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A laboratory and field study on 100% Recycled Cement Bound Mixture for base layers

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Abstract

The infrastructure system has experienced an unprecedented development in the last fifty years. Most of the road pavements have been used for over twenty years and today require increasing maintenance to keep acceptable their levels of performance. In addition, the use of virgin and raw materials has been strongly restricted by raising price and eco-friendly policies. As a result, researchers and companies have focused their attention on recycling techniques with waste and second-hand materials that could lead to the construction and restoration of civil infrastructures without negatively affecting their mechanical properties. The study presented in this paper pursues this trend of research, by the evaluation of the performance of two different 100% Recycled Cement Bound Mixture (RCBM) for base layers. Data were always compared to those obtained for a traditional Cement Bound Mixtures (CBM) entirely made of virgin aggregates. The experimental programme was divided into two different and consecutive phases: a laboratory study and a trial field phase. In the first, the aim was the mix design and the physical and mechanical characterization of three mixtures. In the second phase, a full-scale trial field was realized: in situ tests and sampling were planned in four dates, corresponding to 0, 60, 180 and 365 days of trafficking. Based on results, the replacement of virgin aggregates with waste materials in CBMs, according to these specific mix designs seems to be a practicable solution for the construction of base layers with suitable performance.

1. Introduction

According to the Communication from the European Commission named "Resource Efficiency Opportunities in the Building Sector", in the EU the building industry is responsible for about half of the extracted materials and of the energy consumption, as well as about a third of the water consumption. It is obvious that the direct and indirect impacts of those activities on the environment and on the population are no more acceptable in a modern society [1,2]. Thanks to a growing awareness of policy and public opinion of sustainable development, several policies and researches have been developed aiming a reduction of costs and consumptions related to the construction and maintenance of civil infrastructures [3–5]. The use of resources is largely determined by the design and by the choices of building materials; in addition, the construction and maintenance of civil infrastructure entails the production of high quantities of discarded materials [6–9]. This type of material is named Construction and Demolition C&D) waste and according to EU, this nomenclature includes all waste generated under NACE code F construction sector): mainly road by-products Reclaimed Asphalt

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Pavement, RAP), crushed concrete, tiles, ceramic, bricks and wood [10–12]. Recycling of these waste materials is becoming more and more important as a means to improve the efficient and conscious usage of resources and to avoid the negative impacts connected to the use of raw materials. The target proposed by EU for 2020, is to increase the recycling of C&D waste to 70% (Directive 2008/98/EC). In the last decade, a wide number of researches have been carried out on the use of C&D waste, and many studies clearly show the feasible reuse of these discarded materials within bituminous or hydraulically bound mixtures for road pavements [13–15]. If we consider base and subbase layers, different studies have shown the good results achieved by the partial substitution of virgin aggregates with RAP within bound and unbound mixtures [16,17]. The technological evolution and the growing interest of researcher in recycling have gradually allowed to increase the quantities of waste materials combined within recycled mixtures, without detrimental effects on the mechanical properties. Following this trend, the present research was focused on the analysis of two different fully Recycled Cement Bound Mixtures (RCBMs) for base layers. The primary goals of this study were:

- The analysis of the mechanical and physical properties conferred to the mixture by the total substitution of virgin aggregate with C&D wastes.
- The evaluation of the feasibility of the entire process, from in plant production to the paving operations.

To achieve both targets, the experimental programme was divided into a laboratory and a trial field phase, in which the properties of the two experimental RCBMs were compared to a traditional Cement Bound Mixture (CBM) entirely made with virgin aggregates.

2. Experimental programme, test methods and materials

The research programme was divided into two:

- Laboratory: in this phase the optimal mix design was defined and the physical and mechanical characteristics of the mixtures were evaluated. Two RCBM mixtures were analysed, both made with more than 40% of RAP and other waste aggregates: one (RCBMt) with tiles waste, the second (RCBMc) with crushed concrete waste. Their mechanical properties were compared with those obtained from a fully virgin CBM, labelled CBMv.
- Trial field: according to the experimental mix designs defined after the mechanical characterization, the three mixtures were laid in a full-scale trial field. In this step all the processes, from the in plant production to the paving operations were assessed and in situ tests and collection of samples were planned at regular intervals. The objective was the analysis of the development of the mechanical properties of the mixtures under traffic loads.

