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Crumb Rubber in cold recycled bituminous mixes: Comparison between Traditional Crumb Rubber and Cryogenic Crumb Rubber

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HIGHLIGHTS

- Use of rubber in Cold Recycled Mixes containing 100% Reclaimed Asphalt Pavement.
- Comparison between Traditional and Cryogenic Crumb Rubber in Cold Recycled Mixes.
- The presence of Crumb Rubber influences the volumetric characteristics of mixes.
- The use of CCR seems to be less detrimental than TCR for mechanical characteristics.
- The use of TCR or CCR generates similar mechanical responses for fatigue life.

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ABSTRACT

Today recycling is one of the most innovative and interesting techniques for the rehabilitation of destressed road pavements. In recent years the increased interest in this process, has led to the development of various alternative methods for the recovery and the reuse of road bituminous materials. Cold recycling is, among the recycling techniques, certainly the most studied and developed: it allows the recovering of bituminous material from an existing pavement without the addition of heat, whilst ensuring the creation of high quality bound base layers. A wide range of materials have been tested together with Reclaimed Asphalt Pavement (RAP) and, consequently, there is a large number of variables that can be considered in the mix-design process of new eco-friendly Cold Recycled Mixes. In particular, the present research involves the use of Crumb Rubber within a mixture containing 100% Reclaimed Asphalt Pavement, cold recycled with bitumen emulsion and cement. Two different Crumb Rubbers were adopted: one from the ambient production method, and one produced with the cryogenic process. The goal of this research project was to analyze and evaluate the different physical and mechanical characteristics induced by the shared use of two different types of Crumb Rubber in the Cold Recycled Mixes.

1. Background

For the modern road infrastructure engineer the concept of sustainability often requires to focus on various main design aspects: economic, environmental and architectural. In recent years the trend is to reduce the cost of construction, maintenance and the negative externalities (habitat fragmentation, noise and air pollution, landscape alterations) caused by the new infrastructure on the surrounding environment and the population [1]. This leads to the using of eco-friendly construction techniques, to reduce the use of virgin raw materials and to promote the recycling and reuse of the so-called secondary raw materials (materials which, after complete initial use, may be used repeatedly in production as starting material). An ever increasing number of innovative and environmentally friendly materials has been launched on the market, and others are still under study, with the step of characterization of the materials of crucial importance. In the field of road engineering, the use of recycled materials has become important because of the limited availability of aggregates and the difficulties and excessive disposal costs for milled materials [2].

Cold Mix Asphalt (CMA) and Rubberized Asphalt Concrete (RAC), were investigated in this study. Cold Mix Asphalt has gained

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increasing popularity in the last ten years for its versatile properties. The benefits of using this eco-friendly material are above all the reduction in energy consumption and emissions during production and laying. Hence, compared to the traditional hot technique it is possible to design high-performance paving without the addition of heat [3]. There are many other advantages of using cold technique, for example Cold Mix Asphalt mixtures can be produced in concrete plants. Since the laying is carried out at ambient temperature materials can be handled with more flexibility in time. CMA mixtures can be used in many fields: from the rehabilitation of more or less deep layers to the functional upgrading of high traffic roads, and minor maintenance activities.

Highway engineers around the world have tried to incorporate scrap tire rubber in asphalt pavements since the 1950s [4]. The task was difficult and early applications of rubber in Hot Mix Asphalt concretes provided little or no benefit. It was not until the 1960s that a formulation was discovered that brought clear profits. After a long period of research the so-called Asphalt Rubber was introduced in the United States market in the mid 1980s and today is considered an environmentally friendly alternative to conventional asphalt pavements [5]. Though few authors and studies highlighted some environmental issues regarding hazardous fumes and emissions [6]. According to the ASTM definition, Asphalt Rubber is "*a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles*."

Crumb Rubber markets encourage the development of new technologies that use the material, and nowadays there is a large number of different solutions [11]. For each application the material characterization is a basic step to understand the fundamental properties of the materials used.

