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The effect of Cryogenic Crumb Rubber in cold recycled mixes for road pavements

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HIGHLIGHTS

- Including Cryogenic Crumb Rubber in 100% Reclaimed Asphalt Pavement (RAP) cold mixes.
- The percentage of CCR substitution is a basic variable to be controlled during the mix-design.
- The presence of CCR affects and reduces the mixture tensile strength.
- The rubber does not modify the thermo-dependence of the mix or its curing in terms of ITSM.
- CCR can positively improve the crack initiation resistance, while it negatively affects the fracture toughness.

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ABSTRACT

Over recent years, the necessity of reducing the environmental impact of building new infrastructures has increasingly directed research toward developing innovative manufacturing methods and materials that can satisfy these objectives. Cold recycling, widely used in renovating road pavements in Italy, is also moving in this direction, lowering the manufacturing temperatures of bituminous mixes and reducing or ultimately eliminating the use of virgin raw materials. Currently, a wide range of materials are used and, consequently, the number of variables to be considered in the mix-design process of cold recycled mixes for road bases is considerable. Furthermore, new products are continuously being introduced or developed for recycling purposes. The objective of this research project was to test the effects, both mechanically and environmentally, of crumb rubber included in 100% Reclaimed Asphalt Pavement cold mixes for road bases, bound with bitumen emulsion and cement. The crumb rubber is produced cryogenically with granulometric selection, which together with the bitumen, the cement and the fine fractions of the mix forms a resilient mastic capable of imparting significant fatigue resistance properties to the conglomerate.

1. Introduction

According to Directive 2008/98/EC of the European Parliament, European member states must take the necessary measures to increase their recycling processes. In particular, by 2020, the re-use, recycling and recovery of other materials, including non-hazardous construction and demolition waste, must be increased to a minimum of 70% by weight. In this context, efforts to increase the use of recycled materials in road infrastructure construction processes must be maximized, while at the same time develop and promote high performance and durable materials that are suitable for further re-use.

Alongside the environmental benefits deriving from using Reclaimed Asphalt Pavement (RAP), there is today a wide-spread use of warm-mix technology for bituminous surface layers and cold-mix technology for base courses, sub-bases and foundations [1]. A number of studies also aimed to evaluate the performance contribution of RAP when mixed with virgin aggregates and cement to manufacture cement bound layers. Isola et al. field-tested mixtures containing up to 70% of RAP, concluding that, if correctly designed, these can be a viable solution for RAP recycling without compromising pavement performance [2].

On the other hand, the use of RAP in the mix-design of bituminous mixtures has become very common in the hot process. With the existing plant technologies, the only limit to the amount of adopted RAP is given by the final temperature of the mix [3]. New production methods and warm asphalt techniques are

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somehow overcoming this limit and percentages higher than 30% have been recently experimented [4].

When cold recycling of RAP is considered, the number of possible technical solutions is larger and processes can be successfully implemented in plant or in situ. The potential quantities of RAP in the mixtures are up to 100% and the use of combined binders (bitumen and cement) has been proven to be practically and mechanically effective [5]. To go beyond the potential problem of unrepresentativeness of laboratory compacted specimens, Martínez-Echevarría et al. recently suggested a laboratory method for reproducing the density of field compacted cold recycled materials [6].

Together with RAP, the use of Crumb Rubber from scrap tires in road pavements has been experimented in many ways, especially when rubber is incorporated directly into the bitumen (wet process) or, subsequently in the bituminous mixture (dry process). Lee et al. to mention one, conducted and intensive laboratory investigation on the properties of binder containing crumb rubber as a function of the processing and production method of crumb rubber and its content in the wet modified bitumen [7]. When the dry process is adopted to produce hot or warm mixes the digestion time becomes an important aspect of the mixtures' production. According to Moreno et al. the interaction time between rubber particles and bitumen has a certain influence on the final properties of the mixes [8]. This aspect, together with the swelling of compacted mixtures containing Crumb Rubber, has always been addressed as the major drawback of recycling rubber in bituminous mixtures.

Trying to overcome these issues, this article proposes the innovative incorporation of fine Cryogenic Crumb Rubber (CCR) obtained from scrap tires in 100% RAP cold mixes produced at a plant or directly on site [9]. An exhaustive description of both cryogenic and ambient crumb rubber is given by Lee et al. [7].

No consistent references have been found in the literature when the use of crumb rubber, either cryogenic or ambient, is foreseen for the production of cold-recycled mixtures containing high percentages of RAP. Thus, the main objective of this study was to assess the performance when CCR is included in recycled cold mixes for road base courses. This was mainly due to the larger use of the cold recycling technique for the lower part of the pavement either on motorways and highways, being the tested mixture a valid example of a possible Italian plant produced material.

Two different proportions of cement were analyzed to see if and how the cement and its interaction with the crumb rubber affects the characteristics of the mastic. The practical aim of the study is, therefore, to test how the CCR, in relation to the characteristics of the binding agent, can act on the final volumetric and mechanical properties of the mixes. In addition to type testing of the constituent materials, tests were also carried out to determine the workability of the mixes (using a gyratory compactor), Indirect Tensile Strength, stiffness modulus, resistance to crack propagation and repeated loading. Among the latest, Indirect Tensile Fatigue tests have been introduced to establish the fatigue strength of each blend and perform a primary classification of materials for road pavement design purposes [10].

