Laboratory investigation into the effects of fibres and bituminous emulsion on cement-treated recycled materials for road pavements

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Introduction

Waste recycling in the field of transportation infrastructure presents itself as a possible solution for two key issues: the increasing problem of disposing of waste materials and the need to find alternative sources to traditional quarried stone aggregates. In addition, when recycling is carried out directly on site, this also helps to reduce heavy trafficon roadways in the vicinity of landfills, given there is less to dispose of (Giustozzi, Crispino, & Flintsch, 2012; Horvath, 2004; Pittenger, 2011; Wang, 2007). Moreover, as far as transportation infrastructure rehabilitation works are concerned, involving the demolition of old infrastructures and their reconstruction, the reusing or recycling of waste arising from the demolition can be a strategic way of producing new pavement materials (Bolouri & Khayati, 2012; Carrera, Dawson, Grenfell, Windsor, & Proctor, 2012; Giustozzi, Toraldo, & Crispino, 2012; Ling et al., 2013; Moreno, Rubio, & Martinez-Echevarria, 2011; Nam, Maherinia, & Behzadan, 2014; Toraldo, Saponaro, Careghini, & Mariani, 2013). However, the structural characteristics of pavement layers must suit the pavement design. To this end, it is necessary to fine-tune the recycling process, in order to obtain a recycled material with the same characteristics as the virgin one. Nowadays, cement-treated materials (CTMs) are normally used as base or sub-base layers in so-called semi-rigid pavements, employed in the construction of highways, heavy-traffic roads and airports. Such materials are composed of aggregates, cement (normally up to 6%) and water (White & Gnanendran, 2002; Xuan, Houben, Molenaar,

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& Shui, 2012). Cement provides an increase in the bearing capacity of the layer, reducing strain on the subgrade and tensile stress at the bottom of bituminous layers. In some cases, the presence of cement produces excessive stiffness and brittleness, as well as the phenomena of cracking. However, in order to avoid cracking, it is possible to add fibres to reduce cracking propagation, and/or bituminous emulsion (BE) to provide viscoelastic properties to the CTMs (Da Rios, Toraldo, & Mariani, 2008; García, Lura, Partl, & Jerjen, 2013; Hamidi & Hooresfand, 2013; Zhang, Liu, Li, & Zhang, 2013).

Within the framework described above, a research study was carried out in the Road Research Laboratory of the Politecnico di Milano, with the aim of studying, through a comparative laboratory investigation, the effects of two commercially available fibres and a BE on recycled CTMs. The aggregates used throughout the investigation result from the demolition of old concrete slabs.

The investigation was divided into two principal phases. During the first phase, the mechanical performances (e.g. Unconfined Compressive Strength (UCS), Dynamic Modulus and Indirect Tensile Stress) of CTMs containing two types of fibres, each one in two different lengths, were defined. On the basis of the results obtained, the second phase focused on the evaluation of the effects of curing and in-service temperatures on the mechanical performance (Dynamic Modulus and Indirect Tensile Stress) of both the CTMs studied in the first phase, and the same CTMs treated with BE.

This article provides an overview of the results obtained and describes some details of the specific protocols followed during the research project.

Experimentation

Key materials

The stone matrix of all the mixtures investigated was entirely recycled as it was the result of in-field milling and a selection process using the 40-year-old concrete slabs of airport pavements. The process included the following operations: the milling of the slabs, by means of an asphalt miller; the discarding of the slabs' steel reinforcement using a magnet; the crushing and selection of the recycled aggregates using a hammer mill equipped with a 40-mm sieve. The particle-size distribution of aggregates is given in Figure 1. Dispersion bars in the figure also display the maximum and minimum result of each sieve passing. These were obtained by analysing 25 samples weighing 5 kg each, deriving from a single 500 kg batch collected in the field during the aggregate production. The results in the figure show a clear variation of the aggregates' distribution, especially in the sieves between 1 and 16 mm. The resistance of the recycled aggregates to fragmentation was evaluated by means of the Los Angeles Coefficient (European Committee for Standardization, 2010a) (LAC of 26%), in accordance with Italian specifications (Italian Ministry of Infrastructures, 2001), which require LAC < 30%.