Generally there are two different techniques to incorporate rubber either hot or cold in the bituminous mixture. The first one is the wet process, in which rubber is inserted in the asphalt cement of the mix [7]. In the dry process, instead, rubber is incorporated directly in the mixture blend [8]. The rubber particles in the first case act as bitumen modifier pairing the effects of traditional modifiers (SBS, EVA, etc.) [9] and in the second case they become part of the mixture mastic and contribute to the layer endurance during its service life. Asphalt Rubber is not the solution to the waste tires problem, but when utilized by agencies preferring its beneficial engineering characteristics such as durability, flexibility, strength, road noise attenuation and resistance to cracking, it contributes significantly to the reduction of the amount of waste tires [10].

2. Scope

The present research starts from the idea that Crumb Rubber can be advantageously used in a Cold Recycled Mixture containing 100% aggregates from Reclaimed Asphalt Pavements [12]. The aim is to evaluate the different properties associated to the bituminous mixture by using either Traditional or Cryogenic Crumb Rubber. The former is produced at ambient temperature and here it was named Traditional Crumb Rubber, but it appears as Ambient Crumb Rubber (ACR) in several scientific publications. The research focuses also on the influence of particle size of the two different types of Crumb Rubber on the mechanical behavior of mixtures. The rubber particles are incorporated directly into the mixtures blends and become part of their mastics.

The lack of specific technical requirements and procedures testing and controlling Cold Recycled Mixtures with Crumb Rubber demands for a careful preliminary research step. Variables that play a significant role include: percentages, type and particle size of rubber, type and gradation of RAP, percentage of bituminous emulsion, temperature and aging time. The study has firstly focused on the mix-design with particular attention to the materials compactability and workability [12]. Gyratory compaction was the application of choice for the laboratory densification process. Mechanical tests either static and dynamic were selected for the mechanical characterization of the specimens. Eventually the use of Indirect Tensile Fatigue tests has been introduced to assess the fatigue strength of each mixture [13].

3. Materials and experimental program

The materials used in the experimentation are: Reclaimed Asphalt Pavement (RAP), Traditional Crumb Rubber (TCR), Cryogenic Crumb Rubber (CCR), Cement (C) and Bituminous Emulsion (EM). A small amount of water was added to the mixture to regulate the workability and to reach the maximum dry density during compaction.

3.1. Reclaimed Asphalt Pavement (RAP), Traditional Crumb Rubber (TCR) and Cryogenic Crumb Rubber (CCR)

RAP was collected from a single highway pavement, milling the full depth of asphalt concrete. The material was subsequently divided into three different fractions: coarse RAP 10-10+ (10–30 mm), coarse RAP 5-10 (5–10 mm) and fine RAP 0-5 (0–5 mm). Table 1 summarizes the properties of the aged asphalt binder recovered from the same RAP. The Crumb Rubber was obtained by two different processes: ambient and cryogenic. In the first one, rubber is processed through a hammer mill shattering it into smaller particles. The product is classified into specific gradations. The whole process occurs at ambient temperature.

During the cryogenic process instead the rubber is cooled down to −80 °C using liquid nitrogen before being milled. The product is dried and classified into specific sizes. Compared to the Crumb Rubber worked at ambient temperature, CCR particles generally have smoother surfaces (Fig. 1), because the material is worked almost in its vitreous phase. Ambient processing has the advantage of being more economic.

The RAP, TCR and CCR grading curves are represented in Fig. 2.

3.2. Recycled mixtures

Cold mixes are designated depending on the material types and characteristics used in the mixture, as shown in Table 2. The aggregate gradations of all the design mixtures used in this investigation were based on the Fuller's curve using the following formula:

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

where P is the percentage passing the sieve d, d is the aggregate size being considered, D is the maximum aggregates size to be used, n is the parameter which adjust the curve assumed 0.5.