2. Methodology

The constituent materials used for the cold mixes were Reclaimed Asphalt Pavement (RAP), Cryogenic Crumb Rubber (CCR), Cement (C) and Bitumen Emulsion (E). A small amount of water was added to improve workability and to reach the maximum density during compaction.

2.1. Reclaimed Asphalt Pavement (RAP) and Cryogenic Crumb Rubber (CCR)

RAP was collected from a single road pavement, milling the full depth of the asphalt concrete. The materials were then separated into three fractions: coarse RAP 10–30 (10–30 mm), coarse RAP 5–10 (5–10 mm) and fine RAP 0–5 (0–5 mm) (Fig. 1). Table 1 summarizes the properties of the aged asphalt binder recovered from the RAP. The crumb rubber was obtained through a cryogenic process, in which the rubber was cooled using liquid nitrogen and subsequently processed through a hammermill. The output was dried and classified into different gradations. Compared to crumb rubber worked at ambient temperature, CCR particles generally have a smoother surface [11]. The RAP and CCR grading curves are given in Fig. 1.

2.2. Recycled mixtures

Table 2 shows materials and quantities for the cold mixes. The Fuller curve, Eq. (1), was used to design the aggregate gradations of all the studied mixes:

$$P = \left(\frac{d}{D}\right)^n \tag{1}$$

where P is the percentage finer than sieve d,
d is the aggregate size being considered,
D is the maximum aggregates size to be used,
n is the parameter adjusting the curve, and assumed equal to 0.5.

CCR was blended into the mixtures by volumetric replacement of the fine fractions of RAP (RAP 0–5). The preliminary characterization focused on evaluating the workability and Indirect Tensile Strength of the material in order to understand the role played by CCR. Different percentages of CCR were analyzed during this phase (from 0% to 5%). Fig. 2 plots the gradation of the cold mixes (a) and the theoretical maximum densities (b), relating to the different percentages of rubber and cement, calculated following the mathematical procedure set out in EN 12697-5.

The binder used was a cationic bitumen emulsion (61% bitumen) with 55 penetration grade SBS modified bitumen (Table 3). The cement, used as active filler, was a typical Portland Cement 32.5.

2.3. Experimental program

The experimental program was divided into three phases: (1) a pilot phase, where the optimal amount of CCR was determined workability and classification studies (2) stiffness evaluation and (3) fatigue and fracture toughness testing.

The pre-qualification phase was introduced to determine the volumetric characteristics and workability of the mixes using a Gyratory Compactor. In this phase, Indirect Tensile Strength (ITS) was determined for the different proportions of crumb rubber. The primary purpose of this pre-qualification phase was to optimize the proportion of CCR to be used in the subsequent two steps of the research based on the volumetric properties and respective Indirect Tensile Strengths. Thus, the mixes with different CCR percentages were analyzed to determine potential benefits and drawbacks.

The second phase concentrated on studying the stiffness modulus (ITSM) of the optimized mixes. In particular, this was evaluated in relation to the curing time and thermal sensitivity of the mixes.

In the third phase, fatigue resistance (ITFT) and fracture toughness (KIc) were studied in order to understand the potential contribution of CCR in terms of mechanical performance. Table 4 summarizes the number of tested specimens. All the tests for mechanical characteristics were carried out on fully cured specimens.

2.4. Production of samples, curing and testing equipment

All specimens were compacted with a gyratory compactor. Compaction of 150 mm diameter specimens was carried out at 600 kPa of axial pressure with an external gyration angle of 1.25°. All mixes were subjected to the same compaction energy of 180 revolutions.

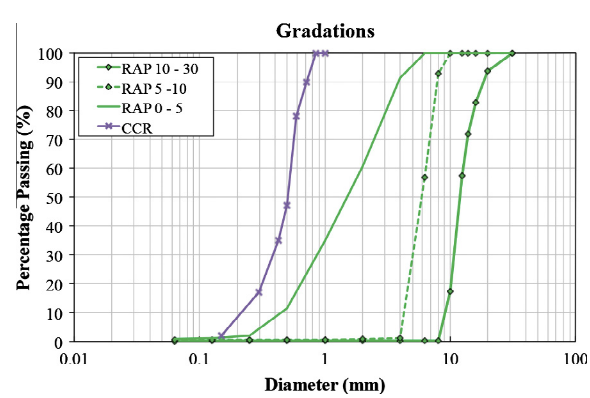

Fig. 1. RAP fractions and Cryogenic Crumb Rubber gradations.

Table 1
Properties of the aged asphalt binder derived from RAP.

	Unit	RAP 10-30	RAP 5-10	RAP 0-5	Standard
% Binder	%	3.10	3.27	6.13	/
Penetration @ 25 °C	dmm	9	7	7	EN 1426
Soft. point	°C	73.8	75.5	78.8	EN 1427
Dynamic Visc. @ 60 °C	Pa s	52,625	58,015	95,305	EN 13702-1
Heptane insolubles	%	42.4	41.2	39.6	ASTM D3279

Table 2
Designation and composition of the cold mixes.