2.1. Laboratory phase

Once the right amount of water to reach the maximum dry density (EN 13286-2) was defined, 24 specimens for each mixture were prepared for the static mechanical characterization. Twelve of them were compacted according to AASHTO Mod Proctor compaction (85 blows, 5 layers) and 12 by the means of gyratory compaction (ASTM D6925), according to a constant compaction pressure of 600 kPa, 180 gyrations and an external angle of 1.25°. The specimens were kept under constant moisture and temperature curing conditions.

Tests for the determination of the Unconfined Compressive Strength (EN 13286-41) and the Indirect Tensile Strength (EN 13286-42) were carried out after 3 and 7 days of curing. To provide statistical significance to the results, 3 specimens for each mixture realized with both the compaction processes were tested. The mechanical characterization was supported by the analysis of the Stiffness Modulus according to EN 12697-26 standard.

2.2. Trial field phase

On the basis of the correct mix designs and once defined the basic physical and mechanical properties of the experimental recycled mixtures, these were laid for the construction of a full-scale test truck. In order to assess the development of the mechanical properties of the mixtures, in situ tests and collection of samples were planned in four dates, corresponding to 0, 60, 180 and 365 days of cumulative traffic. For each mixture, three samples were prepared by the means of the gyratory compaction (ASTM D6925), with the material collected from the paving screed. The gyratory setting and the number of revolution were the same used during the laboratory phase. The indirect tensile strength was also evaluated (EN 13286-42). The samples cored and collected from the trial field were tested according to EN 12697-26 to evaluate the development of the mechanical properties under traffic load. The change and development in stiffness was also assessed using a Light Weight Deflectometer (LWD) (ASTM E2583).

2.3. Materials

The experimental work here presented, involved the mix designs and the laboratory and in situ characterization of three different mixtures: a traditional CBM and two different RCBMs.

While the traditional CBM (labelled CBMv) was made with virgin aggregate, the other two experimental mixtures were entirely produced with C&D wastes: one, named RCBMt designed with RAP and discarded tiles, the other, named RCBMc with RAP and crushed concrete. For both CBMv and RCBMt a traditional Portland cement 32.5 was used as binder, while RCBMc was designed with an innovative hydraulic stabilizing agent made of fibres. For each mixture, a calculated (EN 13286-2) amount of water was added to reach the maximum dry density. Both the recycled mixtures were prepared with recycled sand 0/4 (0–4 mm), produced form crushed and sieved C&D wastes.

RAP was first milled from a single highway pavement made in asphalt concrete and then divided into three different fractions: coarse RAP 20/40 (20–40 mm), medium RAP 0/20 (0–20 mm) and fine RAP 0/10 (0–10 mm). Crushed concrete and waste tiles were added to the mixtures according to the 0/31.5 (0–31.5 mm) grading.

3. Laboratory tests and analysis

3.1. Mix design

All the experimental mixtures were designed on the basis of the C&D wastes characteristics, following a grain-size distribution from a common Italian technical specification for a Cement Bound Mixture for base layers.

The amount of each material used for RCBMt and RCBMc is shown in Table 1, while Fig. 1 shows the gradation of the three different mixtures. For CBMv, 3.5% of cement (by the weight of aggregates) was added to the mixture.

Fig. 1 clearly shows that the mixtures have very similar gradations.

3.2. ITS and UCS results analysis after Proctor compaction

The static mechanical characterization was made with Indirect Tensile Strength (ITS) and Unconfined Compressive Strength (UCS) according to EN 13286-42 and EN 13286-41 standards. Twelve specimens were prepared by Proctor compaction (AASHTO Mod): the moulds were filled with material in 5 different layers, each of which compacted by 85 blows. Six specimens were tested after 3 days of curing under wet sand to provide adequate moisture, other six were tested after 7 days.

Results of ITS test are given in Fig. 2, while Fig. 3 shows the UCS average results after 3 and 7 days of curing.

All the mixtures, apart from RCBMt after 3 days of curing, reached the ITS limits imposed by the Italian technical

Table 1
Designation and composition of RCBMt and RCBMc.

