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STRUCTURAL AND ENVIRONMENTAL ASSESSMENT OF HIGH-PERFORMANCE ASPHALT MIXES WITH A HIGH RECLAIMED ASPHALT PAVEMENT CONTENT: A CASE STUDY

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Abstract

Nowadays, attention in the construction sector is increasingly turning towards the concept of sustainability, efficiency and durability to reduce atmosphere emissions. The A4 Turin-Milan motorway is pushing in this direction. In particular, from the pavement point of view, one of the most important innovations introduced by the road manager is the study of bituminous mix with about 70% of reclaimed asphalt pavement (RAP); this methodology is today possible thanks to the use of rejuvenating agents, the implementation of next-generation asphalt plants, and the introduction of a graphene-enhanced polymeric compound (GPC), through which it is possible to obtain high-performance asphalt concrete (up to +75% of service life) with a consequent reduction in future maintenance if compared to the existing pavement. The new technology was experimented first in the construction of a 1 km long trial section at the end of 2022. With the aim of validating the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analyses prior to the production of the mixtures, laboratory and field tests were carried out specifically aimed at assessing the structural characteristics of the mixtures. Mixtures used were previously tested in the laboratory and showed an increase in the average stiffness and strength values at 20 °C and 25 °C up to 50% compared to average values of traditional mixes. From the time of construction, the trial section is being monitored visually as well as by Falling Weight Deflectometer (FWD) tests. The results obtained in the first 500 days of life seem to be promising compared to the assumptions made for the LCA and LCC analyses (10% less deflection when compared to materials traditionally used by the road operator). In fact, a very stable and effective behaviour of the new pavement under relevant traffic loads could be recognized.

Key words: asphalt concrete, graphene-enhanced polymeric compound, service life, sustainability, rejuvenator

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1. Introduction

The transport sector has grown strongly in recent decades, and this has led to a significant impact on the environment (Yang et al., 2015). Several countries around the world are pushing for policies that urge the replacement of the linear economy model with a circular economy model (Mantalovas and Di Mino, 2020). These directives have also been implemented in the field of road construction. In order to drastically reduce atmospheric emissions and achieve climate neutrality by 2050, the two strategies promoted by the European Union are the use of recycled material and the extension of the service life of pavements (MIMS, 2022). Specifically, materials must be carefully selected to take into account both performance and economic, social and environmental aspects (Aurangzeb et al., 2014).

Nowadays, to assess the environmental and economic impact of a technology, or simply to compare two different solutions with each other, there are two different tools, namely Life Cycle Assessment

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(LCA) and Life Cycle Cost Costing (LCC) (Salehi et al., 2021).

The use of by-products and/or waste has the dual benefit in reducing environmental impact, in terms of reduced space in the landfill, and limiting the use of raw materials from both renewable and non-renewable resources (Andersen, 2007; Yaro et al., 2023). An example of circular economy application is the use of RAP for the construction of new asphalt concrete mixes (da Costa et al., 2024). However, in some countries around the world, RAP is not seen as a valuable resource and therefore national regulations severely restrict their use in road pavements (Jaawani et al., 2021). RAP consists of aggregates coated with aged bitumen (which has undergone oxidative processes over time), which when used in high quantities, if not properly treated with regenerating products, leads to a drastic increase in the stiffness of the final bituminous mix, resulting in premature cracking (Prosperi and Bocci, 2021). There are various types of products on the market for using RAP, however it is important to emphasise that not all of them are capable of restoring the chemical properties of RAP aged bitumen (Abe et al., 2023). Among them, we can distinguish between softening agents, which simply reduce the viscosity and stiffness of aged bitumen (Ismael and Khaled, 2018), and regenerating agents, that restore the physical-chemical properties of aged bitumen (Loise et al., 2021). Thanks to the latter and the advent of increasingly advanced asphalt plants, it is possible to recycle large quantities of RAP up to 60-70% (Lee et al., 2015; Lu et al., 2019; Pasetto et al., 2021; Porot et al., 2017).

Another possibility for sustainability is to increase the service life of pavements using high-performance materials. The reduced environmental impact is due to the minimised use of materials and energy during the life cycles (PIARC, 2019). There are numerous studies by the scientific community on high-performance materials (Huang et al., 2023; Li et al., 2017; Ma et al., 2016; Mi et al., 2022; Moreno-Navarro et al., 2016; Ranieri and Celauro, 2018). Noteworthy among them are asphalt mixes modified with graphene-based compounds (Asim et al., 2022). These special compounds improve asphalt performance by increasing the rutting resistance (Hafeez et al., 2019), the fatigue resistance (Adnan et al., 2021), the fracture toughness and fracture energy (Wang et al., 2018), and reducing the temperature sensitivity (Hafeez et al., 2019) and the ageing susceptibility (Li et al., 2021a; Li et al., 2021b; Wu et al., 2017). In the last years, a special compound of graphene and selected recycled plastics has been introduced. These compounds allow both to improve the performance of the asphalt mix, but at the same time to reduce the environmental impact thanks to the reuse of plastics normally destined for waste-to-energy plant (Russo et al., 2022). Being a dry modification method, they are added directly into the mix and not through the bitumen (wet modification method), so that highly modified mixes can be obtained even when high quantities of RAP and consequently low quantities of raw bitumen are used (Bruno et al., 2024). They have already been used in several important applications such as bridges, high traffic roads, motorways and airports showing excellent potential (Meroni et al., 2022; Moretti et al., 2021; Russo et al., 2022; Venturini et al., 2022).