Material	Max density (g/cm^3)	1.5C_5.0E	3.0C_5.0E
RAP 10–30	2.62	49.0%	49.0%
RAP 5–10	2.62	13.0%	13.0%
RAP 0–5	2.53	35.0-a%	35.0-a%
CCR[a]	1.08	a[a]%	a[a]%
Cement (C)	3.00	1.5%	3.0%
Bitumen Emulsion (E)	1.00 (at 25 °C)	5.0%	5.0%
Additional Water	0.99 (at 25 °C)	0.7%	0.7%

[a] A 0–5% of RAP was replaced with an equivalent volume of CCR. 0%<a%<5%.

Table 3
Properties of the bitumen emulsion.

Characteristic	Unit	Value	Standard
Characteristics of the cationic emulsion			
Water content	%	39	EN 1428
pH value	°	4	EN 12850
Settling tendency @ 7 days	%	6	EN 12847
Characteristics of the extracted binder			
Penetration	dmm	55	EN 1426
Softening point	°C	62	EN 1427
Fraass breaking point	°C	−16	EN 12593

All the specimens were cured for six days in an oven at 40 °C, wrapped in foil for three days and unwrapped for further three days. The final conditions of curing were achieved by keeping the specimens at the constant temperature of 20 °C until constant mass was reached. The weight was controlled every seven days.

The adopted standard for Indirect Tensile Strength (ITS) was EN 12697-23. Before testing, all the specimens were kept at the testing temperature of 25 °C in a climate chamber for six hours. The load was applied displacement controlled with a constant displacement rate of 50 mm/min.

Standard EN 12697-26 was used for the indirect tensile stiffness modulus tests (ITSM). The standard defines an impulsive load, with rise-time of 124 ms, to achieve the target horizontal deformation of 7 ± 2 µm.

The indirect tensile fatigue test (ITFT), as defined by BSI ABF 1995, was used as a practical method to estimate the resistance to crack initiation [12]. The test was carried out at 20 °C in controlled stress mode, with a rise-time of 124 ms. The failure was established as being the complete fracture of the specimen. The system measured the cumulative deformation of the specimen throughout the test and the number of loading cycles to failure.

Finally, fracture toughness was studied following standard EN 12697-44. The semicircular specimens (SCB) were tested at 10 °C. It should be noted that the test only describes a method to determine the resistance to crack propagation of an asphalt mixture, corresponding, in theory, to the second part of the failure mechanism. The first phase, which is the crack initiation phase, is mainly covered by fatigue testing.

3. Results and discussion

3.1. Compaction properties and evaluation of workability

The laying phase is essential for bituminous cold-mixes. For the case under examination, optimizing the components is fundamental, because RAP, Emulsion (E), Cement (C) and Cryogenic Crumb Rubber (CCR) interact differently depending on the relative quantities used. In particular, the effect of the crumb rubber on workability was studied during and after compaction in terms of variation of volume of the specimen. Tests were carried out on samples with CCR volume fractions between 0% and 5%. Compaction and workability properties were tested on 36 specimens, three for each sample mix. The mass of each compacted specimen was 4500 g.

Figs. 3 and 4 and Table 5 show all the gyratory compaction curves and the relative compaction models given by Eq. (2):

$$\%\rho_m = a \cdot \ln(x) + b \qquad (2)$$

where $\%\rho_m$ is the percentage of maximum density,
a is the slope of the compaction curve,
x is the number of gyrations,
b is the intercept of the regression curve.

The workability properties of the mixes are similar for both cement contents. CCR contributes toward self-compactability of the mixes. The parameter b, which defines the intercept with the y-axis of the model, representing the compaction curves for each mix (Table 5), increases as the content of crumb rubber increases. Still, all mixes achieve similar values in terms of the level of densification reached at the end of compaction (after 180 revolutions). With both the different percentages of cement, the maximum level

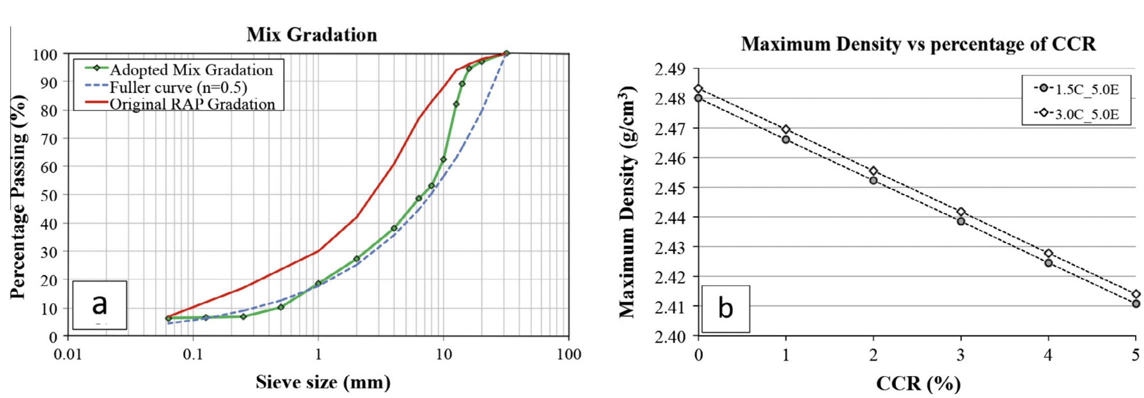

Fig. 2. Mixture gradation (a), theoretical maximum density with different percentages of CCR and cement (b).