The hydraulic binder was Portland cement type Cem II/B-LL 32.5 R according to EN 197-1 (European Committee for Standardization, 2011). The cement content (%C) was equal to 4.0% by weight of aggregates.

Fibres employed during the investigation were monofilament polyolefin and polypropylene fibrillated, herein referred to as F1 and F2, respectively (Figure 2). Two lengths for each fibre were considered for the study: 19 and 54 mm. The fibres content was 1 kg/m^3 by weight of aggregates.

The fluid phase of the mixtures was defined on the basis of a preliminary investigation of the aggregates, by which the optimum water content was assessed and fixed at

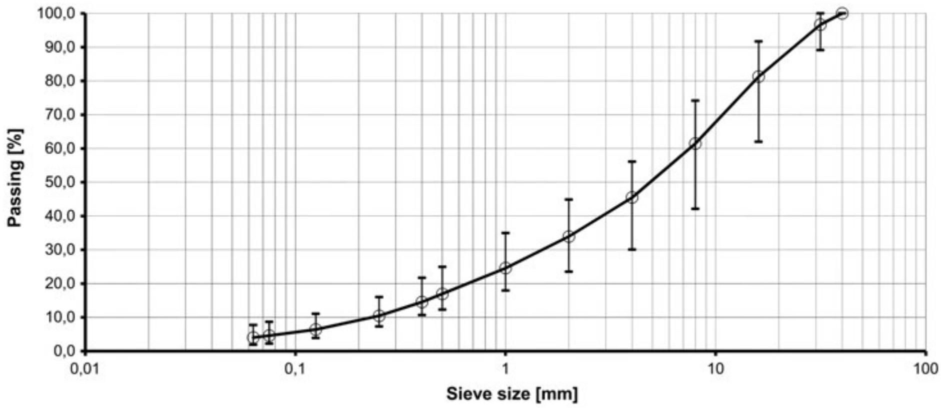

Figure 1. Gradation of the recycled aggregates.

Figure 2. Fibres investigated.

9% by weight of aggregates, according to the Modified Proctor method (European Committee for Standardization, 2010b).

The cationic bituminous emulsion content was maintained constant during the investigation (%BE equal to 2% by weight of aggregates).

The fluid phase of the mixtures containing the BE was defined as the sum of BE content (equal to 2%) and water (7%), according to the Proctor results.

In Table 1, the main characteristics of both fibres and BE are reported.

Experimentation programme

The experimental investigation involved a number of tests selected to highlight the effects of both the four types of fibres and the BE on the CTMs' performances. To this

Table 1. Basic characteristics of fibres and BE.

Fibre Code	Main component	Aspect	Fusion point [°C]	Burning point [°C]
F1	Polyolefin	Monofilament	~220	~650
F2	Polypropylene	Fibrillated	~160	~590
Bituminous emulsion	Bitumen content		Bitumen Characteristics	
	58–62%		Penetration	100 dmm
			Ring and Ball	45 °C

end, ten mixtures were prepared in the laboratory. Specifically, five mixtures were prepared using cement as the sole binder, of which only four contained fibres. Of the remaining five mixtures, both cement and BE were used as binders, but again, four of the mixtures contained fibres, while the last was prepared without them.

Within this article, the mixtures are indicated by a code formed by the acronyms of the mixture and the binder used (CTM or CTM-BE), and a subcode indicating the presence of fibres (NoF, F1 or F2) and the corresponding length (19 or 54 mm). For instance, the code of a mixture having cement and BE as binders and containing fibre F1 with a length of 19 mm will be CTM-BE-F1-19.

The mixtures' production was carried out using a common drum mixer. Materials were added to the mixer according to a precise sequence: first recycled aggregates and fluids (only water for CTM mixtures, or water and BE for CTM-BE mixtures), then cement. At a later stage, fibres were added gradually, following a methodology developed at the Experimental Road Laboratory of the Politecnico di Milano (Crispino, Mariani, & Toraldo, 2013). The mixing process was performed at room temperature.

The investigation herein described consisted of two main phases, as summarised in Table 2.

Phase 1 focused on the comparison of the mixtures having cement as the sole binder (CTMs).