In the last decade, the increase in vehicle traffic, technological development and the introduction of self-driving vehicles have led to roads being thought of not only as a means of carrying loads, but rather as a means of communication and information exchange, if not even as a source of energy (Smart Roads) (Trubia et al., 2020). Among the systems that can be used in a smart road are those that allow real-time monitoring of vehicular traffic, analysis of user behaviour, electronic payment, charging of electric vehicles, monitoring of pavement condition through Building Information Modelling (BIM) models, self-driving vehicle movement, etc (Bosurgi et al., 2019; Finogeev et al., 2019; Pompigna and Mauro, 2022; Trubia et al., 2020).

This paper presents the results of LCA and LCC analysis of asphalt mixes modified with GPC and high percentages of RAP (approximately 70%) suitably designed to realize the asphalt concrete (AC) of the A4 Turin-Milan motorway (one of the busiest roads in the northern Italy), at the end of the service life of the existing pavements. The investigation was conducted by comparing the proposed technology (identified by the code GPC) with those traditionally used on motorways, i.e. a conventional non-modified AC (marked with the code NM) and a polymer modified bitumen (with Styrene Butadiene Styrene, SBS)AC (code: PMB). The estimation of the service life of the different technologies was carried out using the rational design method, employing the results of laboratory tests obtained with respect to previous applications on other reference test sites. The design hypotheses were then verified in full scale with both laboratory tests and in situ road pavement surface monitoring, with the aim of validating the assumptions made for the LCA and LCC analyses.

2. Site description

The trial section was 1 km long. The work was carried out in the month of October, 2022, and the new technology (GPC) was laid only on the slow lane of the carriageway in the direction of Milan, which is the most trafficked by heavy vehicles (Fig. 1). In detail, the new pavement was spread out over the existing 20 cm thick subbase layer, which was made of reclaimed asphalt and at the moment of the work appeared in very good conditions (Fig. 2), and was composed by the following AC layers:

- wearing course (4 cm) in SBS-modified porous AC;
- binder course (6 cm) in AC modified with GPC and 66.6% of RAP;
- base course (10 cm) in AC modified with GPC and 67.0% of RAP.

Figure 3 shows the paving stage of the proposed asphalt concrete.

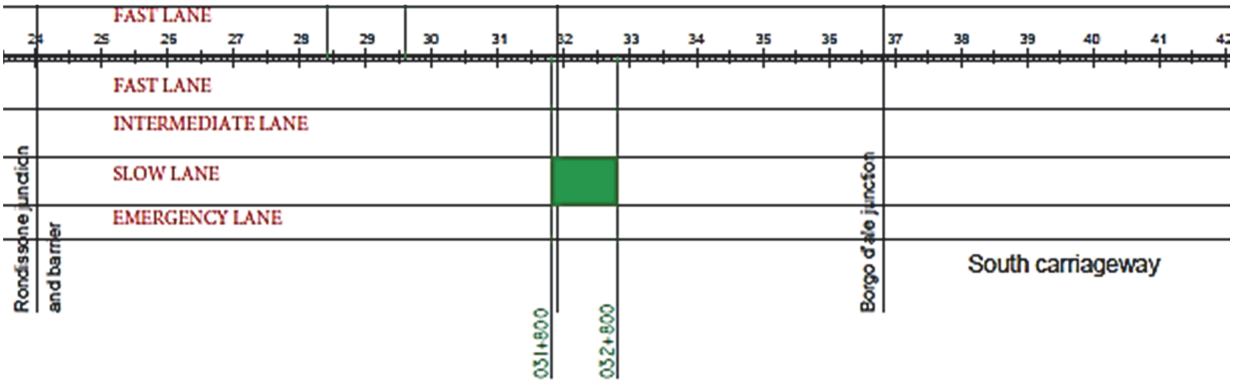


Fig. 1. Trial section layout

Fig. 2. Exiting pavement detail after the milling operation

Fig. 3. Paving stage of GPC modified AC

3. Materials

RAP aggregates were sampled at the mix plant and characterized in terms of gradation (EN 933-1) and bitumen content (EN 12697-1) in according to the European standard. Raw and RAP aggregates were then adequately proportioned in order to fit the grading envelope in accordance with the standards provided by one of the most important road management authorities in Italy (ANAS, 2021).

Two different types of RAP aggregates were used, with a maximum size of 12 mm and 20 mm, and a bitumen content of 3.68% and 2.45% respectively. Due to the large amount of RAP used, it was necessary to incorporate a rejuvenating agent capable of restoring the chemical properties of the RAP aged bitumen. In particular, an additive consisting of a mixture of vegetable derivatives was used at a quantity of 0.1% by weight of RAP. The characteristics of the additive are shown in the Table 1. This type of additive was selected based on the investigation on the preliminary given properties of the additives available in the market and the potential of being used in future project. Instead, no RAP material was included for the wearing layer. It is worth noting that a new generation asphalt plant was used for the production of the mixes, which is capable of handling very high percentages of RAP and at the same time allows high hourly production rate (Santolini et al., 2024).

Table 1. Properties of the rejuvenator used in this research

Typical properties	*Unit*	*Value*
Appearence	-	liquid
Colour	-	dark brown - purple
Density at 25°C	g/cm^3	0.85-0.95
Viscosity at 25°C	mPa·s	50-150
Flash point	°C	≥ 200
Pour point	°C	≤ 0

The virgin binders used in the present study were a 50/70 bitumen for binder and base layer (with a content of 4.65% and 4.01% respectively) and an SBS-polymer modified bitumen for the wearing layer (5.0%). Lastly, a GPC composed by graphene nanoplatelets and selected recycled hard plastic (Fig. 4) was used as AC modifying agent of the binder and base layers (6% by weight of bitumen). The physical properties of the GPC additive are shown in Table 2. Further information on the chemical properties of this product is available in the experimental study by D'Angelo et al. (2022).