Table 4
Summary of the tested specimens.

Type of cold mixtures		Number of tested specimens											
		1.5C_5.0E						3.0C_5.0E					
% of CCR		0	1	2	3	4	5	0	1	2	3	4	5
Preq. Phase	Gy. compaction	3	3	3	3	3	3	3	3	3	3	3	3
	Indirect Tensile Strength	3	3	3	3	3	3	3	3	3	3	3	3
2° Phase	ITSM vs curing time	4	/	/	4	/	/	4	/	/	4	/	/
	ITSM vs temperature	4	/	/	4	/	/	4	/	/	4	/	/
3° Phase	ITFT	9	/	/	9	/	/	9	/	/	9	/	/
	Fracture toughness	4	/	/	4	/	/	4	/	/	4	/	/

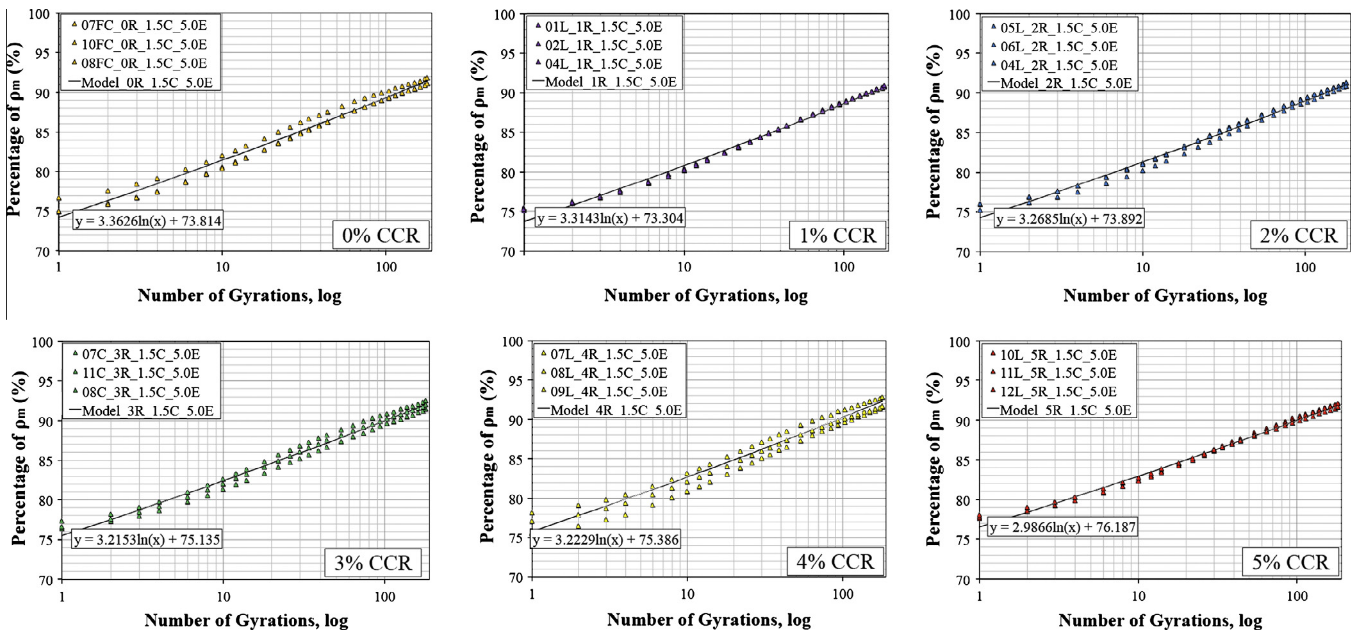

Fig. 3. Compaction curves of the cold mixes with 1.5% C and different CCR%s.

