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Experimental study on the grading distribution of cold recycled asphalt mixtures produced with bitumen emulsion and high strength cement

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Abstract. Cold recycled asphalt mixtures (CRAM) can lead to real economic advantages only if their performance is comparable to that of traditional hot mix asphalt. This experimental study aims to investigate the effect of the grading distribution on the volumetric and mechanical properties of CRAM produced with high reclaimed asphalt dosage (>70%), bitumen emulsion and high strength cement. Four grading distributions were analysed: two continuously graded curve (derived from the Fuller-Thompson maximum density curve) with nominal maximum aggregate size (NMAS) 16 mm and 10 mm. The third was obtained increasing the filler dosage, and the fourth grading distribution was a gap-graded type, with NMAS 16 mm. Workability and compactability of the fresh CRAM were evaluated using the gyratory compactor. CRAM long-term complex modulus was measured using cyclic compression tests. Results showed that the gap-graded and the high-filler grading distributions allowed obtaining the lower voids in the mixture. Having fixed the number of voids in the mixture, the gap-graded CRAM showed a higher stiffness modulus and lower phase angle if compared to CRAM produced with the continuously graded curve.

Keywords: Cold Recycling, Reclaimed Asphalt, Grading Distribution, Bitumen Emulsion, Complex Modulus.

1 Introduction

Cold recycled asphalt mixtures (CRAM) are an effective technology in terms of sustainability and cost-effectiveness, but they typically have lower performances compared to traditional hot mix asphalt [1]. Lower mechanical properties can be related to a higher void content in CRAM. Moreover, they need a curing time before reaching their final properties [2, 3]. Study of CRAM workability and compactability is essential because of the effect of the voids on CRAM final properties [4, 5]. The proper choice of the intergranular water content is crucial to have a good balance among mixability (homogeneous mixture) and compactability (reduction of voids) of CRAM. An excess of water is discouraged as well, to avoid leakage of liquids and

filler-sized particles during the compaction (with the consequent alteration of the CRAM composition) [2]. Generally, continuously graded curves are adopted in cold mixtures production. To promote the use of CRAM in upper pavement layers, their mechanical properties should be improved. Recent studies attempted evaluating the effect of different grading curves on the mechanical properties of CRAM [6, 6]. Other researches proposed the use of not conventional types of cement for improving the response of cold mixtures. Supplementary blended cementitious fillers increase the mechanical performance of cold mixtures [8], whereas rapid hardening cement has been found to improve the early strength of cold mixtures [9].

The goal of the present laboratory investigation is to evaluate the effect of grading distribution on CRAM suitable for upper pavement layers. Voids of CRAM both at fresh and cured state were evaluated through a volumetric analysis. Mechanical properties evaluation was carried out by measuring complex modulus.

2 Experimental Plan

The CRAM were produced in the laboratory using reclaimed asphalt (RA) aggregate, natural limestone sand, limestone filler, bitumen emulsion, cement and additional water. Three gradations of the same RA aggregate source were used. The original RA aggregate, coming from the milling of the bituminous layer of end-of-life pavements, was RA0/16. Further RA fractions (i.e. RA0/10 and RA2/16) were derived by sieving operations. Two commercial cationic slow-setting bitumen emulsions with 60% of residual bitumen were used: a traditional and a modified emulsion (C60B10 and C60BP10, according to EN 13808). Two high strength cement were employed as co-binders. The first was a sulfo-aluminous cement (CSA) with a compressive strength of 80 MPa after 28 days. The second was a Portland slag cement, type II/B-S (PSC), strength class 52.5N (EN 197-1).

Four grading distributions, labelled FT-16, FT-10, Fine-16, GG-16, were considered (Table 1 and Fig. 1). The reference gradation (FT-16) was the Fuller-Thompson maximum density curve with exponent 0.45 and nominal maximum aggregate size (NMAS) 16 mm. The second (FT-10) was obtained reducing the NMAS of the reference distribution to 10 mm, and the third (Fine-16) was obtained adding 5% of filler to the reference distribution. The fourth grading distribution (GG-16) was a gap-graded type, with NMAS 16 mm. Emulsion dosage (with respect aggregate weight) was 5.0%, whereas cement dosage was 2.5%. Mixing was carried out in the laboratory following a procedure developed in previous studies [2]. Two specimens for each mixture were obtained with the gyratory compactor using 150 mm moulds.

Table 1. Composition of aggregate blends

Grading	Type	NMAS	Composition
FT-16	Max density (exp. 0.45)	16 mm	80% RA0/16, 17% sand, 3% filler
FT-10	Max density (exp. 0.45)	10 mm	75% RA0/10, 17% sand, 8% filler
Fine-16	Continuous, high filler	16 mm	80% RA0/16, 20% filler
GG-16	Gap graded	16 mm	70% RA2/16, 20% sand, 10% filler

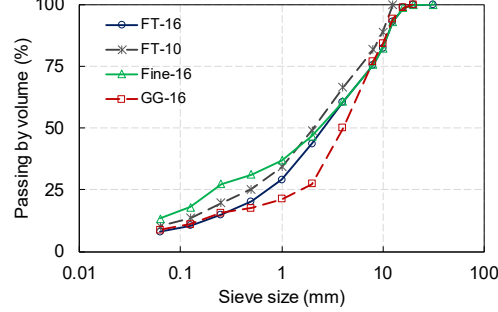


Fig. 1. Grading distributions

The experimental plan was developed in two phases (Fig. 2). During phase A, specimens were produced fixing the energy of compaction (number of gyrations equal to 100) to study the influence of water content on the compactability of the mixtures. Each CRAM was mixed considering 3 different intergranular water content. Compactability was assessed using a volumetric analysis [4] in terms of voids in the mixture at the fresh state $V_{m,fresh}$ (i.e. the percentage of the total mixture volume occupied by air and intergranular water):

$$V_{m,fresh} = (V_{v,A,fresh} + V_{W,F}) / V \quad (1)$$

where V is the volume of the specimen, $V_{v,A,fresh}$ and $V_{W,F}$ are the volume of air and intergranular water, respectively.