Both the TCR and the CCR are added into the mixture in volumetric replacement to fine fractions of RAP (RAP 0-5). The preliminary materials characterization focused on workability and volumetric characteristics evaluation in order to understand how the presence of rubber influences these fundamental properties. During this phase, two different percentages of rubber were analyzed: 0% for the reference mixture (NCR) and 3% (TCR and CCR). As a result of different manufacturing processes, TCR and CCR have different granulometry. Compared to the Crumb Rubber worked at ambient temperature, CCR particles have smoother surfaces and in fact a higher percentage of finer particles. The theoretical maximum density, related to two different percentages of rubber, was calculated following the mathematical procedure of EN 12697-5.

The adopted binder was a cationic bitumen emulsion (61% bitumen content) with a 55 pen grade SBS modified bitumen (Table 3). The cement, used as active filler, was a typical Portland Cement 32.5. Its function was to increase the mixture mechanical properties in terms of resilient modulus, temperature susceptibility and water damage [14].

Table 1
Properties of the aged asphalt binder from RAP.

	Unit	RAP 10-10+	RAP 5-10	RAP 0-5
% Binder (on mass of RAP)	%	3.10	3.27	6.13
Penetration @ 25 °C	dmm	9	7	7
Soft. point	°C	73.8	75.5	78.8
Dynamic Visc. @ 60 °C	Pa·s	52,625	58,015	95,305
Heptane insolubles	%	42.4	41.2	39.6

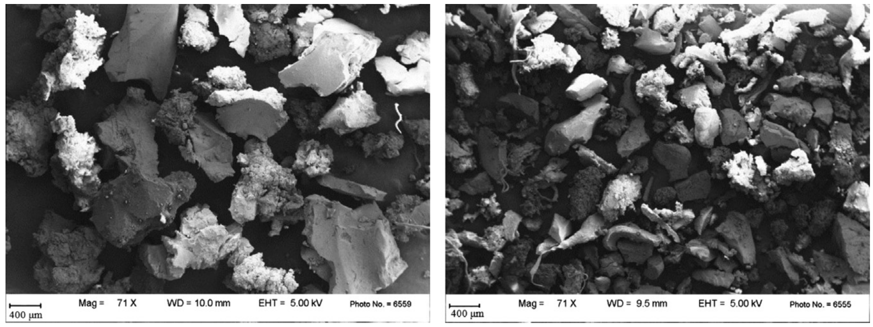

Fig. 1. Pictures by Scanning Electron Microscope (SEM): Cryogenic Crumb Rubber (left) and Traditional Crumb Rubber (right).

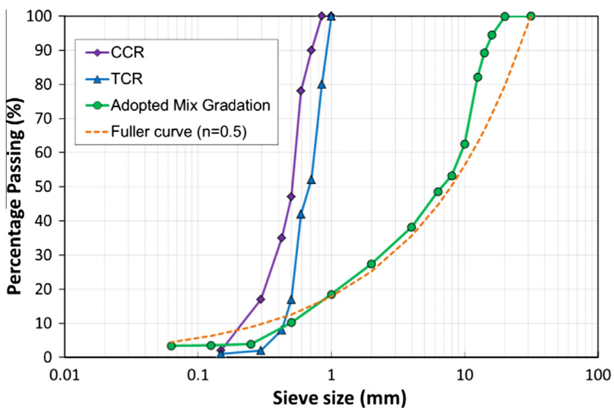

Fig. 2. Adopted (100% RAP) Mix, TCR and CCR gradations.

Table 2
Designation and composition of the cold mixes.

Material	Density (g/cm^3)	Mixture 3.0C_5.0E (%)
RAP 10-30	2.62	49.0
RAP 5-10	2.62	13.0
RAP 0-5	2.53	35.0-*a*
TCR	1.12	*a*[a]
CCR	1.08	*a*[a]
Cement (C)	3.00	3.0
Bitumen emulsion (EM)	1.03 (at 25 °C)	5.0
Additional water	0.99 (at 25 °C)	0.7

[a] Amount of TCR and CCR variable: 0% or 3%

Table 3
Properties of the bitumen emulsion.