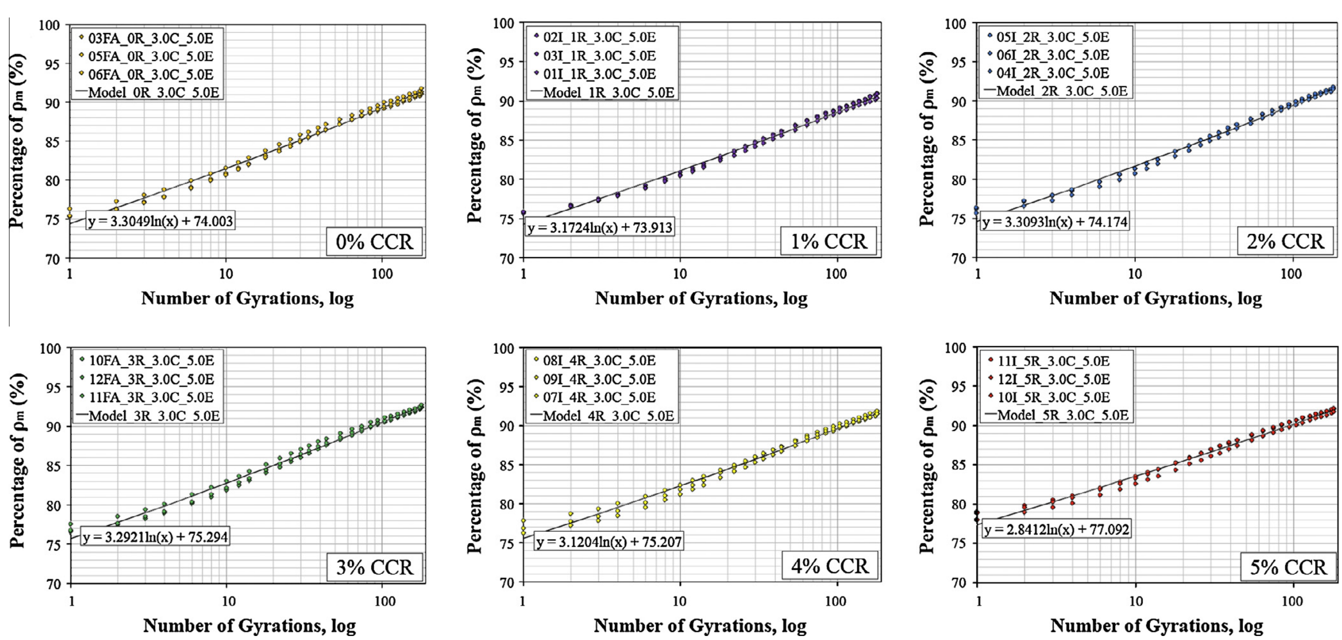

Fig. 4. Compaction curves of the cold mixes with 3.0% C and different CCR%s.

Table 5
Compaction models representing each sample.

Material	*a*	*b*	Material	*a*	*b*
0R_1.5C_5.0E	3.3626	73.814	0R_3.0C_5.0E	3.3049	74.003
1R_1.5C_5.0E	3.3143	73.304	1R_3.0C_5.0E	3.1724	73.913
2R_1.5C_5.0E	3.2685	73.892	2R_3.0C_5.0E	3.3093	74.174
3R_1.5C_5.0E	3.2153	75.135	3R_3.0C_5.0E	3.2921	75.294
4R_1.5C_5.0E	3.2229	75.386	4R_3.0C_5.0E	3.1204	75.207
5R_1.5C_5.0E	2.9866	76.187	5R_3.0C_5.0E	2.8412	77.092

of densification achieved after 180 revolutions (ρ_m% gyr in Fig. 5) is between 91.0% (0% CCR) and 92.0% (5% CCR).

All the mixes with rubber showed a (limited) increase in volume relative to the compaction achieved immediately after the gyratory compaction process (Fig. 5). This is related to the elastic response of the crumb rubber adopted into the mixes despite different quantities of RAP sand were replaced by the same volume of crumb rubber. The average percentage of ρ_m reached at the end of compaction (Av. ρ_m% gyr) is measured automatically as the height of the specimen at the 180th revolution for all the studied percentages of CCR. These results were compared with the respective values measured on the same specimen after curing (Av. ρ_m% cured). The Average $\Delta\rho_m$% is the difference between these two values for each CCR%.

It was seen that the Average $\Delta\rho_m$% is strongly correlated to the percentage of CCR added to the mix. On the contrary, no significant variation in percentage of ρ_m after curing was measured for both cement percentages and up to 3% CCR. Furthermore, with 1.5% cement, the percentage of ρ_m (ρ_m% cured) was between 89.7% (0% CCR) and 88.7% (5% CCR). When 3% cement was used, the cured ρ_m% decreased from 89.9% (0% CCR) to 88.1% (5% CCR).

3.2. Indirect Tensile Strength analysis

All specimens were tested using the Indirect Tensile Strength Test at 25 °C. Results are shown in Fig. 6.

Based on the obtained results, it is possible to infer the following:

- the Indirect Tensile Strength of both mixes is affected by the CCR content; the higher the CCR%, the higher the reduction in ITS values;
- the cement content (1.5% or 3.0%) does not seem to affect ITS when 5% of bitumen emulsion is adopted.

However, an increase of the percentage of CCR affects the vertical displacement at the failure point; the lower the cement content, the higher the measured vertical displacement (Table 6).

The pre-qualification phase meant that it was possible to evaluate how CCR, added in variable percentages, can affect the mix's properties in terms of workability and resistance to indirect traction. Analyzing the results together with economic considerations (potential cost saving of using crumb rubber), it was found that the maximum percentage of crumb to be used is 3%. In fact, increasing from 3% to 4% CCR, there is a significant reduction of ITS equal to 10%, which represents the most significant reduction value among the various quantities of crumb rubber being studied.

Therefore, in the following phases, an evaluation will be made of the characteristics of stiffness and resistance to crack initiation and propagation of the mixes designed with 3% CCR.

3.3. Analysis of the Indirect Tensile Stiffness Modulus results

Fig. 7 summarizes the stiffness measured through the ITSM test on fully cured specimens. The temperature dependency was described using the following analytical model (3) [12]:

$$\log S = -\alpha \cdot T + \beta \quad (3)$$

where S is the stiffness modulus at temperature T, and α and β are experimental parameters varying with the material. Temperature sensitivity is here represented by α, the slope of the regression curve in a semi-logarithmic graph (Fig. 7). Higher values of α correspond to a more temperature sensitive material.

