Innovative cement-based material as environmental and efficient technical alternative for pavements

Innovative Cement-Based Material as Environmental and Efficient Technical Alternative for Pavements

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ABSTRACT. Over time, pavements must guarantee smooth and safe driving surface. Often, considering the remarkable age of the Italian road network and the increasing damage rate due to the increase in traffic over years, reaching adequate safety and comfort standards requires maintenance actions that involve also deep pavement layers. Consequently, the intervention becomes too burdensome and costly. In this context, ANAS, the main Italian road agency, is constantly promoting innovative design solutions aimed at maximizing technical efficiency and environmental sustainability (longer service life and reduced maintenance needs).

For these purposes, particularly performing and eco-sustainable materials for binder and base layers can substitute traditional HMA guaranteeing thinner layers with, at least, same final performance.

Specifically, a cement-based material, developed through laboratory studies and real-scale experiments, has been tested. It is a mixture of aggregates, potentially even entirely composed of RAP, mixed at room temperature with a specific bituminous emulsion and reactive filler. It combines rigid and flexible pavements benefits, with environmental and technical advantages:

- reduction of execution time (fluency, no need of compaction efforts);
- less air pollution (cold mix);
- high stiffness modulus (reduction in layer thickness);
- high elasticity (high fatigue resistance) and rutting resistance;
- resistance to chemical aggression and atmospheric agents;
- combination with high percentages of RAP (reduction of virgin materials);
- no temperature sensitivity of the layer.

All these peculiarities mean longer service life compared to traditional pavements and make this material particularly suitable for accomplish environmental goals established by the new regulations in the context of the European Green Deal.

First laboratory studies were started in 2014. Afterwards, full-scale trial sections were realized also involving an Anas road segment still under monitoring (i.e. SS3 "Flaminia", pk. 136+100 to 136+600). Optimum performance were detected in terms of bearing capacity, fatigue, rutting and cracking.

Other trial sections are scheduled in the coming year to confirm the potential of this material, particularly useful where deep and time consuming maintenance actions cannot be carried out.

This paper describes the material potential, with particular reference to the results obtained with Accelerated Pavement Testing with FastFWD on the trial sections involved in the project.

Keywords. Cement-Based Material, Semi-Flexible Pavement, Reactive Filler, Long-Term Performance.

Background

Hard surfaced pavements, which constitute the majority of Italian national roads, are typically categorized into flexible, rigid and semi-rigid pavements (surfaced with bituminous materials, Portland cement concrete and a combination of both, respectively). Each of these pavement types distribute loads over the subgrade trusting on different mechanisms. Rigid pavements, thanks to its high stiffness (high elastic modulus), tends to distribute the load through the cement concrete layer over a wide area with a consequent low stress transferred to the subgrade. On the contrary, flexible pavements distributes loads over a relatively smaller area relying on a combination of several bituminous ductile layers for transmitting the load to the subgrade. Semi-rigid pavements represent a solution in between which combines asphalt and cement bound aggregates.

An additional pavement type can be referred to the so-called semi-flexible pavements (SFP), which simultaneously exhibit flexible properties of asphalt pavements and high bearing capacity (stiffness) of concrete pavements (Hassan et al., 2002; Hassani et al., 2020). They combine the advantages of both pavement types with significant improvements in terms of durability, especially in those areas subjected to heavy and slow-moving loads. SFPs consist of a surface layer made of open-graded hot mix asphalt (HMA) with high air void content (i.e. 20-25%) filled by injecting special highly flowable cementitious grouting materials (i.e. Grouted Macadam) (Zoorob et al, 2002). However, the construction complexity of this technology, which implies a two-stage operation for laying down with many manpower efforts, leads to a reduction in the construction speed (normally two consecutive days) and requires high initial production costs (at least four times than a traditional wearing layer), so limiting the application and the advantages of this solution to few areas of modest extension (e.g. airports, ports, container terminals) (De Oliveira et al, 2006; Zoorob et al, 2002). Moreover, the benefits of this material are deeply related to the void connectivity (that guarantees the possibility for the grout to flow through them) and to a suitable grout workability for completely filling all the voids available. Both cases could mean unfilled voids that may cause premature pavement failure (Hassani et al, 2020).