Fig. 4. Graphene-enhanced polymeric compound

Table 2. Properties of the GPC additive

Typical properties	*Unit*	*Value*
Appearence	-	granules
Colour	-	black
Apparent density at 25°C	g/cm^3	0,4-0,6
Softening point	°C	160-180
Melt Flow Index at 190°C/5kg	g/10’	4-10

4. Test methods

4.1. LCA and LCC analyses

The LCA analysis was conducted according to a “cradle-to-grave” approach in compliance with the European regulations (UNI EN ISO 14040, 2021; UNI EN ISO 14044, 2021). The methodology consists in four interconnected phases: goal and scope, inventory analysis, impact assessment and interpretation. The LCC analysis has also been carried out in parallel to assess the economical sustainability of the two solutions.

In particular, the proposed solution (see Chapter 2) was compared with a solution normally used on motorways, and consisting of open-graded surface course, binder course and base course in SBS-polymer modified asphalt concrete (with no RAP content for surface course and 30%for binder and base courses).

Figure 5 shows the system boundary considered to perform the analysis. In particular, in this system, recycled material (RAP) was considered as an external product that would otherwise be landfilled in its original life cycle (“avoided waste”). The analysis was carried out considering a reference service life of 35 years and a number of resurfacings for each individual layer shown in Fig. 5.

Moreover, the two different solutions were also investigated and compared to highlight the effective environmental advantages of the use of high reclaimed asphalt percentages and high-performance technologies capable of increasing the service life of the pavement. The environmental analysis was conducted using the OpenLCA software and the Ecoinvent v3.7.1 database. Table 3 shows primary data on consumption and costs of raw materials and production processes taken from surveys carried out by the road operator and asphalt production plants, as well as from the OpenLCA software database . The analysis were performed considering the production of SBS-modify asphalt concrete (with 30% of RAP) and GPC asphalt concrete (with about 70% of RAP) in two different production plants since the incorporation of about 70% of RAP requires the use of a new generation asphalt plant that is technologically advanced. The production of traditional hot mix with 30% of RAP can be produced in a traditional asphalt plant (Nicolini et al., 2023). Furthermore, it is important to note that the contribution of the chemical additives in the life cycle of the pavement, even if these are used in small quantities, has been evaluated as an increase, albeit minimal, in the amount of virgin bitumen entering the system (hypothesis). It has not been possible to consider the exact contribution of the products constituting the regenerating agent because the exact chemical nature of these products is the intellectual property of the manufacturer.

A section of road 1 km in length, 4 metres in width and 20 cm in thickness was considered to perform the analysis, taking a reference period of 35 years: this corresponds to the best theoretical estimation of the service life for the GPC-based pavement technology, under the traffic loads expected by the Road Manager, following the implementation of Miner's law on the base of the stress-strain calculations that were performed with the help of a computational software (Fig. 6). This service life was estimated during the design phase using an empirical-rational method, based on a number of variables whose knowledge was possible thanks to the contribute of the Road Manager and to the availability of historical information in Sina's databases. The mechanical properties of the subbase, foundation and subgrade layers were derived from in-situ investigations having been realized from the birth of the motorway, while the expected performance of the asphalt mixes was derived from laboratory mix pre-qualification tests and the outcomes documented with respect to previous applications on other reference test sites. Results were reported in terms of kilograms of carbon dioxide equivalent (CO_{2equ}), energy consumption (kW/h), raw material consumption (kg), and reuse of recycled plastics (t).

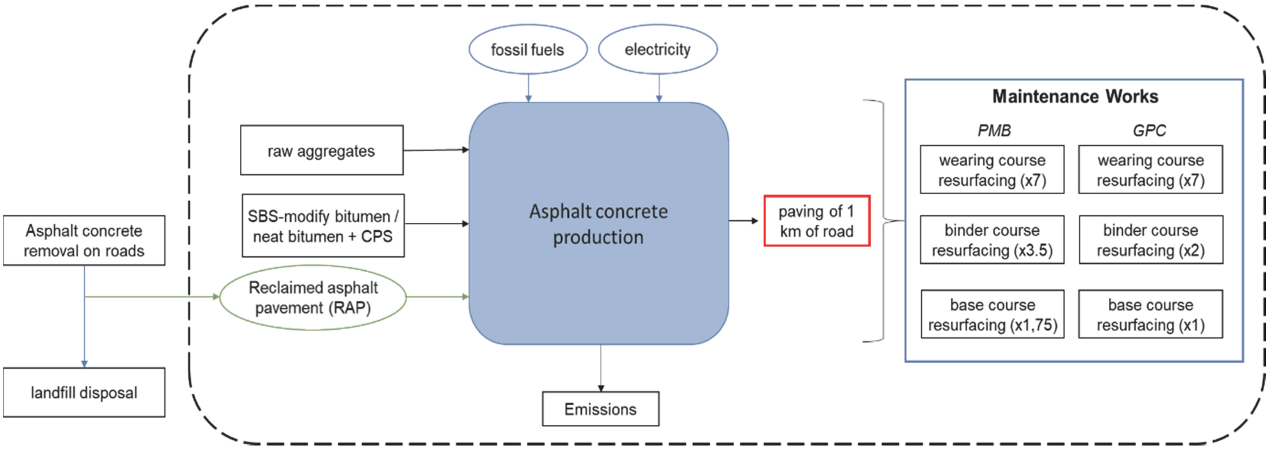


Fig. 5. System boundary considered for the analysis

Table 3. Input data for LCA

Input	*Type of asphalt plant*	
	Discontinuous	*New generation*
Type of fuel	Methane*	methane
Fossil fuel consumption [m3/t]	3.5*	8.0
Production [t/h]	120*	240*
Power consumption [kWh/t]	1.7*	1.7
Virgin aggregate transport distance [km]	100*	100*
Bitumen transport distance [km]	100*	100*
RAP transport distance [km]	65*	65*
Aggregate cost [€/t]	11*	
Modified bitumen cost [€/t]	550	
Methane cost [€/kW h]	0.106	
Electricity cost [€/kW h]	0.0624	
Transport costs [€/t km]	0.425	
Asphalt concrete disposal cost [€/t]	10*	

