an initial strain of 75 μm/m has been considered. The comparison with this initial strain revealed that the asphalt mixtures such as GRPA-0, GRPA-1, GRPA-2, CA-1, CA-2 have a fatigue life more than 74 %, 67 %, 36 %, 41 %, 23 % respectively to that of conventional mix. In this regard, it is evident that the influence of recycled plastic enhanced the fatigue life of the mixtures at each recycling cycle nevertheless fatigue life over each cycles decline compared to their predecessors. This was expected, as during the repeated recycling at a 50 % rate, the content of the recycled plastic-modified mixtures gets reduced over the recycling phases, along with the rejuvenation could impact the behaviour of the mixture.

5. Conclusions

The present study investigated the feasibility of multi-recycling asphalt mixtures modified with and without a recycled plastic modifier at a recycling rate of 50 % for two recycling cycles. An innovative recycled plastic, the GRP modifier, was used in this study to modify the

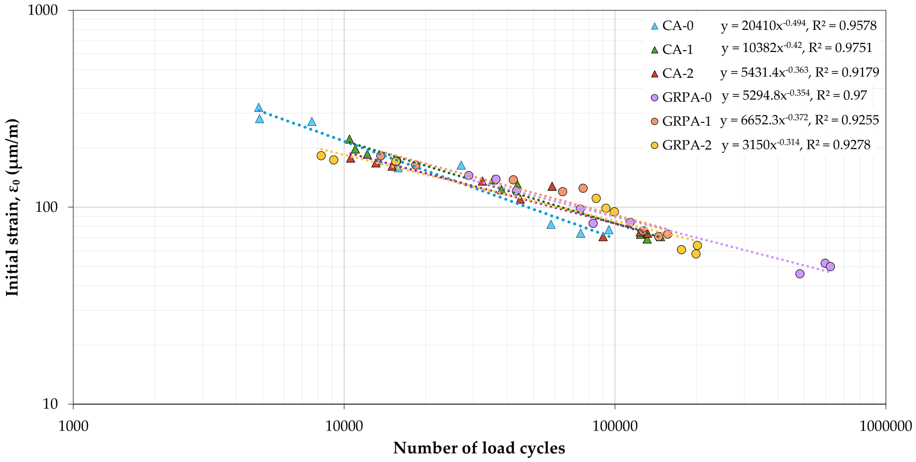

Fig. 9. Fatigue behaviour of the mixtures.

asphalt mixture using the dry method. The viability of recycling these asphalt mixtures for two cycles was comprehensively evaluated through volumetric and mechanical characterization. The following conclusions can be drawn based on the findings.

- The incorporation of the innovative recycled plastic modifier in the asphalt mixture via the dry method significantly improved the volumetric and mechanical performance of the asphalt mixture, as evident when compared to the unmodified mixture.
- The influence of the rejuvenator did not have a negative effect on the compactability and mechanical behaviour of the recycled mixtures over two recycling cycles. However, a slightly lower stiffness modulus was observed at 20 °C compared to the conventional one, although the results are within the recommended limits of Italian technical specifications.
- The asphalt mixtures, both modified with and without the recycled plastic, at a recycling rate of 50 % over the two cycles demonstrated higher tensile strength and improved resistance to moisture compared to the recommended technical limits.
- All recycled mixtures, regardless of their origin and recycling cycle, exhibited substantially higher resistance to rutting compared to the conventional mixture.
- The analysis of fatigue life indicated that the asphalt mixture modified with recycled plastic has superior fatigue resistance compared to the conventional mixture. Additionally, all the recycled mixtures with a 50 % recycling rate also showed significant improvement in the fatigue life cycle. This implies that an effective recycling approach could enhance the fatigue resistance of mixtures containing a high RAP content, regardless of their origin.

Overall, based on the findings, it is evident that the asphalt mixture, when modified with a recycled plastic modifier, can be effectively recycled over multiple life cycles without compromising their volumetric and mechanical characteristics, which are comparable to conventional asphalt. The study contributes to understanding the potential recyclability of asphalt mixtures containing recycled plastic, which is crucial for promoting circular economy practices in the road engineering sector. This approach creates confidence and opportunities for stakeholders and decision-makers to implement closed and open-loop recycling strategies, integrating more waste alternatives into the road industry. Consequently, this reduces the reliance on virgin materials, thereby lowering costs and energy consumption while enabling products to maintain their value and performance in the market for an extended period. Further research is underway to explore a wide range of recycled plastics and incorporate them into asphalt via both wet and dry methods to gain a broader perspective.

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CRediT authorship contribution statement

Vineesh Vijayan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Evangelos Manthos:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis. **Konstantinos Mantalovas:** Visualization, Data curation. **Gaetano Di Mino:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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