To solve the abovementioned issues without renouncing to the advantages guaranteed by SFPs, a new technology has been recently implemented as a valid performing and eco-sustainable alternative of Grouted Macadam.

This material, called Ready to Mix (RTM), can substitute traditional HMAs guaranteeing less thick layers with, at least, same final performance at lower costs and reduced construction times compared to grouting materials (Pratelli et al, 2018).

It is worth noting that, differently to the Grouted Macadam, RTM showed the potential to be used also as a structural layer and not just as an improved wearing course. Moreover, this mixture has been developed taking into account also sustainability in terms of recycling and energy saving, so enlarging its potential applications as well as ensuring additional environmental benefits. In fact, RTM is a cement-based material made of aggregates, potentially even entirely composed of reclaimed asphalt pavement (RAP), mixed at room temperature (i.e. cold mix) with a specifically designed slow-setting cationic bituminous emulsion (ECL 60-type C60B4, dosage between 4,6% and 6,8% by mixture weight), a special cementitious reactive filler (around 30,0% by mixture weight) and water (around 5,0% by mixture weight depending on the desired flow ability).

The results of preliminary laboratory studies and real-scale experiments seem demonstrate the potential of this material to combine rigid and flexible pavements benefits, with environmental and technical advantages:

- reduction of execution time (fluency, no need of compaction efforts);

- room temperature production (less air pollution);
- high stiffness modulus (reduction in layer thickness);
- high elasticity (high fatigue resistance);
- resistance to chemical aggression and atmospheric agents;
- combination with high percentages of RAP (reduction of virgin materials)
- no temperature influence on stiffness.

The next paragraphs summarize the main implementation steps and in-situ trial sections experienced with this mixture in order to provide an overview of its potential applications.

Preliminary laboratory evaluation

RTM was optimized trying to develop a mixture that allows the laying down process in a single layer even with high layer thickness (around 20 cm), guaranteeing high bearing capability, good fatigue behaviour and resistance to chemical aggression and intense heat. The determination of the optimum mix composition required an iterative optimization process, which in each phase evaluated the effect of different components (e.g. aggregates, reactive filler, bituminous emulsion, water) and dosages on mixture performance.

A wide range of mechanical tests was carried out in laboratory according to well-defined criteria and the main technical standards for pavement materials characterization (Figure 1). Compared to traditional mixtures and open-graded mixtures prepared with grouting materials, a significant increase in stiffness modulus (i.e. more than double values, 27,000 MPa instead of 12,000 MPa of Grouted Macadam) and ductility was observed, as well as a remarkable improvement in terms of fatigue resistance (no failure was observed even by applying the highest load achievable through the standard asphalt testing machines). The material showed also high Indirect Tensile Strength (ITS) and resilient modulus, high resistance to chemical agents and fuels and low sensitivity to temperature (Pratelli et al., 2018).

Compressive Strength [N/mm^2-MPa] UNI EN 13286-41	Indirect Tensile Strenght [MPa] UNI EN 13286-42	Stiffness Modulus IT-CY UNI EN 12697-26 Annex C	Fatigue Testing IT-CY UNI EN 12697-24 Annex E
22.12	3.32	27,773	With $\varepsilon = 38\mu\varepsilon$ NO FAILURE

Figure 1. RTM preliminary laboratory characterization (Pratelli et al., 2018)

In-situ experiences

Based on the promising laboratory findings, the research activity has deepened the performance analysis to verify the potential of large scale in plant productions of this cement-based material as well as its long-term performance. After the laboratory optimization of the mixture composition and preliminary in-situ attempts realized on specific and controlled production sites, additional trial segments on Italian national roads were constructed and monitored also by means of in-situ tests (i.e. Accelerated Pavement Testing, APT – Metcalf 1996).

The technical specifications provided by the Italian National Road Authorities (Anas, 2016; Autostrade, 2004) for asphalt layers constituted the reference for defining the aggregate distribution of the mixture (figure 2) and verifying other characteristics and performance requested for coarse and fine aggregates.