Material	Density (g/cm^3)	RCBMc (%)	RCBMt (%)
RAP 20/40	2.62	13.0	10.0
RAP 0/20	2.62	32.0	20.0
RAP 0/10	2.63	10.0	15.0
Crushed concrete 0/31.5	2.28	31.5	
Waste tiles 0/31.5	2.20		32.0
Recycled Sand 0/4	2.19	11.0	19.5
Cement	2.95		3.5
Fibre stabilizing agent	0.58	2.5	
Additional Water	0.99 (at 25 °C)	6.2	4.2

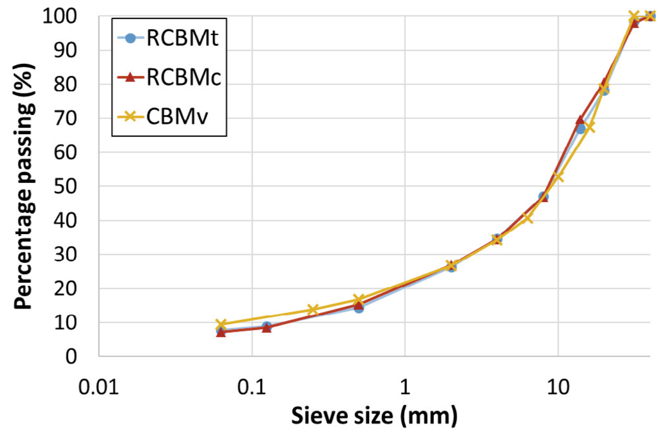

Fig. 1. RCBMt, RCBMc and CBMv gradations.

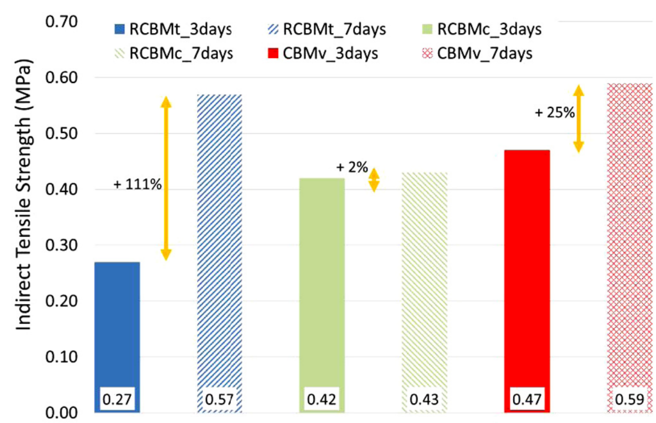

Fig. 2. RCBMt, RCBMc and CBMv ITS average results after 3 and 7 days of curing (Proctor compaction).

specification taken as reference (0.30 MPa after 3 days of curing and 0.32 MPa after 7 days). The different development of the mechanical properties of the three mixtures is evident. RCBMt shows the lowest value after 3 days of curing but also the larger rise in tensile strength after 7 days (+111%). There is not a substantial development of strength for RCBMc from 3 to 7 days of curing, which is probably due to the different type of stabilizing agent used. In absolute terms, after 7 days RCBMc shows the lowest ITS results, while RCBMt seems to be comparable with the reference mixture.

The results of UCS test confirm the data obtained from ITS test: all the mixtures reach the limits imposed by the Italian technical specification taken as reference (1.40 MPa after 3 days of curing and 2.50 MPa after 7 days). In this case, there are no evident differences in terms of development of the mechanical properties between RCBMt and CBMv, even if the last one shows the highest compressive strength. UCS test's results prove the slow development (+2%) of mechanical strength over 7 days for RCBMc, as verified during ITS tests.

At the end of the mechanical characterization on specimens prepared by Proctor compaction, it is clear that, after

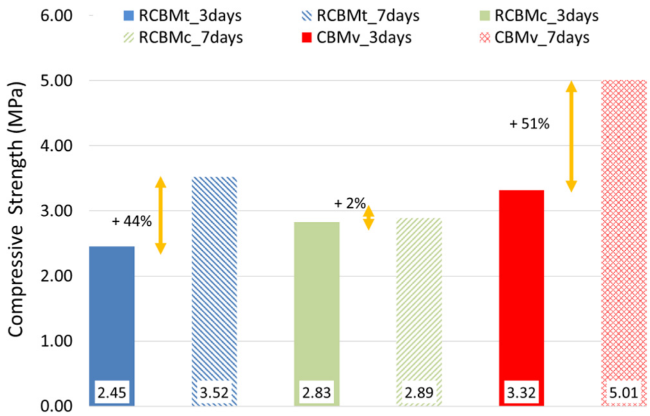

Fig. 3. RCBMt, RCBMc and CBMv UCS average results after 3 and 7 days of curing (Proctor compaction).