Characteristics	Unit	Result	Standard
Characteristics of the cationic emulsion			
Water content	%	39	EN 1428
pH value	°	4	EN 12,850
Settling tendency @ 7 days	%	6	EN 12,847
Characteristics of the extracted bitumen			
Penetration	dmm	55	EN 1426
Softening point	°C	62	EN 1427
Fraass breaking point	°C	−16	EN 12,593

3.3. Experimental program

The experimental program was divided into three phases.

A first phase was planned in order to define the volumetric characteristics and workability of the mixture, together with their Indirect Tensile Strength according to EN 12697-23. The objective was to define limits and behavioral trends of the mixtures in relation to the presence of Crumb Rubbers different in type and gradation.

The second phase was focused on the study of the stiffness modulus according to EN 12697-26. In particular, the variation of modulus with curing time and the thermal sensitivity of the mixture at different temperatures were evaluated. In order to define the potential contribution of Crumb Rubber in terms of performance, in the third step the fatigue strength was studied by means of the Indirect Tensile Fatigue test according to BSI DD ABF 1995.

All tests for mechanical characterization either static and dynamic were carried out on samples at complete curing.

4. Curing and testing procedures

All the 12 tested specimens were compacted with a gyratory compactor according to ASTM D6925. Specimens 150 mm in diameter were prepared setting 600 kPa of axial pressure with an external gyration angle of 1.25° and 180 revolutions. The mass of each compacted specimen was 4500 g.

Laboratory curing of specimens has been carried out in a single way. After the production of specimens, these were sealed in plastic and placed in oven for 3 days at 40 °C. In this case specimens were cured in plastic bags with the intention of simulating equilibrium moisture content on the completion of curing. After three days, curing in the oven was completed for 3 days on unwrapped specimens. In order to attain a full curing condition, the specimens were then kept at 20 °C until they maintained a constant mass (12 days after gyratory compaction). The weight control was done every 7 days.

For the ITS test the EN 12697-23 was adopted. According to this standard, all the specimens were kept at a temperature of 25 °C in a climate chamber for 6 h before testing. A constant speed of 50 mm/min was applied until failure. The referred standard for the ITSM test was the EN 12697-26. The standard defines an impulse load, with rise-time of 124 ms, to generate the target horizontal displacement of 7 ± 2 µm. The ITFT, as defined by the BSI DD ABF 1995, was used as a practical method to estimate the resistance to crack initiation [15]. The test was performed at 20 °C in stress controlled mode, with a rise-time of 124 ms and stopped when the specimen was completely cracked. The system measures the cumulative deformation of the specimen during the test and the number of loading cycles to failure.

5. Prequalification results analysis

5.1. Compaction and workability evaluation

During this phase two basic aspects were evaluated to optimize the laying of the mixtures: the compactability and workability; it was assessed how the presence of rubber within the mixture works to affect these two properties. In particular, the effect that the Crumb Rubber has on the mix workability during compaction and at its end in terms of volumetric changes within the specimens was investigated. Percentages of rubber equal to 0% and 3% by volume of aggregates were considered. A total of 3 different mixtures were prepared with 3% of cement and 5% of bituminous emulsion. One mixture was without rubber, while TCR or CCR were inserted into the other two mixtures. Three samples were manufactured for each mixture. Figs. 3 and 4 and Table 4 summarize all the gyratory compaction curves and the respective compaction models.

From the analysis of the gyratory compaction curves for each mixture and from the comparison of their models, it emerged that Crumb Rubber incentivized the self-compaction of the mixtures. As for the degree of densification attained at the end of the compaction, the mixtures with rubber have obtained a greater degree of maximum density. The mixture with CCR has achieved a degree of 92% of maximum density, while the one with TCR has reached 91%; the mixture without rubber stopped at 90%. The 1% gained by the CRC on the TCR may be attributed to the different particle size and type. It is possible to hypothesize that the particle size of Crumb Rubber influences to some extent the characteristics of workability and final density of the mixtures.