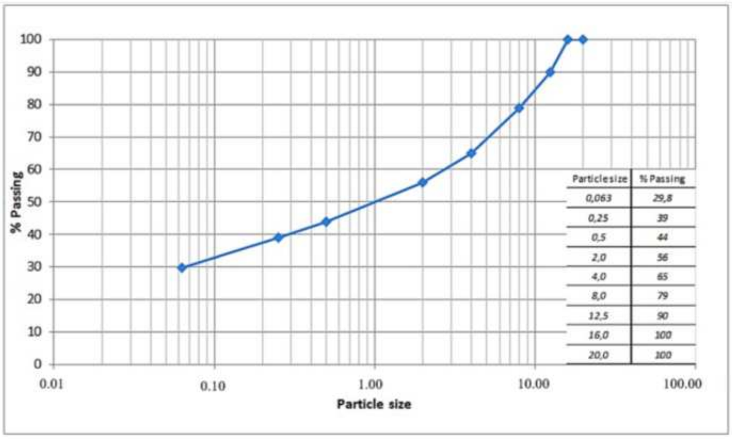

Figure 2. RTM aggregate (Pratelli et al., 2018)

In plant production and laying down operation

Considering the high impact of material components' properties on the development of RTM performance, high attention must be paid on the production process (e.g. materials dosages, mixing time and adding sequences, accurate reactive filler entry operation, moisture content).

Due to the presence of cementitious components and bituminous emulsion, to properly activate cementitious and bituminous bonds the mixture must be appropriately hydrated. At the same time, the amount of water must provide a mixture fluency suitable for laying down the material with traditional paver machines. To this aim, the plant production is equipped with a continuous "loss in weight" dosing system, capable of controlling in real time the flow rate of water, emulsion and reactive filler and, hence, the quality of the mixture produced. Once all the aggregate components have been inserted into the mixer, the right amount of water is added for the complete hydration of the filler allowing the activation of all its components.

At this point, the RTM mixture is loaded directly onto the truck and transported to the construction site where is laid down with standard road pavers with a procedure similar to a traditional HMA (figure 3). It is worth noting that the dosage of mixture components can be adapted for obtaining self-compacting mixtures or less fluid mixtures to be compacted with suitable mechanical rollers.

Figure 3. Laying down operations of RTM by means of a traditional road paver

Trial section 1 and 2

The first in-situ full-scale trial sections were realized on April and June of 2016, respectively. They were located on a production site characterized by the daily and controlled passage of a number of heavy vehicles. Figure 4 describes the pavement structure analysed in the two sections. The first one consists of a 12-cm thick wearing layer of RTM, realized on a pre-existing 7-cm thick bituminous layer. The deepeest layer is a 50-cm thick compacted base course laid on a cohesive subgrade. The second section was specifically designed to emphasise the behaviour of RTM when subjected to repeated dynamic loads under critical stress conditions (to lead the material to failure in a short period). To this aim, the pavement structure involved only a wearing layer of 12 cm laid on a pre-existing granular subgrade.

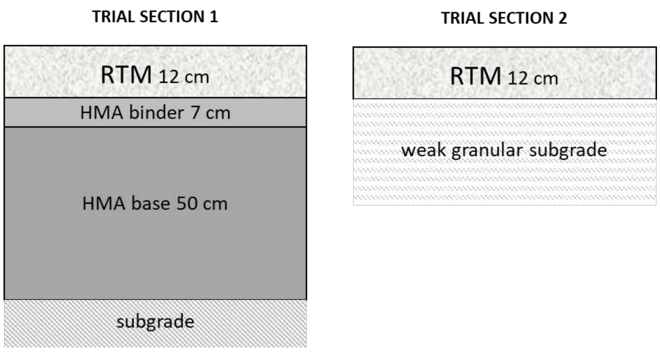

Figure 4. Pavement structure scheme for trial section 1 and trial section 2

Along with the optimization of the in-plant production process and the laying down activities, the primary goal of trial sections 1 and 2 was to study the fatigue behaviour of the material.

In this sense, the field modulus variation trend under dynamic load repetitions was used as indicator of the fatigue performance. It was investigated by means of an APT test performed by means of the Fast Falling Weight Deflectometer (FastFWD – Briggs et al., 2016; Sundgaard et al., 2015) configured with a 300-mm diameter loading plate and with nine deflector geophones used to record vertical displacements caused by the impulsive load (positioned under the loading plate and up to 1800 mm from the plate). During the test, the RTM layer temperature was hourly monitored to verify any temperature influence on test results. Air and surface temperatures were recorded as well.

