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Damage evolution assessment of innovative sustainable semi-flexible pavements through intermediate Accelerated Pavement Testing

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Abstract

The use of semi-flexible pavements allows for the achievement of a good level of performance and safety in heavy-load areas. A wearing layer of grouted macadam usually characterises this pavement type. Grouted macadam is a composite material consisting of a Hot Mix Asphalt (HMA) skeleton grouted using a cementitious matrix in a second phase. Grouted macadam use is limited, being its production process quite complex. To overcome this issue, in recent years, Ready to Mix (RTM) materials have been proposed as a more practical alternative while maintaining high performance. RTM are indeed produced by directly mixing the aggregate with bitumen emulsion and a cementitious filler at ambient temperature. This research presents the results of a testing campaign on an experimental trial section built in 2017 on an Italian road. The RTM was placed as base layer in the semi-flexible pavement structure in the trial section. Specifically, the testing campaign included Falling Weight Deflectometer (FWD) surveys, and an intermediate Accelerated Pavement Testing (iAPT) investigation conducted using a Fast Falling Weight Deflectometer (FFWD). The correlation between the FWD and FFWD results, as well as the traffic survey data, allowed the calibration of the field RTM damage curve to obtain an accurate assessment of the evolution of the RTM performance. The results highlighted that the RTM is characterised by excellent fatigue resistance and, consequently, durability.

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1. Introduction

The most common types of pavements adopted in the transport infrastructure sector can be classified as flexible, rigid, or semi-rigid based on the constituting materials and their load transmission mechanisms to the subgrade. However, another pavement type was adopted mostly for infrastructures subjected to heavy and slow-moving loads in recent years. The so-called semi-flexible pavements are characterised by the flexibility of asphalt concrete and equally high stiffness of cement concrete. Their surface layer is generally a composite material, the grouted macadam (GM). Various studies demonstrated that GM has good durability thanks to the improved resistance to rutting and fatigue, as well as low thermal susceptibility and low-temperature cracking. Besides, it is slightly prone to corrosion due to fuel and chemicals and fire effects (Corradini et al., 2017; Du et al., 2018; Ling et al., 2009; J. R. Oliveira, 2006; J. R. M. Oliveira et al., 2007; Shukla et al., 2021; Spadoni et al., 2022; Toraldo, 2013).

However, the GM production process is very time- and cost-consuming, as it is obtained by grouting with a flowable cementitious slurry, a porous hot mix asphalt in a through a two stages process (Guo & Hao, 2021; J. R. Oliveira, 2006). The pavement opening to the traffic will be possible only after some curing days needed to reach adequate strength. These issues make its use limited to specific situations like circumscribed areas of airports, ports or industrial zones particularly subjected to heavy loads (Khan et al., 2022; Plug et al., 2006; Shukla et al., 2021).

An operatively easiest, cost-effective and sustainable alternative to GM is Ready to Mix (RTM) material (Pratelli et al., 2018; Stimilli et al., 2022) as it is obtained by ambient temperature mixing of aggregate, slow-setting cationic asphalt emulsion, a specifically designed cementitious reactive filler and water (Marradi et al., 2024; Pratelli et al., 2018). Production at ambient temperature reduces greenhouse gas emissions and allows using a high percentage of reclaimed asphalt. Besides, it can be put in place in a one-stage process like traditional HMA with a road paver and standard compactors or by being self-compacting instead.

Laboratory tests on this material and field testing in trial pavement structures including the RTM as surface layers, demonstrated their satisfactory performances in terms of stiffness, strength, high resistance to dynamic repeated loads, self-healing properties and reduced thermal sensitivity (Pratelli et al., 2018). Besides, further studies validated the use of this material as a base layer in semi-flexible pavement structures, as it characterised by a reduced thermal susceptibility and a remarkably higher stiffness (Marradi et al., 2024).