The comparison of mixtures was performed by carrying out mechanical tests (e.g. UCS, Dynamic Modulus and Indirect Tensile Stress) on three nominally alike specimens for each mixture at a temperature of 20 °C. The tests were performed after seven days of curing in a climatic chamber (20 °C with a relative humidity of 95%). With regard to the UCS tests, specimens were manufactured according to the Proctor method (European Committee for Standardization, 2005) and using self-built moulds in order to obtain a height/diameter ratio of two (height of 300 mm and diameter of 150 mm). Dynamic Moduli and Indirect Tensile Stress tests were performed on specimens compacted using the Gyratory Shear Compactor (GSC), according to the protocol specifications defined within the Strategic Highway Research Program (Cominsky, Leahy, & Harringan, 1994) (1.25° gyration angle, 30 rev/min gyration speed, 600 kPa vertical pressure, 150 mm mould diameter). GSC specimens (height of 70 mm and diameter of 150 mm) were compacted at the same level of bulk density previously obtained for the Proctor specimens (2100 kg/m^3).

UCS and Indirect Tensile Stress tests were carried out following the European Specifications (European Committee for Standardization, 2006a, 2006b). The Dynamic Moduli were measured imposing an Indirect Tensile Stress of 100 kPa and a load rise time of 124 ms, in order to observe the behaviour of materials under traffic loads.

Table 2. Materials and mechanical tests.

Mix code	Mix subcode	Cement	Bituminous emulsion	Water (%)	Fibres type	Fibres length (mm)	Mechanical tests		
							Unconfined Compressive Strength	Dynamic Modulus	Indirect Tensile Stress
Phase 1									
CTM[a]	CTM-NoF	4%	NO	9%		No	@ 7 days of curing @ 20 °C of temperature		
	CTM-F1-19				F1	19			
	CTM-F1-54				F1	54			
	CTM-F2-19				F2	19			
	CTM-F2-54				F2	54			
Phase 2									
CTM[a]	CTM-NoF	4%	NO	9%		No	No	@ 7, 14 and 28 days of curing @5, 20, 30 °C of temperature	
	CTM-F1-19				F1	19			
	TM-F1-54				F1	54			
	CTM-F2–19				F2	19			
	CTM-F2-54				F2	54			
CTM-EB[a]	CTM-BE-NoF	4%	2%	7%		No			
	CTM-BE-F1-19				F1	19			
	CTM-BE-F1-54				F1	54			
	CTM-BE-F2-19				F2	19			
	CTM-BE-F2-54				F2	54			

[a]Sieve size distribution according to Figure 1.

Based on the results obtained during the first phase, which are described in the following section (Phase 1: the effects of fibres on CTMs), the purpose of Phase 2 was to evaluate the effects of curing (7, 14 and 28 days) and in-service temperatures (5, 20, and 30 °C) on the mixtures' mechanical performances, by measuring Dynamic Modulus and Indirect Tensile Stress on GSC specimens.

The test temperature range was chosen to cover the typical environmental conditions of the Mediterranean regions, also considering that these materials are used into the pavement structure, as a sub-base or base layer, so not directly influenced by the air temperatures. Extreme climatic conditions are not covered by the experimentation described in this article.

Results and discussion

Phase 1: the effects of fibres on CTMs

In Figure 3, the average results related to the CTMs' mechanical performances (e.g. UCS, Indirect Tensile Stress and Dynamic Modulus) are shown as a function of the type and length of the fibre, including those of the reference mixture (CTM-NoF). Dispersion bars in the graphs also display the maximum and minimum result for each mixture, revealing a significant dispersion of some results, probably due to the variability of the aggregate size distribution, as per the results in Figure 1.

As regards UCS results, it can be noticed that this parameter is not significantly improved by the presence of fibres, except for the mixture CTM-F2-54, which shows a noticeable increase in UCS. This result is probably due to the length and stiffness of the fibre used, which is likely to produce a sort of net to reinforce the mixture, showing positive effects in this type of test configuration. However, the authors believe that UCS parameters are not suitable to correctly highlight the benefits of fibres, even though UCS tests are currently used in Europe to evaluate CTMs performances.