The recorded deflection data were backcalculated on the base of the pavement structure. The modulus evolution of each layer was consequently determined and plotted as function of the number of load cycles (Isola et al. 2013; Pratelli et al., 2018).

Trial section 1 was subjected to 120 kN load level (highest load level configuration) for three days. The test was interrupted after 30,000 load cycles since the recorded deflections did not show any significant variation and the pavement structure was far from failure conditions.

Although this limited number of load repetitions were not significant enough for judging long-term performance of the material, test results gave a preliminary indication of the potential behaviour under repeated load cycles. Moreover, on the base of the results recorded, it was observed a good ability of the material to recover part of its stiffness when not stressed. It was also reasonable to assume that RTM stiffness is not influenced by the temperature within the investigated range (around 16 °C and 32 °C). This low temperature sensitivity is mainly attributable to the cementitious bonds that lead material behaviour (Pratelli et al., 2018).

The second trial section was specifically designed for overcoming the limitations observed in the first attempt and to reach a failure condition in a short period. Several test points were investigated with a total of 60,000 load cycles applied for each one.

Primary, despite the material high stiffness, RTM confirmed promising fatigue properties as demonstrated by the high resistance of the material to dynamic repeated loads. A specific performance relationship to correlate number of loads to failure and initial deformation induced in the material by the test load was identified. Figure 5 describes RTM performance criteria based on in-situ data results. It is worth noting that the strain level applied during the test to verify the material response under repeated load cycles were much higher than what usually recommended for HMAs. This shrewdness was adopted to emphasise RTM fatigue behaviour since for standard strain levels no evidence of cracks or permanent deformation was observed on the tested surface at the end of the investigation. Based on this observation, reasonably, this relationship can be considered conservative suggesting the presence of a fatigue endurance limit (the material never breaks) under traffic-induced strain levels.

Moreover, results showed again a certain self-healing capability (figure 6) and low temperature sensitivity of the material.

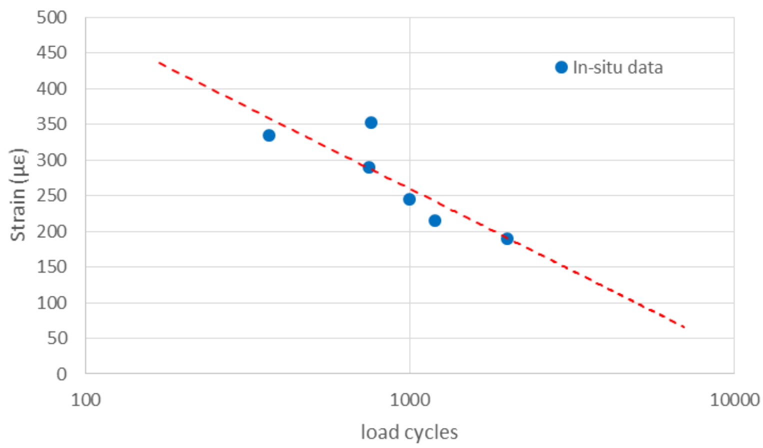

Figure 5. RTM fatigue performance criteria based on in-situ data results

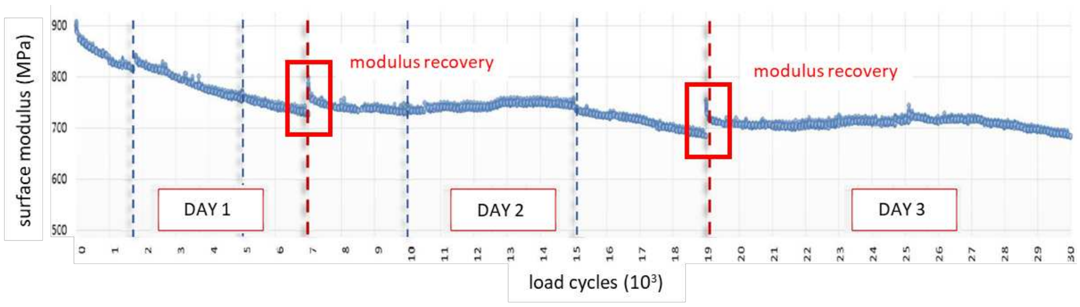

Figure 6. RTM self-healing aptitude

Trial section 3

On July 2017, a third trial section was realized on the Italian national road SS3 “Flaminia” (pk. 136+131 and 136+207, direction SUD). Unlike trial sections 1 and 2, in this case RTM was used as structural layer (base layer) for substituting a traditional HMA at equal thickness as shown in figure 7.