Considering the highest stiffness characterising the RTM, studying its fatigue resistance and damage evolution in the laboratory may be challenging and very time-consuming. The present study presents an alternative procedure for their investigation directly in the field involving the use of a Fast Falling Weight Deflectometer (FFWD) to evaluate the pavement modulus evolution under full-scale loads and real climate conditions implementing an intermediate Accelerated Pavement Testing (iAPT) (Manosalvas-Paredes et al., 2017).

2. Experimental campaign

2.1. General overview

The trial section construction was included within the maintenance activities of the road SS3 “Flaminia” (pk. 136+131 and 136+207, direction Sud) undertaken in July 2017 in Campello sul Clitunno (Italy) (Fig. 1a). During these activities, a 100 m trial section was realised to validate the innovative semi-flexible pavement structure in which the RTM base layer replaced the traditional HMA base layer. Specifically, the pavement structure consisted of a 4 cm of HMA wearing course (open graded), 5 cm of HMA binder layer and 10 cm of RTM base layer placed above the existing subbase (Fig. 1b).

Both HMA materials and RTM were produced in the plant. It must be considered that the travel duration from the production plant to the construction site should not exceed 45 minutes for RTM. Hence, the maximum distance between the sites is about 60 km.

The HMA materials for the wearing and binder layer contained SBS-modified bitumen and were designed to comply with the Italian road agency's technical specifications (ANAS Coordinamento Territoriale/Direzione, 2016). Besides, the wearing layer was realised using an open graded HMA (porous asphalt). The RTM composition was optimised during a previously carried out laboratory study (Pratelli et al., 2018).

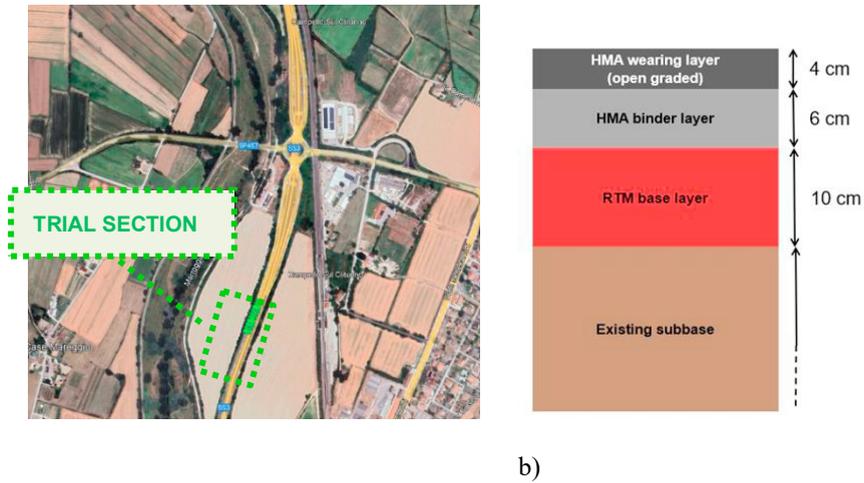


Fig. 1 (a) Location of the trial section along road SS3 and FWD testing stations; (b) RTM laying operations.

To obtain the RTM (Fig. 2a), the mixture composed by of 75% aggregate, 25% reactive filler, and 8% cationic asphalt emulsion (C60B4 according to EN 13808) by aggregate weight and water was carried out at ambient temperature, following a specifically developed process indicating the proper mixing time and adding sequences, reactive filler entry operation, and moisture content control. At the end of the mixing, both HMA and RTM materials were loaded onto the dump trucks to reach the trial section location, where they were laid down using a standard road paver and compacted (Fig. 2b).