Rubber affects the stiffness modulus of the mixtures at all the studied temperatures, but not their temperature sensitivity. The parameter α is in fact constant for all the studied mixes. It is furthermore seen that the rubber has a higher effect on those mixes with the lowest content (1.5% cement). With 1.5% cement, CCR generates an ITSM reduction of approximately 32% compared to the values obtained from the reference mix. When 3% cement is used, the percentage of reduction is on average 19%. The cement thus seems to affect the ITSM value of the mixtures containing CCR more than those without. In fact, when considering the mixes without rubber, the ITSM values are comparable and the cement seems to behave partially as inactive filler.

The influence of CCR on the ITSM development of the mixture is shown in Fig. 8. The modulus increases with the curing time and reaches a maximum value of about 6500 MPa for samples without rubber.

The increase in stiffness is described by a simple analytical model (4):

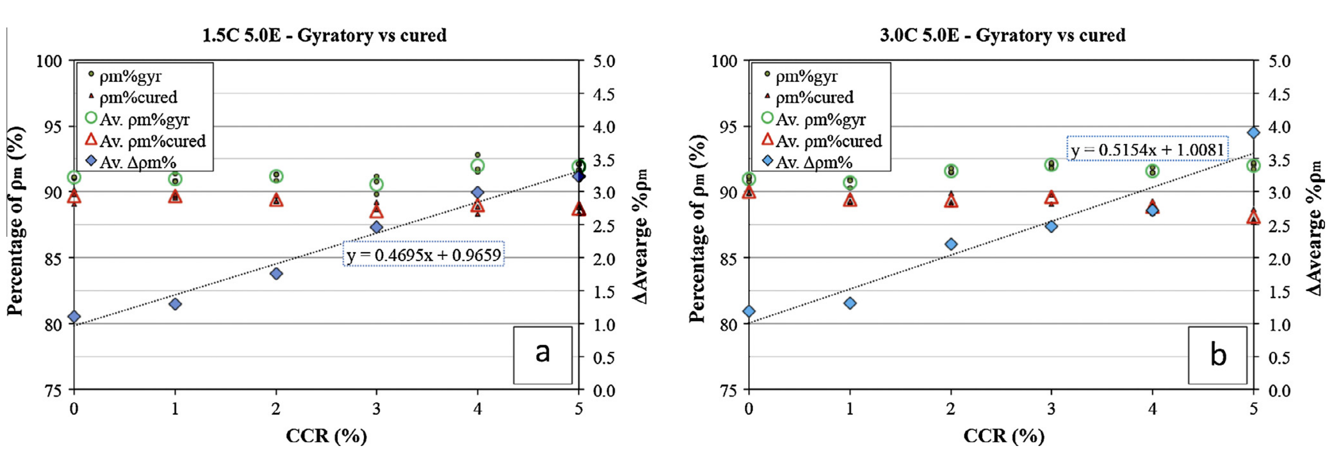

Fig. 5. Variation in volume after compaction, mixes with 1.5% cement (a) and mixes with 3.0% of cement (b).

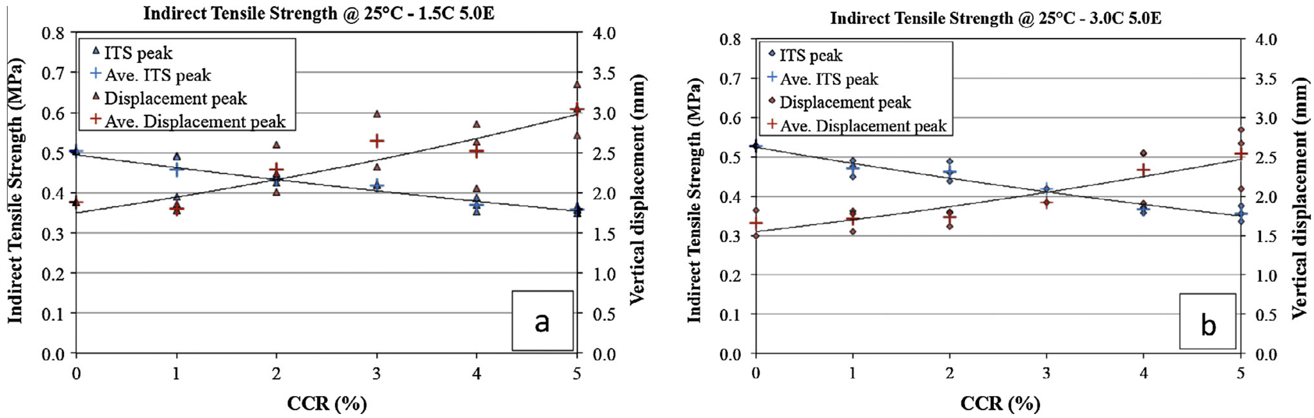

Fig. 6. Indirect Tensile Strength at 25 °C, 1.5% cement mixes (a) and 3.0% cement mixes (b).

Table 6
Average ITS and average displacement results.