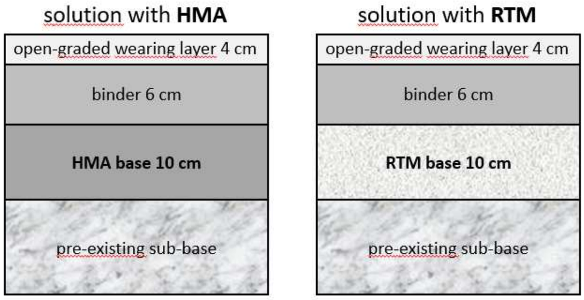

Figure 7. Pavement structure scheme for trial section 3: solution with HMA and with RTM

The main objective of this trial section was to analyse in-situ pavement performance in terms of bearing capacity and resistance to repeated dynamic loads in comparison to a traditional flexible pavement under real traffic conditions.

Two testing campaigns, on September 2017 and June 2018, were carried out by means of the FFWD (Marradi et al., 2018). For each one, the number of load cycles exceeded 50,000 repetitions with a load level of 120 kN. Based on the results obtained in both experimental phases, some observations can be drawn as follows:

- the overall bearing capacity of the pavement made with the RTM base layer was much higher than that one of the traditional pavement structure with asphalt base layer.
- As a result of the total load application, the surface modulus of the measurements points with RTM base layer decreased by 15%, whereas the measurement point with the asphalt base layer suffered a much higher decrease in the surface modulus (figure 8).
- Even after the application of over 15,000 load cycles with a constant load level of 120 kN, the surface modulus of the pavement structure with RTM base layer remained approximately 50% higher than the initial value (measured before the load application; Marradi et al., 2018). This finding is a consequence of the low deflection measured under the load plate, along with a significantly lower increasing rate of the deflection compared to HMA (figure 9). That implies not only better initial performance of RTM, but also the ability to preserve optimum properties over time with a higher and higher performance gap compared to HMA in a long term perspective.
- Low temperature sensitivity was confirmed.

Moreover, elaborating the evolution over time of applied loads and deflections (measured under the loading plate), it was possible to calculate the energy absorbed by the pavement during each load cycle (i.e. energy loss - Rowe, 1996). The graph in figure 10 shows how, in the case of traditional HMA pavements, the energy increases as the test proceeds, whereas for the pavement with RTM the dissipated energy does not increase over time, indicating a substantial stability of RTM under dynamic loads.

Summarizing, the RTM base layer was charcaterized by a stiffness modulus significantly higher than the traditional HMA base layer. The APT results have also highlighted a much higher resistance to repeated load cycles and low temperature sensitivity for the pavement structure with RTM base layer confirming laboratory and first in-situ results.

It is worth noting that, to further monitor RTM performance evolution, an additional investigation was performed in January 2021 with same loading conditions but different test temperature (around 10°C in 2021 *vs* 20-30°C in 2017 and 2018). Test results, currently under elaboration and that will be discussed in details in future papers, suggest the consistency of what observed with the previous analyses and confirmed the optimum behaviour of RTM in a long term perspective (i.e. bearing capacity and fatigue resistance). The comparison between test data acquired in 2017-2018 and 2021 also allowed the identification of specific relationships that describe the deflection as function of temperature.