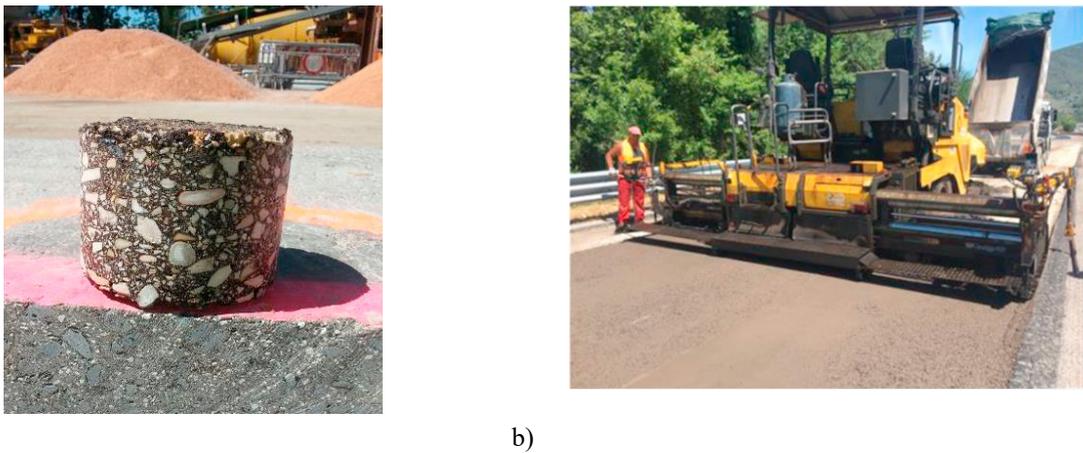


Fig. 2 (a) RTM core and layer section; (b) RTM laying operations.

2.2. Testing campaign

The testing field monitoring campaign consisted of three FWD testing surveys, carried out in September 2017, June 2018, and January 2021, and a FFWD test which took place in June 2018.

The FWD and FFWD both had a 300 mm loading plate, segmented type. The deflections due to the load application were measured by means of nine sensors located at 0, 200, 300, 450, 600, 900, 1200, 1500, and 1800 mm from the centre of the loading plate (Fig. 3).

The FWD measuring stations were along two alignments, corresponding to the right and the left wheel paths (identified as RT and LT, respectively) (Fig. 1a). For each measuring station, three drops were carried out. Table 1 reports the contact pressures applied under the loading plate during the three FWD testing surveys.

The FFWD tests were carried out on two measuring stations (“RTM_1” location: N 42°49’ 19.16”, E 12°45’ 31.57” and “RTM_2” location: N 42°49’ 20.20”, E 12°45’ 35.66”). This equipment is about five times faster per drop than the traditional FWD, enabling more than 2400 load application per hour on the same testing station. Therefore, it allowed the execution of Accelerated Pavement Tests (APT) on the two stations through 10500 load applications for RTM_1 and 15690 load applications for RTM_2. The applied load P was equal to 113 kN, corresponding to a contact pressure of 1600 kPa.

For both tests, the temperature of the pavement was measured hourly by a probe thermometer according to ASTM D5858.

Table 1 Summary of the testing surveys and corresponding parameters (contact pressure and temperature)

Date	Test	Contact pressure (kPa)	Testing temperature (°C)
September 2017	FWD	1700	27
June 2018	FWD	1600	28
	FFWD	1600	29 - 39
January 2021	FWD	1350	10



a)



b)

Fig. 3 (a) FWD equipment; (b) FFWD equipment

The recorded data of the deflection obtained from FWD and FFWD tests were analysed and backcalculated with ELMOD 6 to evaluate the bearing capacity of the semi-flexible pavement structure considering an elastic multi-layer model. The analysis allowed the determination of the surface modulus of the pavement structure E_e , the stiffness modulus of HMA layers (10 cm) E_{HMA} , the stiffness modulus of RTM (10 cm) E_{RTM} and the subgrade modulus E_s . In particular, the moduli at the testing temperatures were obtained through an iterative process carried out using the Method of Equivalent Thickness (MET) implemented in the back-calculation software. More details about the back-calculation analysis can be found in Marradi et al., 2024. For the FFWD deflection data, the modulus loss with respect to the initial value was defined by backcalculating the deflections obtained every 300 or 500 load repetitions.