The degree of maximum density achieved by samples containing rubber, cannot prescind from the nature of the material introduced in the mixtures. The elastic behavior of the rubber in fact favors the compaction during the densification process [12]. All specimens containing Crumb Rubber exhibited an increase in volume with respect to the degree of density achieved at the end of the gyratory compaction (Fig. 5). For this reason and for a proper preliminary characterization of materials it is indispensable to analyze the so-called “springback” exhibited from the specimens with rubber at the end of compaction.

The mixtures with rubber denote a reduction of final density achieved at the end of gyratory compaction appreciably higher if compared to mixes without Crumb Rubber, where only the curing effect is responsible of the volumetric variation. This reduction is very evident especially in specimens with TCR (−4.7%).

5.2. Indirect Tensile Strength results analysis

Once cured, all the specimens prepared with the same compaction energy were tested with the Indirect Tensile Strength test at 25 °C according to EN 12697-23. Results are represented in Fig. 6.

From the analysis of the histogram, it can be seen how the specimens without rubber show greater ITS, while the mixture containing TCR exhibit the lowest values. In particular specimens with cryogenic rubber showed an average reduction in strength of 17.4% compared to mixtures without rubber. As for mixtures with TCR, their resistance values are reduced by 31.6%. These results clearly reflect the influence of the kind of Crumb Rubber used, in particular their different particle size, and are also in accordance with the considerations made on gyratory compactions. In fact, as already mentioned, the TCR has a coarser gradation than CCR, for instance the CCR percentage passing at the 0.6 mm sieve (80%) is twice that of the TCR (42%). This may negatively affect the meshing, and the consequent cohesion between the mixture constituents, resulting in a lower degree of compactability and in a substantial reduction in strength for the TCR mixes.

6. Indirect tensile stiffness modulus results analysis

A servo-pneumatic testing machine was used to characterize the mixtures in terms of stiffness modulus according to EN 12697-26. Tests were carried out in the indirect tensile configuration. For the ITSM, the impulsive load, with rise-time of 124 ms, was adjusted to achieve a target horizontal deformation of 7 ± 2 μm. The measurements were repeated along two diameters and an average ITSM was calculated. To evaluate the thermal sensitivity of the mixtures tests were performed at 10, 20 and 30 °C.

For each mixture 4 specimens were tested; the average stiffness modulus measured at each temperature is reported in Fig. 7. The temperature dependency was described using the following analytical model:

$$\log S = -\alpha \cdot T + \beta \tag{2}$$

where S is the stiffness modulus at temperature T, and α and β are experimental parameters depending on the material. Temperature sensitivity is represented by the parameter α: a higher value means a more temperature sensitive material.

The ITSM modulus values for the mixture without rubber are greater than CCR and TCR mixtures at each temperature. The mixture with CCR undergoes an average decrease in stiffness of 20.3% if compared to the mixture without rubber at each testing temperature, while for the TCR mixture this reduction reaches 25.4%.

The reduction in stiffness modulus is more likely due both to how the rubber particles interact with the binding matrix while final cohesion is achieved [12], and to the stiffness of the rubbers themselves.

Finally the Crumb Rubber influences the stiffness modulus at all the studied temperatures without affecting significantly the thermal sensitivity of the mixtures. This trend is confirmed by the parameter α which varies between 0.015 and 0.020.