*data provided by the road operator

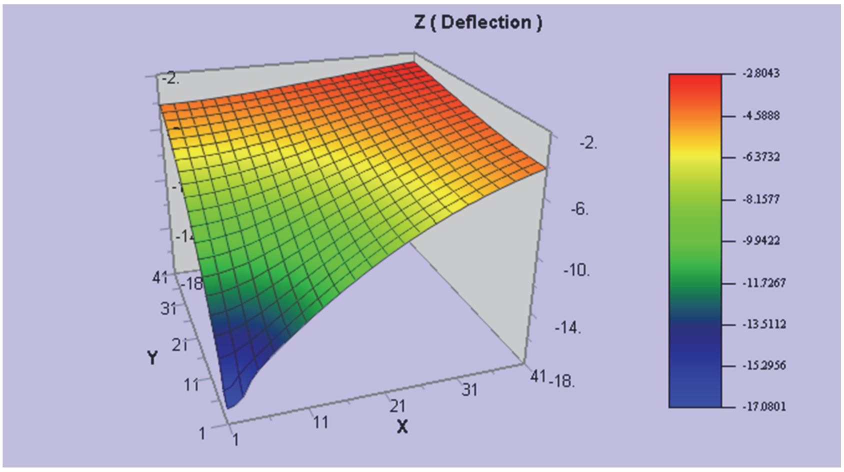


Fig. 6. ALIZE-LCPC software output

4.2. Laboratory tests

In order to check the quality of the mixes laid in the test field and to confirm the assumptions at the basis of the pavement design, material samples were taken in situ. The results were then used to verify LCA and LCC analyses. Subsequently, specimens were producted using a gyratory compactor equipment with up to 200 rotations (EN 12697-31) and through roller compaction (EN 12697-33). The following parameters have been determined on the AC specimens: volumetric properties, stiffness, indirect tensile strenght, water sensitivity, resistance to permanent deformation, tendency to crack propagation at low temperatures and fatigue resistance.

4.2.1. Indirect Tensile Strength Modulus (ITSM) test

The Indirect Tensile Strength Modulus is used to evaluate the elastic properties of ACs in different climatic condition (Iwański, 2020). Moreover, it is considered a very important performance parameter in pavement design (Bocci et al., 2020). The tests were carried out in according to the standard (EN 12697-26). In particular, the standard defines the ITSM parameter (in MPa) as follow (Eq.1):

$$ITSM = \frac{F\cdot(\nu+0.27)}{(z+h)} \qquad (1)$$

where F (N) is the applied vertical load, z (mm) is the amplitude of the horizontal deformation obtained during the load cycle, h (mm) is the mean thickness of the test sample, and ν is the Poisson’s ratio.

The test was performed at three different temperatures (10 °C, 20 °C, and 30 °C) in control-horizontal displacement configuration. A different horizontal deformation was applied during the test as the temperature changed to avoid damage to the material. Specifically, 5 μm was chosen at 10 °C, 7 μm at 20 °C, and 9 μm at 30 °C.

4.2.2. Indirect Tensile Strength (ITS) test

The mechanical resistance was determined in terms of indirect tensile strength (ITS), according to the EN 12697-23 (2017). The test was conducted at 25 °C with a constant deformation rate of 50±2 mm/min until the load, after failure, reaches 30% of the maximum load. The specimens produced for this test were compacted at 120 cycles.

4.2.3. Water sensitivity of bituminous specimens

The water sensitivity of bituminous specimens (A method) is defined through the indirect tensile strength rario (ITSR), which as defined by the EN 12697-12 (2018) is calculated by the following equation (Eq. 2):

$$ITSR = 100x\ \frac{ITS_w}{ITS_d} \qquad (2)$$

where: ITSR is the indirect tensile strength ratio, in percentage (%); ITS_w is the average indirect tensile strength of the wet specimens group, in kPa (at 15°C); ITS_d is the average indirect tensile strength of the dry specimens group, in kPa (at 15°C). The specimens produced for this test were compacted at 120 cycles.

4.2.4. Resistance to permanent deformation

The resistance to permanent deformation was assessed by means of Wheel-Tracking Device (WTD). The test was performed following the B method (small size) indications of the EN 12697-22 (2020) standard. This device simulates the pavement distressess by rolling a wheel (10000 cycles) across a sample of AC under specific temperature condition (60°C). Specifically, the slabs were compacted through roller compactor (EN 12697-33). Two different test repetitions were performed (in dry condition). The wheel-tracking slope (WTS), in mm per 10^3 load cycles, was calculated as (Eq. 3):

$$WTS = \frac{(d_{10000} - d_{5000})}{5} \qquad (3)$$

where d_{5000} and d_{10000} are the rut depth after 5000 and 10000 load cycles respectively (in millimetres).

Moreover, the rut depth (RD) after 10000 cycles (in mm) and the proportional rut depth (PRD) after 10000 cycles (in percentage) were determined.