7 days of curing, all the experimental mixtures assure suitable mechanical properties. However, the traditional mixture shows the best IT and UC strength for equal curing time.

3.3. ITS and UCS results analysis after gyratory compaction

During this step, other 12 specimens were compacted with gyratory compaction (ASTM D6925). According to the technical specification taken as reference, the settings for the gyratory shear compactor were: 180 gyrations, 600 kPa of compaction pressure and external angle of 1.25°. Once again, the mechanical properties of strength were assessed by the means of the ITS (EN 13286-42) and UCS (EN 13286-41) tests after 3 and 7 days of curing. Figs. 4 and 5 show the results and the increase in strength recorded after the longer curing time.

According to the results, there are no evident differences between the three mixtures in terms of mechanical properties. All the mixtures exceed the ITS and UCS limits imposed by the Italian technical specification taken as reference. From ITS results, after 7 days of curing the experimental mixtures show comparable strength even if lower than the reference mix. In this case, the development of strength from 3 to 7 days of curing for RCBMt is equal to CBMv, while it is lower for RCBMc. UCS results confirm the ITS data: the compressive strength of RCBMt is equal to RCBMc but both are lower than CBMv, which shows also a significant increase in strength (+32%) from 3 to 7 days of curing.

At the end of this stage of static mechanical characterization it can be stated that after 7 days of curing, the experimental recycled mixtures show considerable indirect tensile and compressive strength. For all the tests, the results are not far from those obtained with the virgin mixture.

Furthermore, from the comparison between the specimens prepared with the two different compaction processes, it is evident that the mechanical properties are enhanced with the gyratory one. This is due to the high number of revolutions: 180 gyrations induce a substantial compaction energy if compared to Proctor compaction. This is further confirmed by the higher maximum dry density for specimens from gyratory compaction.

3.4. Indirect tensile stiffness modulus results

The mechanical analysis was completed with the dynamic characterization; a servo-pneumatic testing machine was used. The stiffness modulus was calculated according to EN 12697-26 standard, in the indirect tensile configuration. For this phase, for each mixture 3 specimens were first prepared with gyratory compaction and after 7 days of curing were cut by half and tested. The gyratory compactor's settings were the same used for the static mechanical characterization. Results are shown in Fig. 6.

As the plot shows, there is consistent difference in stiffness between the three mixtures. After 7 days of curing, RCBMc has the higher stiffness modulus (12,025 MPa) even if compared to the reference virgin mixture (10,039 MPa); RCBMt shows the lowest stiffness (6908 MPa).

4. In situ tests and analysis

After the laboratory characterization the construction of a full-scale test track followed. The location was an existing unsurfaced road close to a quarry. The section was made of a 60 cm thick layer of unbound granular material classified as A1-a according to AASHTO M 145 standard. The material was compacted by the heavy load traffic over the years; in situ test registered average measured Light Weight Deflectometer Modulus (E_{LWD}) of 70 MPa. This was the foundation for the trial field section. The test track consists in 3 different and consecutive sections, 8 m wide and 12 m long. The road section was formed by 15 cm of RCBMt or RCBMc or CBMv, covered with 4 cm of wearing course made of Hot Mix Asphalt (HMA).

Considering the heavy load traffic, the road section was undersized to promote the beginning of cracking inside the pavement structure. To assess and compare the development of the mechanical properties of the different mixes, in situ tests and collection of samples were planned in four dates, corresponding to 0, 60, 180 and 365 days of traffic. A total of approximately 5000 passes of 42 t dumpers were measured after 365 days.