7. Resistance to repeated loading

The Indirect Tensile Fatigue test is a simple and fast method for testing the resistance to crack initiation of asphalt mixtures [17]. According to traditional ITF Testing, the fatigue life is defined as the total number of load applications before fracture of the specimen occurs. All tests were performed in the stress-control mode, hence the magnitude of the applied stress pulse is maintained constant until failure. According to BSI DD ABF 1995 the failure points

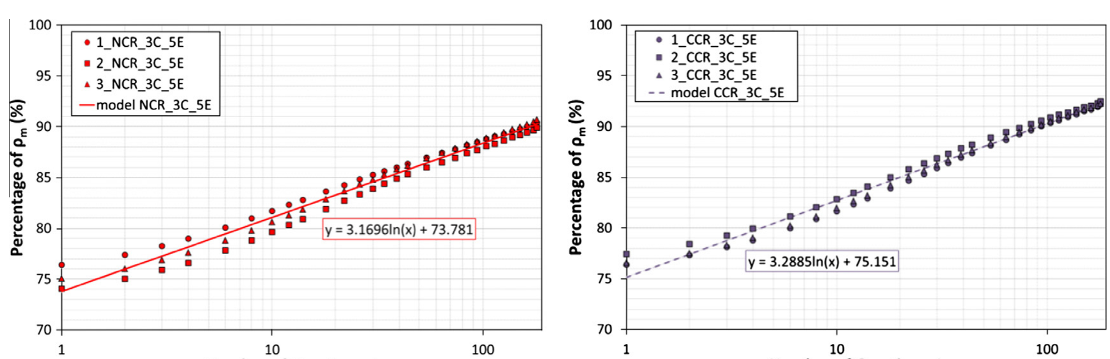

Fig. 3. NCR gyratory compaction curves (left); CCR gyratory compaction curves (right).

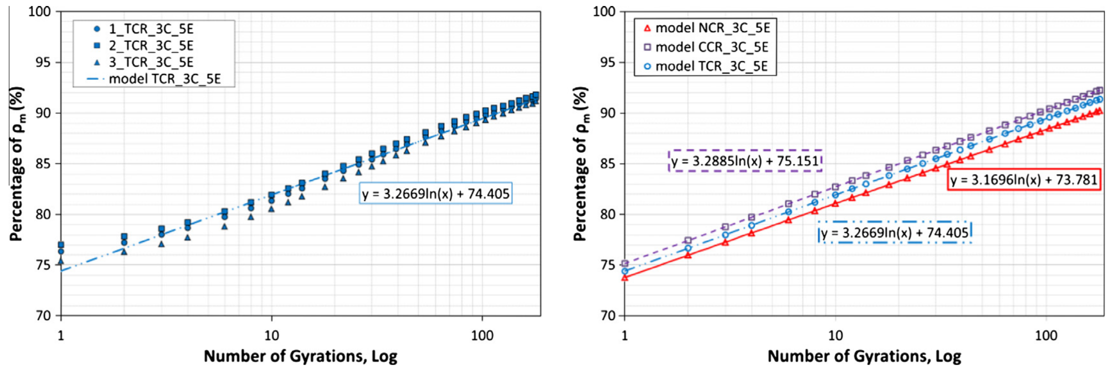

Fig. 4. TCR gyratory compaction curves (left); comparison between compaction curve models of each mix (right).

Table 4
Gyratory compaction curves models.

Material	*a*	*b*
1_NCR_3.0C_5.0E	2.8855	75.338
2_NCR_3.0C_5.0E	3.2903	73.527
3_NCR_3.0C_5.0E	3.3329	72.477
Model NCR 3C_5E	3.1696	73.781
1_CCR_3.0C_5.0E	3.3560	74.570
2_CCR_3.0C_5.0E	3.1714	76.019
3_CCR_3.0C_5.0E	3.3381	74.863
Model CCR 3C_5E	3.2885	75.151
1_TCR_3.0C_5.0E	3.2379	74.554
2_TCR_3.0C_5.0E	3.1822	75.231
3_TCR_3.0C_5.0E	3.3807	73.429
Model TCR 3C_5E	3.2669	74.405