2.3. Traffic conditions

The traffic conditions were estimated to determine the correlation between the degradation model defined with the APT testing and the load axle passages. The traffic data analysed were obtained from the Road Authority website (ANAS, n.d.), where the Average Daily Traffic (ADT) values were reported by sensors located along the entire infrastructure network. Specifically, the present analysis referred to the closest measuring station in Foligno

(N: 42°57'13.6''; E: 12°43'21,7''). The ADT collected are summarised in Table 2. Unfortunately, no data were available for the years 2018 and 2019, while it can be noticed that the number of vehicles for the year 2020 is quite low: such data is consistent with the effect of the Covid-19 pandemic and the consequent periods of lockdown. Eventually, based on the data, for the aim of the present study, an ADT of 20000 vehicles per day and a percentage of heavy vehicles of 5.6% were considered.

The traffic of the infrastructure during its design life (20 years) was estimated in terms of Equivalent Single Axle Load (ESAL) considering a reference axle of 120 kN as follows:

$$ESAL = 365 \cdot ADT \cdot p_c \cdot D \cdot F \cdot \frac{(1+r)^n - 1}{r} LEF_{tot} \quad (1)$$

where p_c is the percentage of heavy vehicles (assumed equal to 5.6%), D is the directional Distribution Factor (here 50%), F is the Design Lane Distribution Factor (90%), r is the growth factor (in the present study two scenarios were considered, with r equal to 0% and 3%), n is the design life, and LEF_{tot} is the total Load Equivalency Factor obtained as:

$$LEF_{tot} = \sum LEF_j = \sum \left(\frac{p_j}{p_s}\right)^c \quad (2)$$

where LEF_j is the load equivalency factor for the axle j , p_s is the standard axle load, and p_j is the axle j load, whereas c is an exponent indicating the damage and assumed in the first phase of the analysis equal to 4. Considering the traffic spectrum defined in the Italian Pavements Catalogue (Consiglio Nazionale delle Ricerche (CNR), 1995) for type B-C roads the value of LEF_{tot} was 0.46.

Consequently, the $ESAL$ obtained was 1696963 vehicles for the first scenario ($r = 0\%$) and 2279699 for the second scenario ($r = 3\%$). The axle standard passages for years from 2018 to 2021 $ESAL_{18-21}$ were then estimated to be equal to 254522 and 262234 axle load passages, for the two scenarios respectively.

Table 2. Traffic data: number of vehicles passages

Year	Light weight vehicles (vpd)	Heavy-vehicles (vpd)	Total (vpd)	Heavy-vehicles percentage (%)
2013	18038	1083	19121	5.66
2014	18308	1157	19465	5.94
2015	19787	1238	21025	5.89
2016	19564	1183	20747	5.7
2017	19204	1050	20254	5.18
2018	-	-	-	-
2019	-	-	-	-
2020	13674	753	14427	5.22

3. Analysis of the results

Fig. 4 displays the results of the FWD three testing surveys obtained from the back calculation for the RTM modulus. A detailed analysis of the FWD results is provided by Marradi et al. 2024. As regards the RTM, it can be noticed that the layer is much stiffer than traditional bituminous mixtures. Besides, a decrease in the modulus was observed during the years; in particular, during the first nine service months, a reduction of 24.16% was observed compared to the value observed in 2017. After that, the modulus reduction was more contained and equal to 5.5% when 2018 and 2021 were compared. The significant stiffness reduction happening during the first year may be ascribed to a physiological modification occurring in the structure of the material. After that, the modulus reduction registered in about 2.5 years is exiguous.

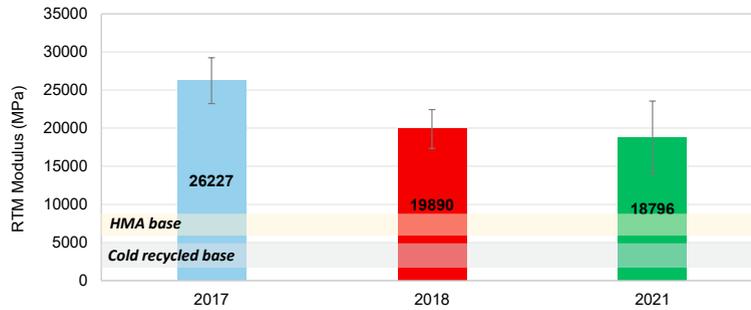


Fig. 4. Results of the FWD surveys on RTM, typical moduli of HMA base and cold recycled base obtained with FWD @ 20 °C are also reported (ANAS, 2016)