CCR%	1.5C_5.0E				3.0C_5.0E			
	Av. ITS (MPa)	Av. disp. (mm)	Av. ITS norm.	Av. Disp. norm.	Av. ITS (MPa)	Av. disp. (mm)	Av. ITS norm.	Av. disp. norm.
0	0.51	1.88	1.00	1.00	0.53	1.66	1.00	1.00
1	0.47	1.80	0.92	0.96	0.48	1.71	0.91	1.03
2	0.44	2.28	0.85	1.22	0.46	1.74	0.88	1.05
3	0.42	2.65	0.82	1.41	0.42	1.92	0.80	1.16
4	0.37	2.52	0.72	1.34	0.36	2.33	0.68	1.41
5	0.36	3.04	0.70	1.62	0.36	2.54	0.67	1.53

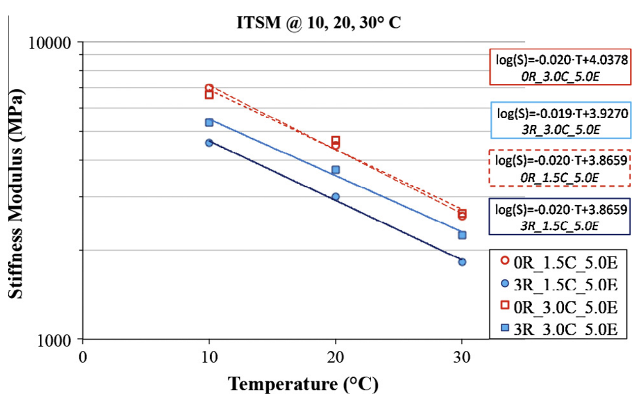

Fig. 7. Indirect Tensile Stiffness Modulus at 10, 20 and 30 °C.

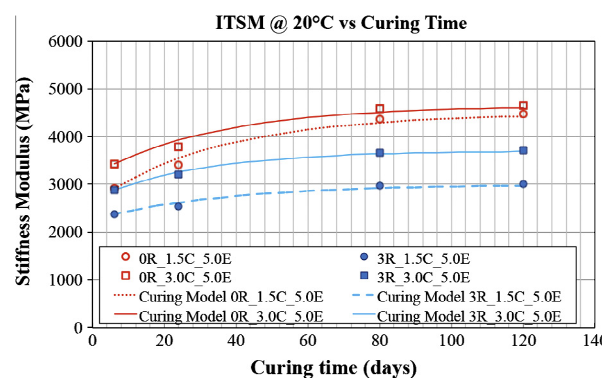

Fig. 8. Evolution of ITSM as a function of curing time.

$$S_t = S_{max} - (S_{max} - S_i) \cdot e^{-b\cdot(t-t_i)} \quad (4)$$

where S_t is the modulus after a specific curing time (t), S_{max} is the maximum (final) modulus, S_i is the initial modulus and b is a coefficient. Assuming $t_i = 6$ days, approximately the same values of b were obtained for all the mixes, indicating similar rates of increase in stiffness (Table 7).

Table 7
Curing model parameters.

Material	S_{max} (MPa)	S_i (MPa)	b
Curing model 0R_1.5C_5.0E	4482	2912	0.028
Curing model 3R_1.5C_5.0E	3012	2384	0.026
Curing model 0R_3.0C_5.0E	4655	3431	0.028
Curing model 3R_3.0C_5.0E	3710	2884	0.032

3.4. Resistance to crack initiation and crack propagation

The repeated load Indirect Tensile Fatigue Test (ITFT) is a simple and fast method for testing the resistance of asphalt mixtures to crack initiation [13]. Although the procedure is widely used to rank asphalt mixes on the basis of their resistance to fatigue, it has not been used to model the structural behavior of materials in the recent mechanistic-empirical design methods [14]. In ITFT, fatigue life is defined as the total number of load applications before failure of the specimen occurs. The tests were performed in stress-control, where the magnitude of the applied stress pulse is maintained constant until failure. According to BSI DD ABF 1997, the failure points were expressed as a function of initial horizontal tensile strain at the center of the specimen (ε_0) calculated as follows (5):

$$\varepsilon_0 = \frac{\rho_0 \times (1 + 3\nu)}{S_m} \times 1000 \quad (5)$$

where

σ_0 is the tensile stress at the specimen center (kPa);
S_m is the stiffness modulus (MPa) at the test temperature;

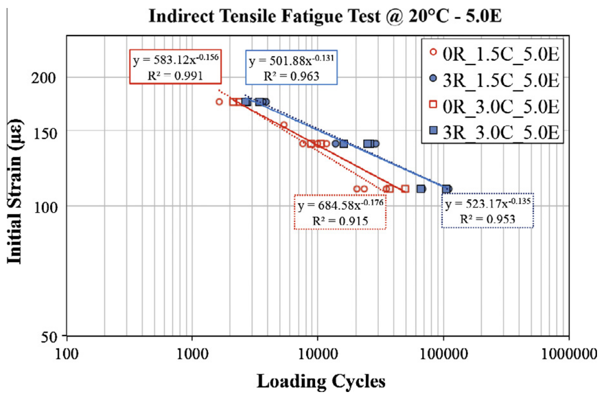

Fig. 9. Comparison of fatigue behavior between cold recycled mixes with and without CCR.

v is Poisson's ratio assumed as 0.35.

Fatigue results (Fig. 9) are traditionally expressed as a relationship between the initial strains and the number of loading applications at failure [15,16]. Comparing the mixes without CCR (empty dots), the increase in cement content does not significantly change the fatigue resistance at all the studied initial strains.