Model equation: $y = a \cdot \ln(x) + b$

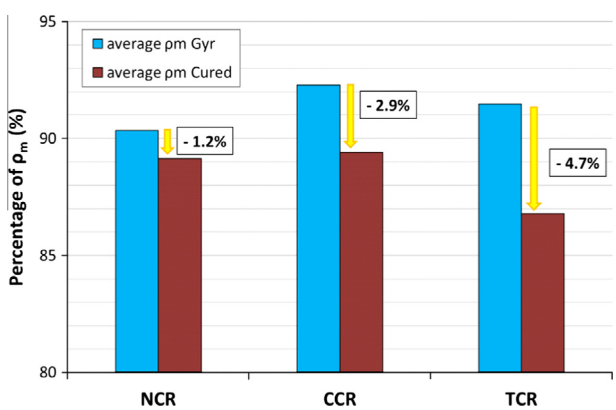

Fig. 5. Variation in volume after compaction.

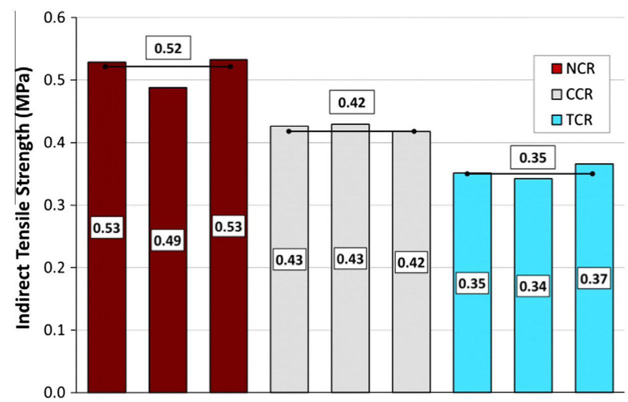

Fig. 6. Indirect Tensile Strength al 25 °C: maximum stress at failure for each specimen.

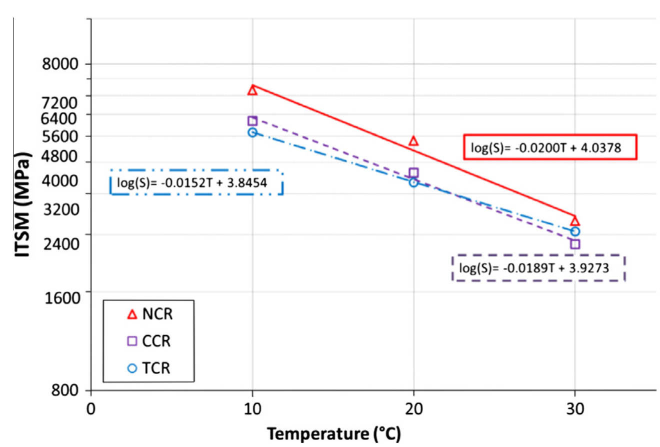

Fig. 7. Indirect tensile stiffness modulus vs. temperature at 10, 20 and 30 °C.

were expressed as a function of initial horizontal tensile strain at the centre of the specimen (ε_0) calculated as follows:

$$\varepsilon_0 = \frac{\sigma_0 \times (1 + 3\upsilon)}{S_m} \times 100 \tag{3}$$

where σ_0 is the tensile stress at the specimen centre (kPa); S_m is the stiffness modulus (MPa) at the testing temperature; υ is the Poisson's ratio, assumed to be 0.35.

The definition of fatigue failure in laboratory test on bituminous mixtures is a controversial topic [16]. In this study the evaluation of fatigue life by means of ITF tests, was assessed according to the energetic approach that defines failure using the $N/\Delta s$ ratio between the number of the *N*th load cycle and the corresponding axial displacement measured on the sample (Δs) [18]. Fatigue results (Fig. 8) are expressed as a relationship between the initial strains ε_0 and the number of load applications that correspond to the maximum value of the $N/\Delta s$ ratio.

Comparing the mixes, the presence of Crumb Rubber influences the fatigue resistance; in particular the use of TCR and CCR leads to an extension of the fatigue resistance at 110 microstrains of more than two times.