Fig. 5a depicts the RTM modulus evolution as a function of the drop ID registered during the FFWD tests carried out in 2018 for the two testing stations. Despite some slight differences, the two sections showed similar behaviour. Besides, it appears that the reduction in the modulus is more contained after the first 8000 drops applications. This result is confirmed by the results in Fig. 5b, representing the percentage reduction of the modulus as a function of the drops applied. After combining the results obtained for both testing stations, a deterioration law was identified. Using this relationship, depicted in Fig. 5b, it was possible to correlate the FWS and FFWD results and identify the number of FFWD load applications corresponding to the modulus reduction registered during the FWD surveys carried out in 2021 concerning the modulus measured in 2018 and equal to 5.50% ($N_{FFWD(18-21)}$). According to the relationship, 94.5% of the initial modulus can be reached after 1159 load applications. Hence, the 1159 load repetitions applied with the FFWD needed to get the modulus reduction registered from June 2018 to January 2021 correspond to the number of passages of the standard axle during the object of analysis (about 2.5 years):

$$ESAL_{18-21} = N_{FFWD(18-21)} * LEF_j = N_{FFWD(18-21)} * \left(\frac{P_j}{P_s}\right)^c \quad (3)$$

where $ESAL_{18-21}$ is the number of passages of the standard axle during the period of analysis, $N_{FFWD(18-21)}$ is the number of FFWD load applications needed to obtain the modulus reduction for the same period, LEF_j is the load equivalency factor relating the j -th axle load to the standard 120 kN one defined according to Equation 2. For the analysis, P_j of the FFWD equipment was assumed to be equal to 226 kN (corresponding to about 22 tons) considering that a single wheel is subjected to a 113 kN load. Considering the value of the damage exponent c equal to 4 as stated above, Equation 3 is not valid.

Previous studies based on field experiences (GeoSolve, 2014) found that c can vary, depending on the pavement type, traffic level, subgrade bearing capacity etc. For example, for pavement with foamed bitumen c varies between 6 and 10.6, for pavements including granular unbound layers c ranges between 3 and 12 as a function of the number of load repetitions and subgrade bearing capacity. Accordingly, the value of the damage exponent for the analysed pavement structure was determined through an iterative process to verify Equation 3 for both scenarios in terms of growth factors. Starting from $ESAL_{18-21}$ equal to 254522 axle for $r=0\%$ and 262234 axle for $r=3\%$ the final value of c after the iterative process was equal to 7.34 and 7.37, respectively. These values are almost double that of the “original” exponent. Therefore, in semi-flexible pavements, the damage caused by an axle much heavier than the standard one is considerably higher and vice versa. For example, the LEF_j of the FFWD equipment is equal to 104 when the growth ratio is null and 106 when it is equal to 3%.

Considering these values of the load equivalency factors, and design life equal to 20 years, the value of the ESAL for the whole pavement structure life ($ESAL_{20\ years}$) are 808812 and 1079690 passages for $r = 0\%$ and $r = 3\%$, respectively. Besides, the number of FFWD load repetitions corresponding to $ESAL_{20\ years}$ ($N_{FFWD(20\ years)}$) are 7779 and 10144 for r equal to 0% and 3%, respectively. Such load application corresponds to a reduction of the RTM modulus of about 29% and 34% according to the relationship depicted in Fig. 5b.

Fig. 6 shows the RTM modulus evolution defined for the two growth rate scenarios confirming the reduced rate of the modulus evolution after the first service year. The RTM pavement layer is characterised by good performance during the whole service life. Besides, this suggests that it is also characterised by a significant fatigue resistance,

considering that the usual definition of fatigue life for HMA is the number of load applications needed to cause a reduction of the initial modulus of 50%. Considering the results obtained, it appears quite challenging to measure the fatigue resistance of the material using the standard laboratory procedures, and, consequently, its assessment through iAPT tests through FFWD can represent a valid alternative. Besides, considering that the RTM base layer allows a considerable reduction in the load transmitted to the subgrade, it seems reasonable to say that semi-flexible pavements including this material as a base layer as the one object of the present investigation, are characterised by a significantly enhanced durability.