4.1. Mechanical analysis: ITS and ITSM results

A specific quantity of material was taken from the paving screed during the laying process and three specimens for each mixture were prepared by gyratory compaction (ASTM D6925), with the same settings and procedures adopted in the laboratory phase. The density of each mixture was evaluated before testing: data reveal a good level of compaction and densities in line with values generally

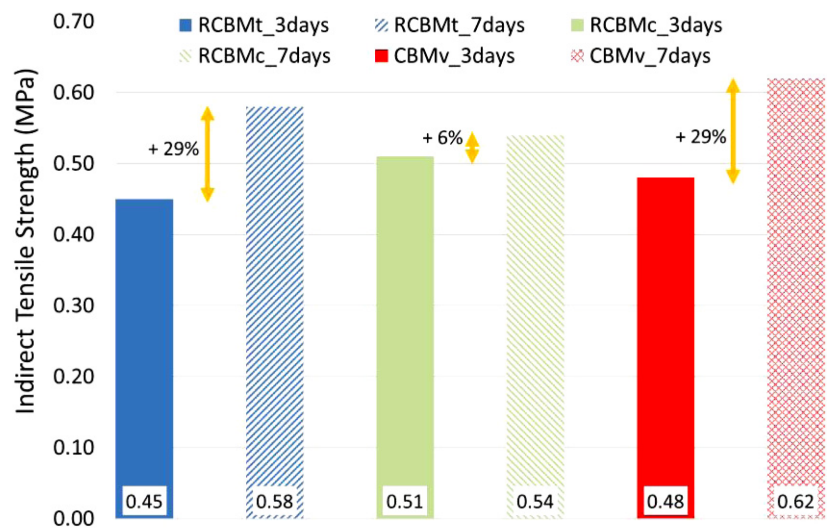

Fig. 4. RCBMt, RCBMc and CBMv ITS average results after 3 and 7 days of curing (gyratory compaction).

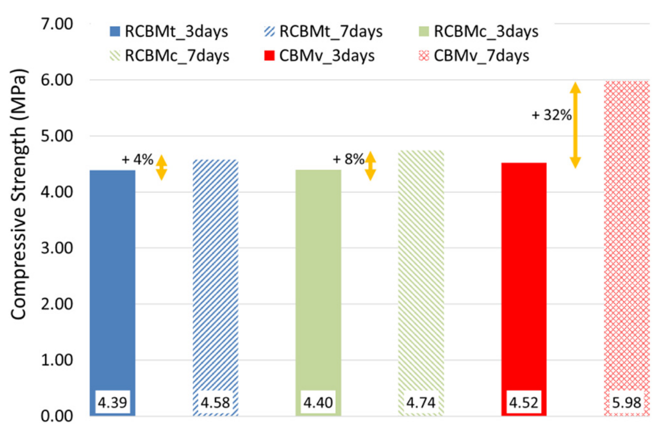

Fig. 5. RCBMt, RCBMc and CBMv UCS average results after 3 and 7 days of curing (gyratory compaction).

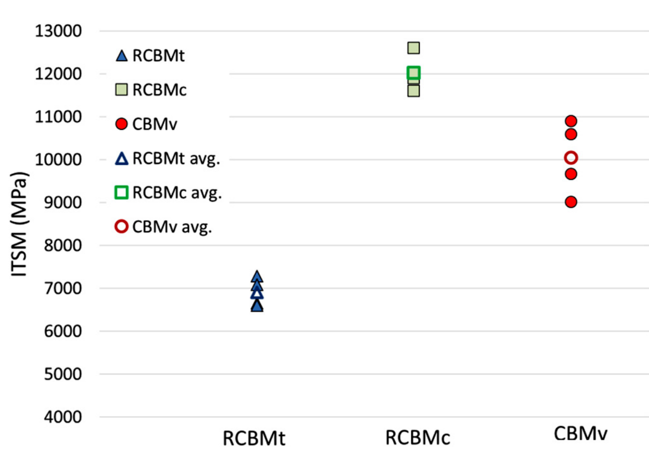

Fig. 6. RCBMt, RCBMc and CBMv ITSM Moduli and average results after 7 days of curing.

specified in the most common Italian technical specifications for CBM mixtures (2.152 g/cm^3 for RCBMt, 2.159 g/cm^3 for RCBMc and 2.165 g/cm^3 CBMv). ITS tests were carried out after 7 days of curing in compliance with EN 13286-42 standard.

Table 2 presents the average results and the comparison between lab and trial field (t.f.) values.

The data show an increase in ITS values for the specimens prepared with the material taken from the paving screed. Trial field's specimens showed the same ITS trend observed during the lab phase: after 7 days of curing results are noticeably high, even if the virgin mixture shows the best strength. The good results obtained for trial field's specimens confirm the quality of the mix designs and validate the in plant production processes.

Moreover, the mechanical analysis was supported by dynamic tests for the evaluation of the development of stiffness moduli. As already mentioned, ITSM tests (EN 12697-26) were carried out on cores collected from the pavement after 60, 180 and 365 days.