Recent research studies showed that the fatigue tests consume much time at low strains so, generally, researchers have used a number of extrapolation techniques to predict the fatigue life. This is permissible if the tensile strain is far from the so called fatigue endurance limit. The endurance limit is defined as the tensile strain below which no fracture or fatigue damage occurs: Monismith

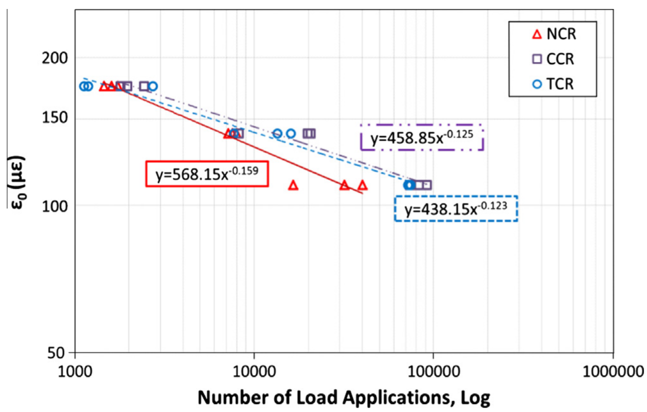

Fig. 8. Indirect Tensile Fatigue test results at 20 °C.

Table 5
Comparison between fatigue's models.

Mixture	Equation	ε_6 (με, after 1,000,000 cycles)
NCR	$y = 568.15 \cdot x^{-0.159}$	63.2
CCR	$y = 458.85 \cdot x^{-0.125}$	81.6
TCR	$y = 438.15 \cdot x^{-0.123}$	80.1

et al. [19] first proposed an endurance limit of 70 microstrain for asphalt pavements. Nowadays many authors suggest a range between 70 and 90 με. It is also generally accepted that FEL condition can be attained when cycles exceed 5,000,000, after which a significant increase of fatigue life is seen. Given that tests were performed at more than 110 με a FEL condition can be excluded and such a linear extrapolation to 1,000,000 could be acceptable. Based on the obtained fatigue model (Table 5), the extrapolated ε_6 after one million of load application is approximately of 63.2 με for the mixture without rubber. The mixture with TCR shows a percentage increase of 26.7%, while the use of CCR leads to an increase of 29.1%.

Based on the experimental data shown in Fig. 8 and on the adopted test configuration, the dry process used in this study to incorporate CCR and TCR into the Cold Recycled Mixtures, leads to an increase in the number of loading cycles to failure.

Comparing the obtained results with the study by Xiao et al. [20] on the influences of Crumb Rubber size and type in HMA containing RAP using wet process, also the addition of rubber in a dry process appears to be advantageous for fatigue resistance of Cold Recycled Mixes. Furthermore, in accordance with Xiao et al., it can be seen that the influence of the rubber type on fatigue resistance seems to be irrespective of the rubber size when rubber particles are larger than 0.84 mm.

8. Conclusions

Based on the experimental data shown in this study, the following conclusions have been reached:

– The replacement of fine RAP with Crumb Rubber improved the self-compaction of the mixtures while influenced their volumetric characteristics after compaction.
– The final density of gyratory compacted samples shows that rubber help into attaining higher degrees of compaction. In particular an increase of 1.1% and 2.1% is achieved respectively by adding TCR and CCR to the RAP mixtures. The difference between the two mixtures with rubber may be attributed mainly to the difference in gradation.
– As with HMA, the studied Cold Mixes containing 100% RAP are shown to have a volumetric variation after compaction. The presence of rubbers enhances this variation with a reduction in% ρ_m up to 4.7% for the TCR mixture and 2.9% for the CCR.
– According to ITS and ITSM results the Crumb Rubber presence in mixtures affects and reduces their mechanical characteristics of resistance to failure: the use of CCR seems to be less detrimental than TCR.
– According to fatigue results the adoption of TCR or CCR in the 100% RAP mixtures generates similar mechanical responses. The number of cycles to failure is extended at all the applied stresses, in particular at the lower strain levels.

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