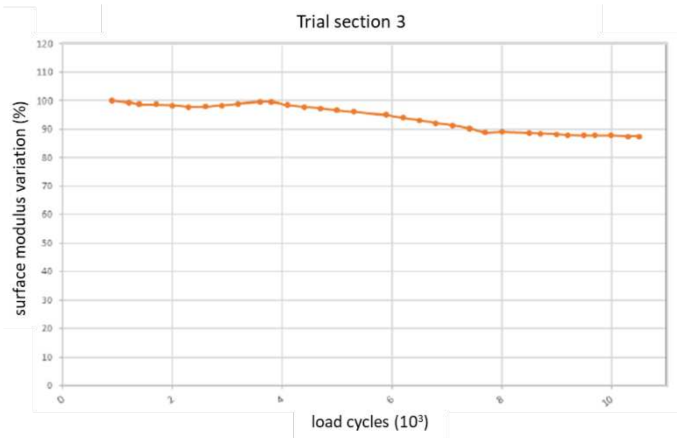

Figure 8. RTM surface modulus variation under repeated load cycles

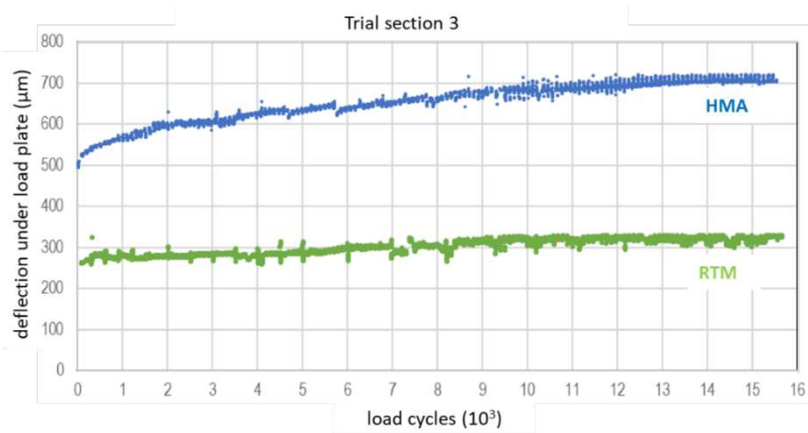

Figure 9. Evolution of the deflection under the load plate after 15.000 load cycles: RTM *vs* HMA

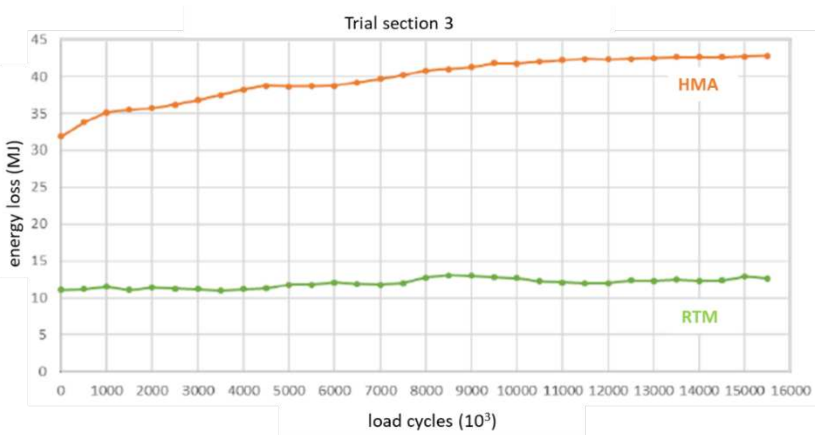

Figure 10. Dissipated energy by the pavement under repeated load cycles (Marradi et al., 2018)

Moreover, correlating FFWD test data with the traffic volume actually experienced on the test road segment in the time gap between 2018 and 2021, the damage equivalence factor that allow the correlation between different load axes was recalibrated in case of pavements with RTM base layers. That will allow a more feasible forecast of the evolution of RTM bearing capacity over the entire road service life (i.e. 20 years), obtaining a precise long-term evaluation of the material modulus, essential aspect for reliably design pavement structure in case of RTM layers.