4.2.5 Semi-circularbending test (SCB)

Low temperature crack propagation tendency was assessed by means of the SCB test (EN 12697-44) at 0°C. By means of an elettro-mechanical press, a constant rate of deformatin of 5.0±0.2 mm/min was applied on the samples until the crack propogated from the notch to the edge of the samples.

The fracture toughness (*K*) was calculated by the Eq. (4):

$$K\ [{}^{N}/_{mm^{1,5}}] = \sigma_{max}\cdot Y\cdot\sqrt{\pi\cdot a} \qquad (4)$$

where: σ_{max} is the maximum failure stress of the specimen; Y is the effort intensification factor in normalized mode; a is the cutting depth of the specimen (in millimeters).

4.2.5 Indirect Tensile Fatigue (ITF) test

The determination of a material's fatigue resistance is fundamental to the evaluation of a pavement's durability in the field and to design the road structural package (Bruno et al., 2024; Wen and Bhusal, 2013). In this research, the resistance to fatigue was analysed in indirect tensile configuration (EN 12697-24). Different horizontal stress amplitudes (750, 1000 and 1250 kPa) were set and a temperature of 10°C was fixed to obtain an initial horizontal deformation ε_0 between 70 and 400 μm/m and a fatigue life between one hundred and one million cycles. The load frequency was 2 Hz. The fatigue failure of the different samples (N_f) was assumed in correspondence to the number of cycle when the specimen broke. Test results were plotted in a log–log-scale graphs, as function of the horizontal strain measured on the undamaged specimen at the beginning of the test.

4.3. In situ road pavement surface monitoring

Non-destructive in-situ testing of pavement condition is a very effective tool for checking the state of the road and for predicting the remaining service life without damaging the pavement or slowing down traffic (Liand Wang, 2018; Vyas et al., 2021).

The investigation of pavement structural conditions was based on the use of the FWD device (Fig. 7), whose first application on the interested site is dated many years before the realization of the new pavement. The FWD testing protocol provided for a loading plate with 300 mm diameter, an impact load of 120 kN and nine geophones positioned at 0, 200, 300, 450, 600, 900, 1200, 1500 and 1800 mm from the centre of the loading plate.

Fig. 7. FWD device

The assessment of the bearing capacity of the existing pavements (both as a whole and with respect to the subbase layer only) was propedeutical to the identification of the requirements of the new GPC-based technology to be applied, and to the design of the proposed solution. Its repetition during the work, instead, supported operators to recognize the suitability of the selected thicknesses and materials, while the continuation of FWD testing over time in the future, at last, has to be identified as the monitoring action that will help the Road Manager understanding the real performance of the applied solution, compared to the one that was considered in the design phase.

5. Design evaluations and results after almost a two years application under traffic

5.1. Life Cycle Assessment (LCA)

Based on the LCA methodology descripted previously (section 4.1) the potential environmental impacts were calculated. Fig. 8 presents the results for the two different technologies (GPC vs PMB). The LCA analysis highlighted the positive environmental contribution of a larger use of RAP aggregates and a neat bitumen with an innovative GPC compound in the binder and base layers, rather than using the traditional mixes. The use of the GPC mixture allowed a reduction of 38.5% in $CO_{2\text{-eq}}$, 30% in energy consumption, 38% in raw bitumen, 40% in virgin aggregates, and the use of 4.9 tons of recycled plastics.

Fig. 8. Equivalent CO_2 consumption for the two solutions (PMB vs GPC)

5.2. Life Cycle Cost (LCC)

The LCC analysis has been performed based on the primary data collected from the company, without opening the boundary of the systems. As can be seen in the Fig. 9, the life cycle cost assessment related to the production of the different layers, also considering maintenance work over the service life (35 years), were 29.7%, 35.3% and 28.3% less for wearing, binder, and base layers respectively. There are also process-related costs to consider, which account for less than 5% of the total cost of the work ("other") and were 102.1% more in the case of theGPC mixture. Overall, the cost of the GPC mixture was therefore 29.4% lower than the solution traditionally (PMB) used by motorway operators in Italy.

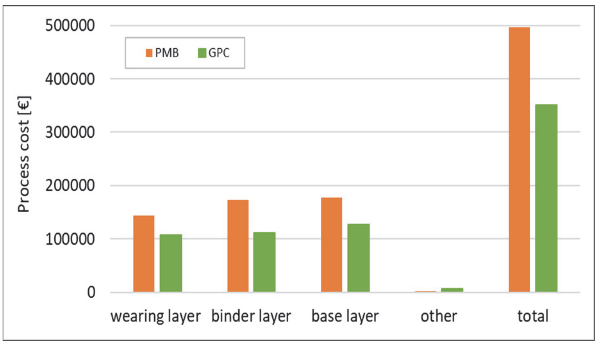


Fig. 9. Process cost for the two solutions (PMB vs GPC)

5.2. Laboratory tests

After the test field was realised, the different GPC mixes were tested (end of October 2022) to check whether they complied with the specifications. The laboratory results of the two innovative mixes (GPC mixtures for base and binder layers) were compared with the test results in the Sina database i.e. NM and PMB mixtures.

5.2.1. ITSM results

Table 4 shows the results of indirect tensile strength modulus at different test temperatures for GPC mixtures (GPC base and GPC binder). The two different mixtures showed no substantial differences in terms of stiffness at the same temperature (with the exception of the results at 10°C), despite a different aggregate grading curve and bitumen content. Furthermore, the table shows that GPC mixtures at a temperature of 20 °C had a stiffness that was about 45% higher than the NM mixture and 27% higher than thePMB mixture.