Results of both Indirect Tensile Stress and Dynamic Modulus tests demonstrate the actual benefits of the use of fibres. In fact, the graphs show an increase in the perfor-mance of all the mixtures containing fibres. In particular, the best results are shown for the mixtures containing 54 mm fibres (CTM-F1-54 and CTM-F2-54).

Moreover, UCS and Indirect Tensile Stress results of all the mixtures investigated meet the Italian specifications (Italian Ministry of Infrastructures, 2001), which require, after seven days of curing, an UCS value between 2.5 and 7.5 MPa and a minimum Indirect Tesile Stress value equal to 0.25 MPa.

Phase 2: the effects of fibres and BE on CTMs

Figures 4 and 5 show the average results in terms of the mechanical performance (e.g. Dynamic Modulus and Indirect Tensile Stress) of the investigated mixtures. Here, both the type and length of fibres are considered as well as the type of binder (only cement or cement and BE), plus those of the reference mixtures (CTM-NoF and CTM-BE-NoF). The results are given as a function of curing time (7, 14 and 28 days) at a reference temperature (5, 20, 30 °C). Dispersion bars in the graphs also display the maximum and minimum result for each mixture, again revealing a significant dispersion of the results, probably due to the variability of the aggregates' size distribution, as per the results in Figure 1.

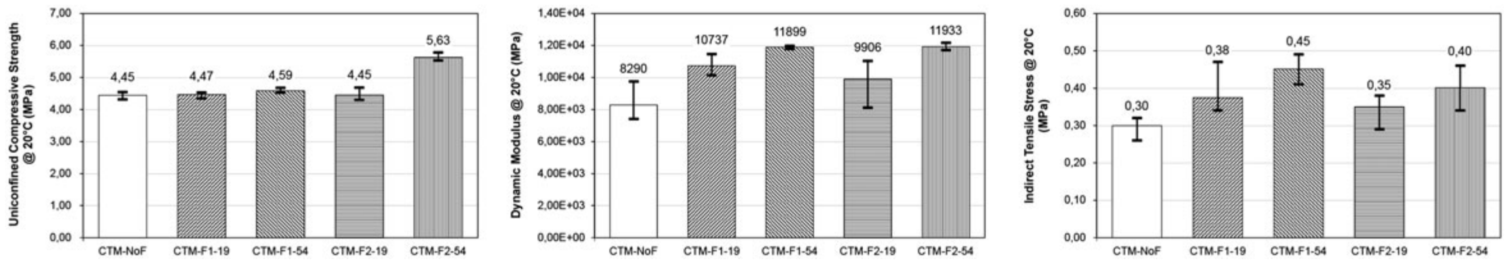

Figure 3. Effects of fibres on CTMs.