Trial section 4 – work in progress

A fourth trial section is currently under development. It will be realized as part of maintenance activities on a segment of the Italian national road SS3bis "Tiberina" (pk. 122+900 and 133+755, direction NORTH) subjected to high heavy traffic volume and, analogously to trial section 3, it will provide the use of the RTM as structural layer. A scheme of the project solution identified as alternative to traditional flexible pavements is depicted in figure 10. The proposed solution assumes, for the driving lane, a 14-cm thick RTM base layer that will substitute 18-cm HMA layers and will be laid down through a two-stage operation. Straddling the joint between the driving lane and the fast lane, in the latter (where the pre-existing asphalt base layer will not be removed) a reinforcement geogrid will be interpose between the pre-existing asphalt base layer and the second RTM layer in order to minimize the possibility of fracture formation due to the high difference in stiffness between materials.

As the previous experiences, the trial section will be continuously monitored during construction, to check the in plant production feasibility of the RTM mixture, the material composition consistency and the adequacy of laying down operations, as well as during the service life to verify the resistance of the material under traffic in a long-term perspective. Results will be discussed in future papers.

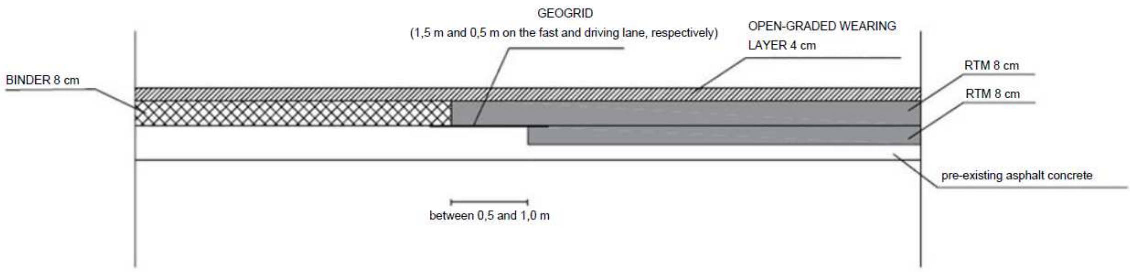

Figure 10. Pavement structure scheme for trial section 4 with RTM

Conclusions and discussion

Laboratory and in-situ experiences undertaken for optimizing and evaluating RTM properties have shown its potential for various applications. RTM, initially developed in laboratory as a cheaper and easier system to realize wearing layer as substitute of Grouted Macadam, demonstrates high performance also for deeper maintenance solutions. The promising outcomes obtained with the preliminary laboratory evaluation largely encouraged the investigation of the material when produced in large-scale amounts. To this purpose, various trial sections were realized to fine-tune all the operational phases and to accurately monitor material performance when subjected to heavy traffic volume.

In-situ trial sections validated laboratory results and certified similar or even superior characteristics compared to Grouted Macadam or traditional HMAs for base layers , as well as excellent properties in terms of stiffness and ductility, which mean optimum bearing capacity and fatigue resistance. Specifically, the latter has been investigated directly in-situ by means of FastFWD. Moduli evolution and surface deflections trends have been analysed and evaluated for all the tested trial sections. Results confirmed a great resistance of the material to repeated loading cycles (no evidence of cracks or permanent deformation was produced on the tested surface at the end of the surveys even by applying the maximum load for a number of loading cycles up to 60,000). This finding, combined with the high RTM stiffness due to the cementitious bonds created by the specifically designed active filler, means superior performance when compared to traditional HMAs. The presence of RTM affects the pavement response when subjected to heavy traffic showing a clear reduction in deflections with no regard to the test temperature (i.e. temperature insensitivity), so allowing a more homogeneous structure in the operating temperature range. A certain self-healing aptitude was also observed.

According to the technical evaluation presented in the previous paragraphs and considering other practical aspects related to the environmental sustainability as well as the ease of construction (e.g. potential of incorporating extreme percentages of RAP, room temperature for mixing and laying down, possibility of using traditional mixers and common road pavers, reduced construction time and materials' amounts), a number of relevant benefits make this material an optimum and desirable alternative for pavement maintenance activities.

Finally, in-situ validation of preliminary laboratory results allowed also the identification of feasible correlation laws and parameters to properly arrange the design of pavement structures that incorporate RTM as wearing or deeper layer. On this matter, studies are still ongoing and results will be discussed in future works.

All the trial sections realized are still under monitoring and additional in-situ sections are planned to further investigate RTM behaviour and validate the material response under different boundary conditions (e.g. loading, temperature, high RAP amount, pavement structure).

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