Finally, both mixtures met the requirements of the specifications (SATAP, 2022), which stipulate that the material stiffness must be greater than 11000 MPa at 10°C, 7000 MPa at 20°C, and 2000 MPa at 30°C for bituminous mixtures modified with polymeric compounds (dry method).

Table 4. Average values of ITSM

Test parameter	*Lab results*		*Reference results*	
	GPC Base	*GPC Binder*	*NM*	*PMB*
ITSM at 10°C (MPa)	17036	19200	-	-
ITSM at 20°C (MPa)	11007	10898	5000-7000	7000-9000
ITSM at 30 °C (MPa)	4861	4620	-	-

5.2.2. ITS results

Table 5 shows the results in terms of indirect tensile strength. For the control mixtures NM and PMB, a reference range from the Sina group database was provided. The GPC mixtures had an average ITS of 1.69 MPa for the base layer and 1.98 MPa for the binder layer. These values were 70-100% higher than for NM mixtures and 10-25% higher than for PMB mixtures. These higher strengths were due both to the use of polymeric compounds, but also to the simultaneous use of very high quantities of RAP. In general, the use of very high RAP content can be deleterious in asphalt mixes, but thanks to the use of the correct dosage and type of rejuvenator product, it was possible to avoid a doubling of ITS values typical for mixes with very high RAP percentages and no rejuvenator agent.

Table 5. Results of indirect tensile strength at 10°C

Test parameter	*GPC base*	*GPC binder*	*NM*	*PMB*
ITS (MPa)	1.693	1.979	0.9-1.2	1.2-1.8

5.2.3. ITSR results

Table 6 showed that both GPC mixtures have no problems in terms of water susceptibility, ITSR correspond to 98%, well above the minimum acceptability limit of 90% (main Italian specifications for NM and PMB mixtures).

Table 6. Average values of indirect tensile strength ratio at 15°C

Test parameter	*GPC base*	*GPC binder*	*NM*	*PMB*
ITSR (%)	98	98	>90	>90

5.2.4. WTD results

Table 7 represents the results of Wheel tracking test. It is noticeable that the values of RD, PRD and WTS are well below the maximum regulatory limits for the acceptance of a mixture specified by the road operator (SATAP, 2022). These results showed that these high-modulus GPC mixtures did not exhibit any problems in terms of accumulation of permanent deformations at high temperatures.

Table 7. Wheel tracking test results at 60°C

Test parameter	*GPC base*	*GPC binder*	*NM*	*PMB*
RD (mm)	1.97	1.76	<2.5	<2.5
PRD (%)	3.28	2.93	<5.0	<5.0
WTS (mm/1000 load cycles)	0.05	0.05	<0.1	<0.1

5.2.5. SCB results

Table 8 shows the results from SCB tests carried out at 10°C in terms of fracture toughness (K). In this case, a significant difference in K value was evident between the two GPC mixtures (17.76 $N/mm^{1.5}$ for the base and 30.36 $N/mm^{1.5}$ for the binder). Both materials met the minimum specification requirements (>15 $N/mm^{1.5}$), with the average value in the case of the GPC binder that was double the minimum required, indicating a good resistance of the material to crack propagation.

Table 8. Semi-circular bending test results at 0°C

Test parameter	*GPC Base*	*GPC Binder*	*NB*	*PMB*
K ($N/mm^{1.5}$)	17.76	30.36	>15	>15

5.2.6. ITF test results

The ITF test results (number of cycles to failure) were plotted in two log-log graphs, as function of the initial horizontal deformation for GPC binder and base mixtures (Fig. 10). For each material, a power function (with a linear trend in the log-log plane) was superimposed to the experimental data to describe the fatigue behaviour. Furthermore, ε_0 values corresponding to 10^6 load cycles were determined from the equation of the determined fatigue lines. The results were then compared with average values present in the Sina Group database, which refer to a NB mix (Table 9). The results showed that GPC mixtures perform better than NM mixtures commonly used by the motorway operator. Specifically, GPC base mixture had an ε_0 at 10^6 cycles of 79 μ strain 20% higher than the NM mixture, while GPC binder mixture had a value of 86 μ strain 10% higher.

Table 9. Initial deformation of mixtures at 10^6 load cycles

Type of mixture	*ε_0 (μstrain)*
GPC (base layer)	79
NM (base layer)	63
GPC (binder layer)	86
NM (binder layer)	78

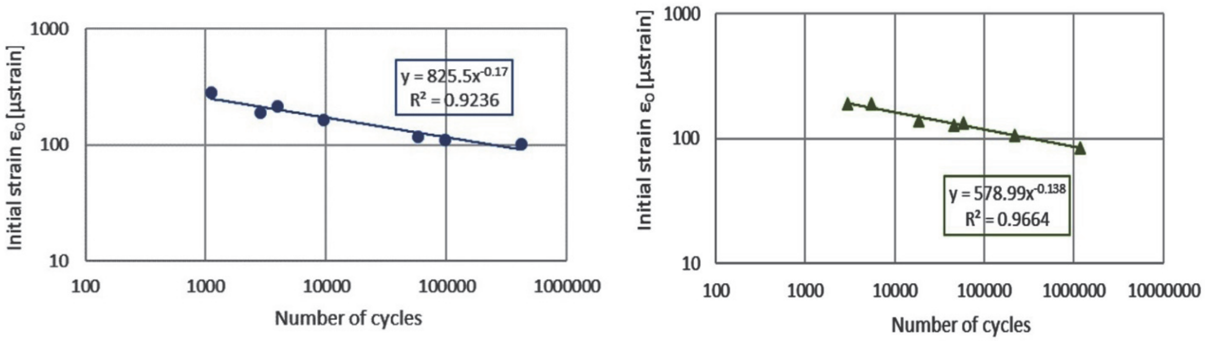
5.3. In situ road pavement surface monitoring

FWD testing and visual inspections started being performed after the construction of the new pavement to assess its behaviour under traffic. After more than 500 days during which the reference section was trafficked by almost 12 million total vehicles (3 of which were heavy vehicles), there is no evidence on the new pavement of any surface degradations nor deformations at all (Fig. 11).