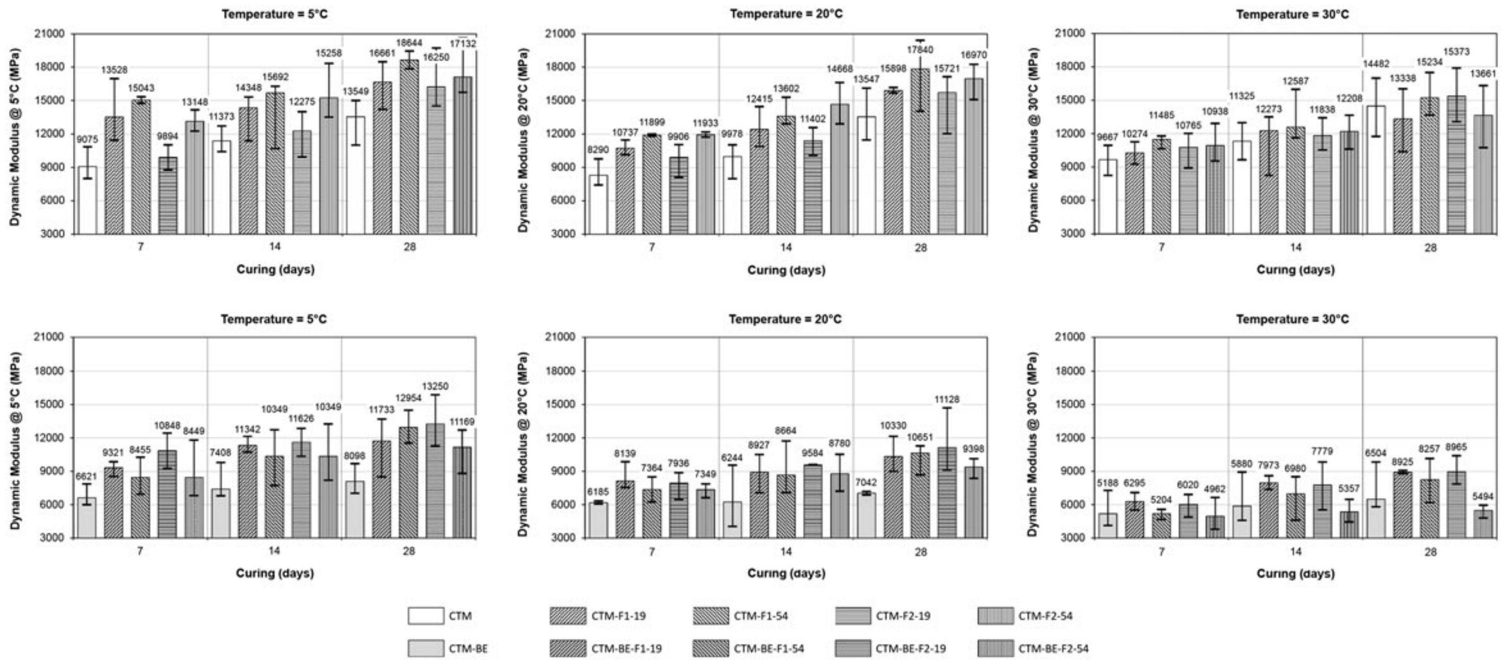

Figure 4. Effects of fibres and BE on CTMs: Dynamic Modulus.