Fig. 7 shows the results for cores while in Table 3 the comparison with data obtained during the laboratory phase is given.

From the comparison between laboratory and trial field results, it is evident the difference in stiffness between the specimens and the cores: this is due to the different curing conditions and compaction affords. However, it is clear the development of the stiffness moduli from 60 to 365 days. This is due to the road pavement settlement given by the traffic. The experimental mixtures, most of all RCBMc, show the highest rise in stiffness, while the reference one presents a flatter trend line. After 1 year, RCBMc is the

Table 2
ITS average results after 7 days of curing.

Mixture	ITS lab (MPa)	ITS t.f. (MPa)	Variation (%)
RCBMt	0.58	0.72	+24
RCBMc	0.54	0.61	+13
CBMv	0.62	0.75	+21

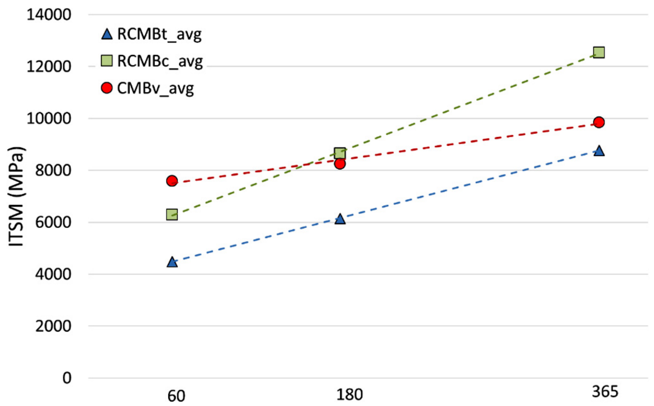

Fig. 7. ITSM test average results at 60, 180 and 365 days of cumulative traffic.

Table 3
ITSM test results for laboratory and trial field phase.

Mixture	Indirect tensile stiffness modulus (MPa) at 20 °C			
	Lab analysis	60 days	180 days	365 days
RCBMt_1	7286	4695	6357	8952
RCBMt_2	6658	4284	6099	8152
RCBMt_3	6598	4476	5995	9192
RCBMt_4	7089			
Avg. RCBMt	6908	4485	6150	8765
RCBMc_1	12,596	6218	8807	13,007
RCBMc_2	11,598	6691	8450	12,100
RCBMc_3	11,897	5985	8669	12,509
RCBMc_4	12,009			
Avg. RCBMc	12,025	6298	8642	12,539
CBMv_1	10,895	7839	8018	10,210
CBMv_2	9663	7323	8299	10,089
CBMv_3	10,586	7596	8457	9235
CBMv_4	9012			
Avg. CBMv	10,039	7586	8258	9845

stiffer mixture (12,539 MPa) while RCBMt has the lower values (8765 MPa). These data validate and prove the ITSM results on specimens prepared in laboratory. Nevertheless, even if the experimental mixtures are made with 100% recycled aggregates, values are in line with those related to traditional CBM. Furthermore, considering the heavy loads due to dumpers transit and since the road section was not designed for these traffic loads, results show that there is no evidence of decay in the mechanical properties of CBMs.

4.2. Light Weight Deflectometer (LWD) analysis

The Light Weight Deflectometer (LWD) is a hand portable device, whose operating principle is a circular plate loaded by a falling mass. The surface modulus can be calculated according to the Boussinesq theory, as a function of the applied stress and measured deflection, on the basis of the Eq. (1):

Fig. 8. LWD test (left) and trial field (right).

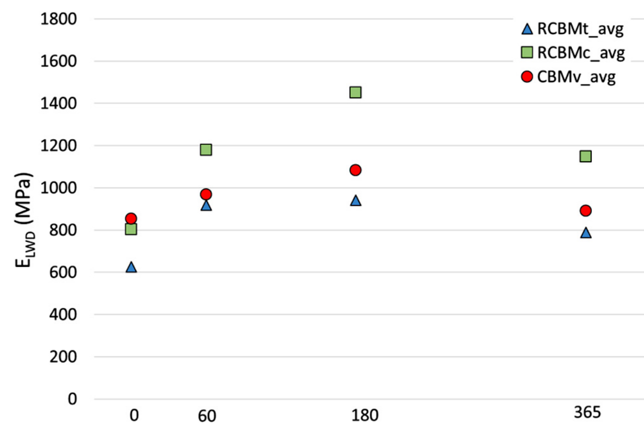

Fig. 9. E_{LWD} average results after 0, 60, 180 and 365 days of cumulative traffic (mainly quarry dumpers).