Instead, having a look at the old pavements being adjacent to the 1 km long section in which the new GCP mixture was applied (Figs. 12-14), it is possible to recognize some typical effects produced by the end of their service life (it is notable to highlight that these pavements were built at the start of the millennium and that their design life was 20 years). After 500 days of traffic, results from FWD testing showed a highly stable behaviour of the new pavement under traffic. Tests performed in comparable climatic conditions and temperatures between 10°C and 20°C, in fact, showed that deflection basins recorded with the use of 9 geophones are very similar independently of the season (spring or autumn) and, most important, of the time passed from the construction. According to this, constant trend rates were determined for some deflection basin indicators (DBIs) that were considered for comparison purposes.

Figures 15 and 16 show the results of FWD testing belonging to both the 1 km long test section and a longer section (2 km at all) which includes two adjacent old pavements together with the new one. The new pavement demonstrated trend rates around zero as regards the $AREA_{@25°C}$ (representative of the whole pavement structural condition) and the $D_{1@25°C}$ (representative of the AC layers) DBIs: this means that no structural modifications occurred from the time of the construction. Also, looking at the Table 10 and at the Fig. 17 representing the surface modulus in (MPa) vs the depth in (mm) it is possible to highlight that there was a strong decrease of the difference between deflections under the AC layers (see D_3-D_5 column and the shift between the red curve – 1 km long section – and the blue one – 2 km long section): this confirms that the new AC structure is able to absorb more stress from the top if compared to that in the old pavements, thus preventing the subbase layer and the unbound bottom layers to receive extra solicitations.

Based on the recorded deflection basins, back-calculation operations were running out in the end. As a result, calculations led to understand that the current elastic moduli of the GCP new pavement layers could be placed between 6500 and 7500 MPa, as the elastic modulus of the whole pavement including the open graded wearing course was estimated in a range of 5200÷5700 MPa.



(a) (b)

Fig. 10. Initial strain fatigue line of GPC mixture:
(a) for base layer (67.0% of RAP) (b) for binder layer (66.6% of RAP)

Detail a Detail b

Detail c

Detail d

Detail e

Fig. 11. Visual inspection 500 days after the construction

Fig. 12. Existing pavement monitoring (detail a)

Fig. 13. Existing pavement monitoring (detail b)

Fig. 14. Transverse regularity of the existing pavement (detail c)

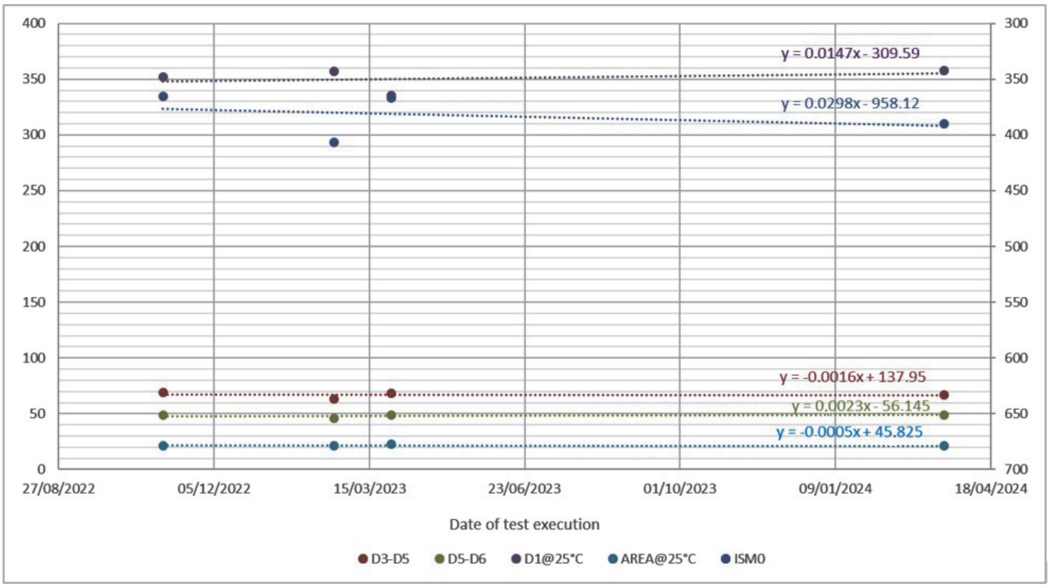


Fig. 15. FWD test result for trial section (1 km long)