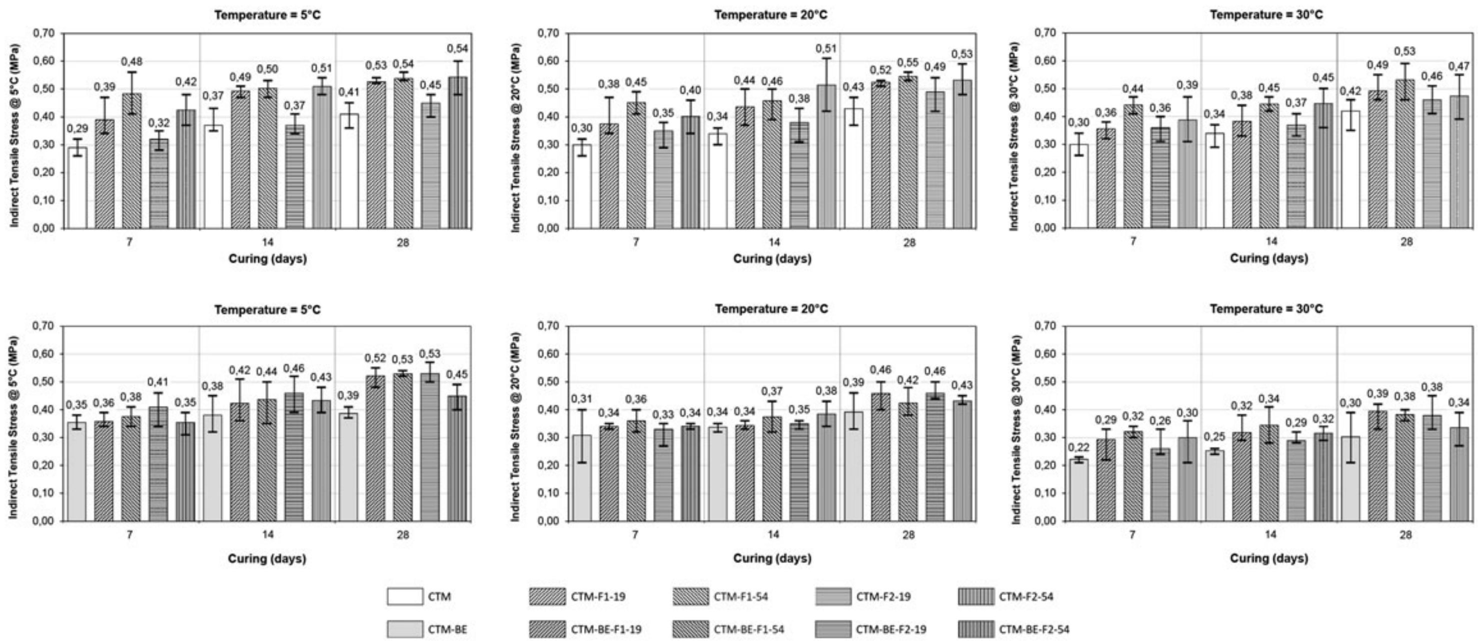

Figure 5. Effects of fibres and BE on CTMs: Indirect Tensile Stress.

Graphs in Figure 4 indicate that the Dynamic Moduli of all the mixtures increase with an increasing curing time. As regards the impact of temperature, it is possible to note that CTMs have a slight thermo-dependency, whereas CTM-BEs show an increase in the Dynamic Modulus owing to a decrease in temperature. This is obviously due to the presence of the BE, which provides viscoelastic characteristics to the mixtures, producing a general decrease in their performance. This clearly does not mean that CTM-BE materials provide worse performances than CTM materials, but suggests that pavement engineers have the possibility to choose and adapt (e.g. by changing the type and dosage of binders) the structural performance of the material for the multilayered pavement system they are designing. As far as fibres' effects are concerned, graphs in the figures show an increase of the Dynamic Modulus due to the presence of such additives, but with some differences. In particular, fibres F1-54 are the most suitable for CTM mixtures, whereas fibres F2-19 show the best performances when bitumen emulsion is used.

Results of Indirect Tensile Stress tests (Figure 5) confirm the trends observed in Dynamic Modulus tests as regards both curing time and temperature effects. Moreover, the effects of fibres on mixtures' performances in Indirect Tensile Stress tests are similar to those obtained in Dynamic Modulus tests. However, fibres F1-54 appear to be the most suitable for CTMs, while fibre F2-19 shows the best performance when BE is used (CTM-BE).

It is probably due to the fact that in the case of CTMs, long, rigid and monofilament fibres create a sort of net into the materials' stone matrix. On the contrary, short and fibrillated fibres are more suitable if BE is used, this because the net is guarantee by fibres characterised by lower stiffness than the longer ones. Such stiffness suits the visco-elastic behaviour of CTM-BE mixtures.

Summary and conclusions

The laboratory investigation described in this article focuses on the effects of fibres and BE on CTMs for road pavements. To this purpose, the investigation was carried out in two phases. The first phase aimed to define the mechanical performances of CTM containing two types of fibres, each one of two lengths. According to the results obtained during the first phase, phase two focused on the evaluation of the mechanical effects of curing and in-service temperatures on both the CTMs studied in the first phase and the same CTMs treated using BE.

Preliminary investigations of the recycled aggregates showed a variable particle-size distribution, probably due to the selection method used, increasing the dispersion of the mechanical results.

Based on the results achieved during the first phase of the investigation, the following conclusions can be drawn:

- UCS tests are not suitable for highlighting benefits arising from the use of fibres in CTMs, although 54 mm polypropylene fibrillated fibres (F2-54) showed to increase the performance of CTMs in this test configuration;
- the use of fibres, particularly 54 mm fibres (F1-54 and F2-54), enhances CTMs performances in terms of Indirect Tensile Stress and Dynamic Modulus;
- all the CTMs meet the Italian Specification for both UCS and Indirect Tensile Stress tests.

With regard to the second phase of the investigation, the conclusions can be summed up as follows:

- performances of both CTMs and CTM-BE increase by increasing the curing time;
- BE reduces the performances of the corresponding mixtures (CTM-BE) when compared to those containing cement as a sole binder (CTM);
- BE increases the viscoelastic characteristics and the thermo-dependency of the corresponding mixtures (CTM-BE);
- fibres prove to be beneficial to all the mixtures investigated in terms of mechanical performance; in particular, 54 mm polyolefin monofilament fibres (F1-54) are the most suitable for CTMs, whereas 19 mm polypropylene fibrillated fibres (F2-19) ensure the best performance when BE is used (CTM-BE).

Disclosure statement

No potential conflict of interest was reported by the authors.

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