$$E_{LWD} = \frac{f(1 - v^2)\sigma_0 a}{d_0} \quad (1)$$

where f is the plate rigidity factor, a is the radius of the plate, σ_0 is the maximum value of the applied stress and d_0 is the measured deflection. Both values are measured under the centre of the plate. The LWD setting for the measurement was 150 mm (plate diameter) and 20 kg (falling mass). As recommended by literature, it was possible to obtain under the centre of the plate a measured deflection always higher than 100 μm according to this configuration. LWD tests (ASTM E2583) were repeated after 0, 60, 180 and 365 days to assess the development of E_{LWD}. Nine test points were fixed and tested for each section and for each repetition (Fig. 8).

The measurement of the surface moduli is influenced by the wearing course and foundation stiffness. Nevertheless, given the LWD measuring depth and the layer thicknesses, authors consider that the results are reliable and representative of the base stiffness. This is mainly because initial in situ test recorded a uniform foundation stiffness along the whole trial field, and constant are the mechanical and physical properties of the HMA surface layer.

The development of E_{LWD} average values is shown in Fig. 9.

In absolute terms, taking as reference literature E_{LWD} values on cement treated mixtures, both experimental mixes are able to provide sufficient stiffness properties to the road pavement. It is also worth noting that LWD tests have been carried out in different climatic conditions: days 0 and 365 correspond to summer climate, day 60 to autumn, while tests at day 180 were performed in relatively cold weather. Thus, the surface bituminous layer's temperature must be considered for a correct analysis of the results. Stiffness moduli registered at days 60 and 180 are generally higher because of the lower temperature of the wearing course. However, from the comparison between the values measured at days 0 and 365, having very similar temperature conditions, E_{LWD} results confirm the data obtained from ITSM tests on cores. RCBMc appears to be the stiffest mixture, while RCBMt presents lower values but comparable to the reference mixture. Moreover, as for ITSM results, data show an increase in stiffness from day 0 to day 365. Finally, the order of moduli in the two days is similar for both testing methods.

5. Conclusions

The objective of the present research was the laboratory and in situ evaluation of the physical and mechanical properties of 100% Recycled Cement Bound Mixtures for base layers. Two experimental mixtures were analysed both containing RAP and each a specific C&D waste: tiles waste or crushed concrete waste. The experimental programme considered a laboratory and a test track phase: test results have been compared with those registered for a traditional CBM and with common Italian technical specifications.

According to the presented experimental results, the following conclusion can be deduced:

- ITS and UCS after 3 and 7 days of curing show suitable mechanical properties for both the experimental mixtures, even if RCBMt does not reach ITS limit after 3 days of curing. Results are lower but comparable to the reference CBM and in accordance with the limits imposed by the technical specifications taken as reference. As for ITSM test, both recycled mixtures present suitable performance and RCBMc shows the highest stiffness even if compared to the virgin mixture. This may be related to the type of stabilizing agent. As indirect result of the mechanical characterization, the presence of RAP and C&D wastes do not seem to prevent the compactability properties and the achievement of the higher layer densities.
- From ITS test on specimens prepared with the material taken from the paving screed, the good mechanical properties evaluated during the laboratory phase are confirmed. The in situ tests carried out after the laying (day 0), validate the mix designs and the good workability and compactability characteristics of the experimental mixtures.
- The development of the stiffness moduli for RCBMc and RCBMt follows the same trend of the reference mixture. However, the recycled mixture with crushed concrete waste presents the highest stiffness even if compared to the CBMv. The high presence of RAP and C&D wastes does not determine a reduction in stiffness after 365 days of traffic.
- LWD tests confirm the high performance of RCBMc as verified during the dynamic characterization on core samples. RCBMt presents lower stiffness that is comparable to the virgin mixture.

According to the results here presented, the similarity of data obtained in the laboratory characterization and in the test track phase is evident. The high mechanical properties achieved, confirm the quality of the experimental mix designs and the validity of in plant production and paving processes. However, the performances of the mixtures are strictly related to the type and quality of recycled materials used.

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