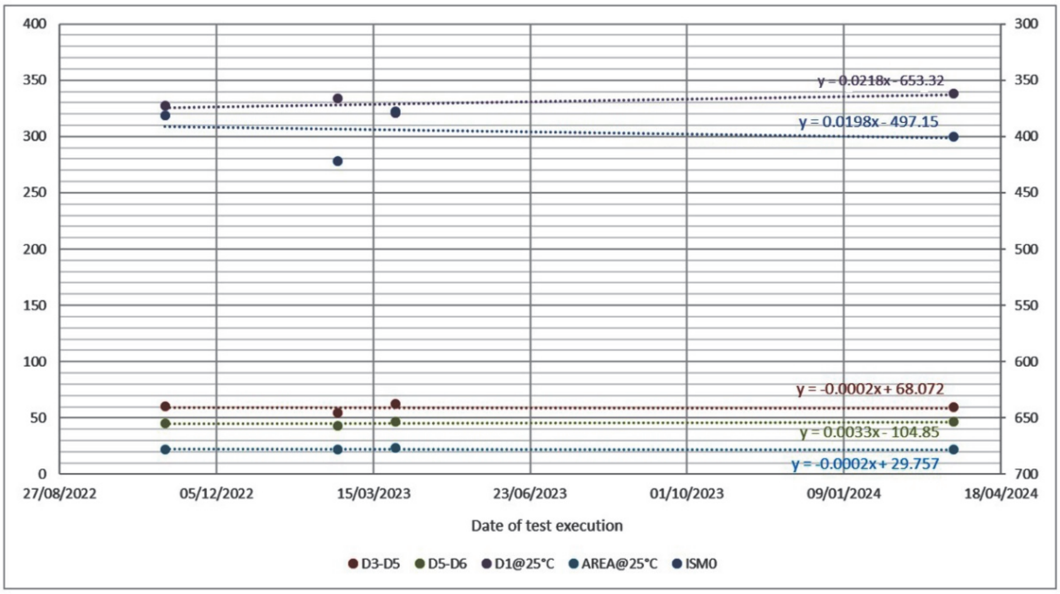


Fig. 16. FWD test result for trial section and adjacent old pavement (total length of 2 km)

Table 10. Falling weight deflectometer test results

Date	*Progressive*	*Temperature (°C)*	*ISM_0 (MPa)*	*D_3-D_5 (MPa)*	*D_5-D_6 (MPa)*	*$D_{1@25°C}$ (MPa)*	*$AREA_{@25°C}$*
Nov/2022	31+300 – 33+300	20.32	366	69	49	352	22
	31+800 – 32+800	20.58	381	61	45	327	22
	Difference, %	1	4	-12	-7	-7	2
Feb/2023	31+300 – 33+300	13.58	407	63	46	357	21
	31+800 – 32+800	13.63	422	55	43	334	22
	Difference, %	0	4	-13	-7	-6	3
Mar/2023	31+300 – 33+300	20.38	367	68	49	336	22
	31+800 – 32+800	20.70	378	62	47	321	23
	Difference, %	2	3	-9	-4	-5	4
Mar/2024	31+300 – 33+300	17.82	390	67	49	358	21
	31+800 – 32+800	17.78	400	59	46	338	22
	Difference, %	0	3	-11	-6	-6	4

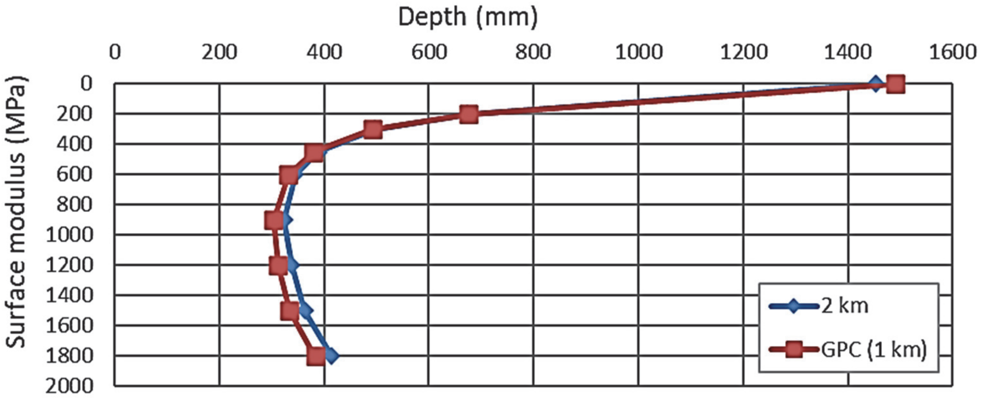


Fig. 17. Surface modulus vs depth

6. Conclusions

The objective of this research was to quantify the reduction in environmental impact achieved using high-performance AC modified with GPC compound and with a high RAP content (about 70%). An LCA analysis was carried out, which allowed us to estimate a reduction in environmental impact in terms of CO_{2eq} of almost 40% compared to the technologies normally used in motorways, considering a 35-year analysis time interval.

A subsequent LCC analysis, on the other hand, made it possible to estimate the economic savings brought out by these technologies, which is equal to almost 30%, mainly due to the lower maintenance operations that the road operator is expected to carry out during the pavement's life cycle. To refine the assumptions underlying the LCA and LCC analyses and to understand the behaviour of the designed mix under traffic at a full-scale level, a 1 km long test field was set up on the A4 Turin-Milan motorway. After the test field was set up, laboratory tests were carried out to verify the performance of the materials against the specification limits.

Laboratory tests and in situ road pavement assessments were carried out to verify the performance of the materials against the minimum requirements for the hypothesises based on the LCA and LCC analyses to be verified. The results showed that these materials performed well despite their very high RAP content.

The results were then compared with the data in the motorway management group's database, which showed that the materials studied performed better than those normally used on motorways (the ITSM value at 20°C was 10-25% higher than that of PMB and the average PD of 1.86 mm was significantly below the typical values for NC and PMB mixtures). Finally, the pavement was monitored with FWD tests as well as visual surveys, which showed that almost two years after the construction of the test field, the pavement is in very good condition and no issue has been detected. On the basis of the FWD surveys, it was possible to recognise a significant improvement in the deflection basin indicators considered (around 10%).

These results would seem to convince that the material is on the right track to be able to aspire to a service life significantly higher than 20 years (between 30 and 35), thus letting the design assumptions be thought as reasonable. However, this section will need to be constantly monitored in the coming years to reinforce this statement.

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