The volumetric replacement of RAP sand with 3% CCR (filled dots) increases the resistance to repeated load applications in the indirect tensile configuration of the mixes blended with either of the cement percentages (1.5% and 3.0%). Based on the calculated fatigue models (Table 8), the extrapolated ε_6 at one million loading cycles is approximately 80 $\mu\varepsilon$ for the mixtures with rubber and 60 $\mu\varepsilon$ for those without.

The semicircular specimen bending test (SCB) was successfully applied to measure the fracture resistance of Hot-Mix Asphalt (HMA) [17,18]. The test is ideal for determining the fracture toughness (KIc) of the mixtures (EN 12697-44). The notched SCB specimen, obtained from standard laboratory compacted cylinders, and used for cold mixes characterization, have a diameter of 150 mm and an average thickness of 50 mm. A vertical notch, 10 mm deep and 0.5 mm wide, was sawn at the center axis of the specimen [19]. The SCB test was performed in an open-loop servo-hydraulic testing machine equipped with an environmental chamber. Before testing, the specimen was conditioned at the test temperature of 10 °C for four hours to ensure uniform temperature distribution within the sample.

Table 8
Indirect tensile fatigue models.

Mixture	Equation	ε_6 ($\mu\varepsilon$, @ 1E+6 cycles)	Number of cycles at ε_0 = 100 $\mu\varepsilon$
0R_1.5C_5.0E	$y = 684.58 * x^{-0.176}$	60.2	5.58E+04
3R_1.5C_5.0E	$y = 523.17 * x^{-0.135}$	81.0	2.11E+05
0R_3.0C_5.0E	$y = 583.12 * x^{-0.156}$	67.6	8.11E+04
3R_3.0C_5.0E	$y = 501.88 * x^{-0.131}$	82.1	2.23E+05

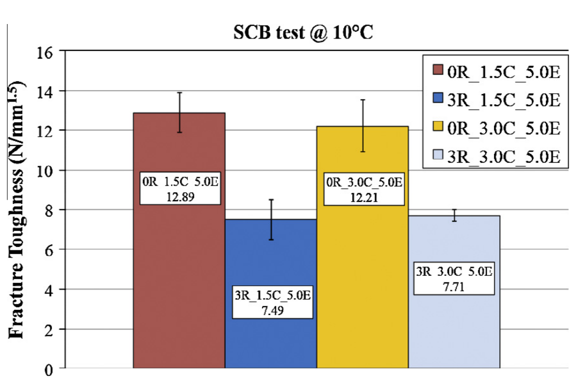

Fig. 10. SCB test results at 10 °C.

Fig. 10 shows the KIc values and the respective standard deviation calculated for four tested specimens. In general, the presence of 3% CCR affects the fracture resistance and reduces the fracture toughness. A 40% and 36% reduction is calculated comparing mixtures with and without rubber, respectively, when blended with 1.5% and 3% of cement.

4. Conclusions

This research project, focused on the adoption of Cryogenic Crumb Rubber in Cold Recycled mixtures for road base courses, was developed aiming to improve their fatigue performances. Other properties such as workability, Indirect tensile Strength, Stiffness Modulus and Fracture toughness were studied in order to verify how the variation in fatigue may be related to these physical and mechanical properties.

Based on the described results, the main and preliminary conclusions are listed below:

– the replacement of RAP with fine (<1 mm) CCR improved the self-compaction of the mixtures, and also conditioned their volumetric change during and after compaction. Since the change in volume depends on the amount of rubber, the percentage of substitution is a basic variable to be controlled during the mix-design;
– the mixtures' mechanical response is characterized, similarly to HMA produced with the dry process, by the interaction between rubber and bitumen. According to ITS results, the presence of CCR affects and reduces tensile strength. Higher ITS reduction occurs when higher percentages of CCR are used;
– when 5.0% bitumen emulsion is used, the cement does not significantly affect the ITS. Lower percentages of cement show higher deformability at the failure point;
– different mechanical responses are generated from the replacement of CCR in the mixtures when Indirect Tensile tests on cylindrical specimens are used for strength, modulus or fatigue characterization. The first two are reduced, following the evidence that the difference in cement percentages influences the stiffness modulus more than the ITS. The rubber does not modify the thermo-dependence of the mix or its curing in terms of ITSM;
– with regards to phase two of fatigue resistance, specifically crack initiation and crack propagation, CCR, when appropriately selected and added into the mix, can positively improve the crack initiation resistance. Still, it negatively affects the fracture toughness, thereby increasing the crack propagation tendency. The first aspect may be seen as a consequence of mechanical interaction involving the RAP and CCR particle aggregates during ITFT. The reduced value of fracture toughness can be related to the fact that the mix cohesion can be affected by the presence of CCR, and that adhesion between bitumen and rubber is lower when compared to that between bitumen and RAP aggregates.

In order to verify the interaction between CCR and bitumen at cold mixing temperatures, the authors expect to complete Scanning Electron Microscopy (SEM) analysis combined with the study of the mastic rheological properties using Dynamic Shear Rheometer (DSR).

The described general findings are based on the laboratory study reported in this paper. Any other investigation into crumb rubber replacement for fine aggregates in cold mixes may differ with changes in the materials' characteristics, mixture ingredient proportions, curing procedure, and use of admixtures and additives.

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