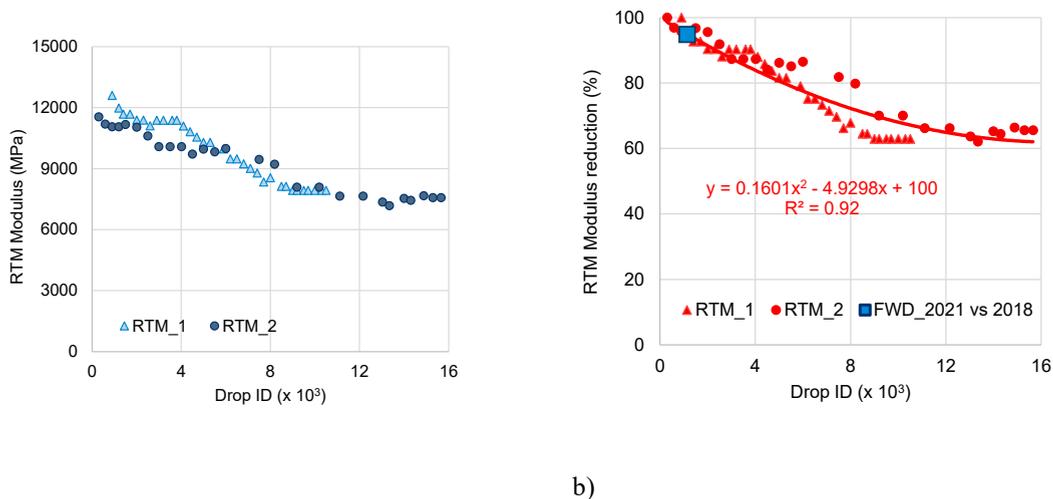


Fig. 5 RRWD RTM results (a) modulus evolution with load applications; (b) modulus reduction with load applications

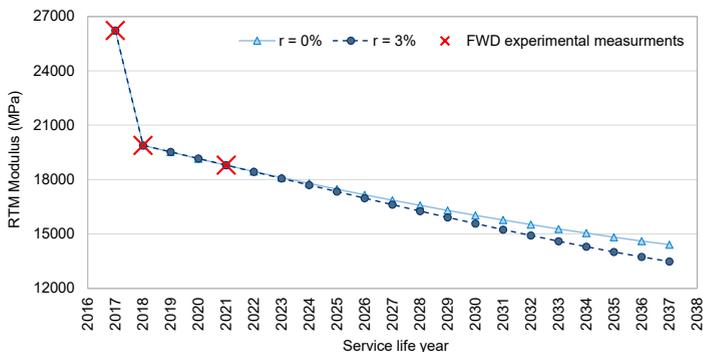


Fig. 6. RMT modulus evolution scenarios

4. Conclusions

In this research, a FastFWD equipment was used to evaluate the stiffness evolution of an actual semi-flexible pavement structure including an innovative, sustainable high-resistant material: the RTM. The outcomes were compared to those obtained during three FWD testing surveys carried out in the early service years of the pavement also. The results confirmed the expected higher stiffness of the RTM material compared to traditional hot bituminous mixtures. Besides, from the FFWD results, it was possible to identify a relationship describing the deterioration law of the RTM as a function of the load applications and to link it to the actual traffic. As a consequence, an adequate damage exponent was identified for the RTM in order to define the load equivalency factors and its value was about 7.35. Finally, it was possible to estimate the stiffness evolution of the material during the pavement service life (20

years) considering a traffic scenario with a null growth rate and a second one with a 3% of growth rate per year. The results showed that, under these conditions, the material is characterised by an excellent fatigue response. The modulus reduction respect to the initial value was equal to about 29% and 34%, indeed, far lower than the 50% modulus reduction usually adopted to define the bituminous materials fatigue life.

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