Specimens were cured at 25 °C and RH=70% for at least 90 days. During curing part of the water evaporates and part of the water is bounded in the cement hydration process. Nevertheless, a small amount of water can remain trapped in the specimen, in the form of not-interconnected voids. Besides, cement changes its volume because of hydration. The hydrated cement (consisting of reacted cement and the non-evaporable water) has a higher volume than the anhydrous one [10]. Thus, if the amount of trapped water is negligible, the voids of the cured mixture are:

$$V_{m,cured} = V_{v,A,cured} / V \quad (2)$$

where $V_{v,A,cured}$ is the volume of air obtained by summing $V_{v,A,fresh}$ and the volume of evaporated water. CRAM will have different volumetric properties with respect to the fresh state, specifically $V_{m,cured} < V_{m,fresh}$. The volume of voids of cured specimens $V_{m,cured}$ was calculated according to EN 12697-8. The volume of non-evaporable water (bounded by the cement) was considered on par of the other solid components of CRAM.

In Phase B the fixed height compaction mode was selected to produce specimens with $V_{m,fresh}$ of 9.5%. CRAM were produced with both types of cement, modified emulsion and gradings FT-16 and GG-16. The adopted intergranular water content was 3.3% and 2.9 for the two CRAM gradings, respectively. Curing was performed for 6 months at 25 °C and RH=70%. Specimens were cored to get cylindrical specimens with 75 mm diameter. The complex modulus was measured using the testing system AMPT PRO. The axial strain was measured in the middle of the specimen

with three LVDT, placed 120° apart, with a measuring base of 70 mm. To obtain an axial strain with a target amplitude of 30 microstrains, a haversine compression loading was applied. Test temperatures and frequencies ranged from 5 to 55 °C and 0.1 to 10 Hz, respectively. 20 loading cycles were applied at each frequency.



Fig. 2. Experimental plan

3 Results and Analysis

Fig.3 displays $V_{m, \text{fresh}}$ as a function of the intergranular water content on the CRAM produced with modified emulsion. CRAM with traditional emulsion exhibited similar behaviour. The adoption of grading distributions different from the reference one results in different $V_{m, \text{fresh}}$. Specifically, comparing the voids of the CRAM produced with the same w_F (i.e. 3.0% for CSA mixtures and 2.5% mixtures for PSC) and different grading distribution, better compactability is obtained using Fine-16 (average reduction of $V_{m, \text{fresh}}$ on the four CRAM equal to -1.4%) and GG-16 (-0.9% on average). The influence of the decrease of the NMAS from 16 mm to 10 mm is smaller (-0.4% on average). The effect of the type of cement and emulsion is less relevant.

Fig.4 displays the reduction of the voids in the mixture due to the passage from fresh to cured state. Some differences may be highlighted among mixtures with different grading distributions. Nevertheless, the effect of the grading distribution is not clear, which may be due to the variability of the test. As regards the influence of the type of binders (i.e. cement and emulsion), the use of CSA and PSC allow reducing voids on average of 1.4% and 1.7%, respectively. Then it may appear that hydrated PSC has a higher volume compared to CSA. However, the difference between the reduction measured for CRAM produced with the two cement is not considered significant and may be due to the variability of the experimental data. Further studies are needed to deepen this effect. The effect of the type of emulsion is even more negligible (average reduction of 1.5% and 1.6% with traditional and modified emulsion, respectively). It can be stated that the improvement of CRAM volumetric properties must be obtained at the fresh-state through a proper mix-design and compaction. After curing, CRAM will always have lower voids compared to the fresh state. The reduction of voids could be slightly related to the type of binders. Overall, the effect of the

type of binder is less significant compared to those obtained through the mix-design optimisation.

Fig.5 shows the results of complex modulus measurement on mixtures with CSA and grading curves FT-16 and GG-16. CRAM with PSC exhibited similar behaviour. Experimental data, displayed in the Cole-Cole diagram (Fig.5a) and Black diagram (Fig.5b), form a continuous curve. Then, the Time-Temperature Superposition Principle is considered valid. Despite the same composition and volumetric properties, CRAM with GG-16 had higher stiffness modulus both at low and high temperatures (high and low frequencies). The phase angle is lower in CRAM with GG-16 at all frequencies.

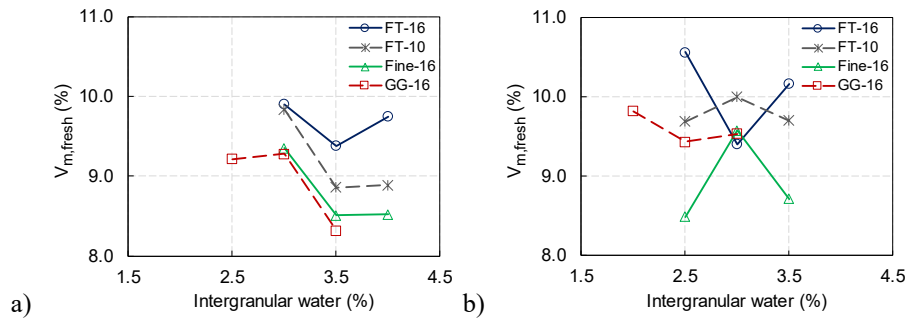


Fig. 3. Voids in the mixture as a function of the intergranular water of CRAM with modified emulsion and cement: a) CSA, b) PSC

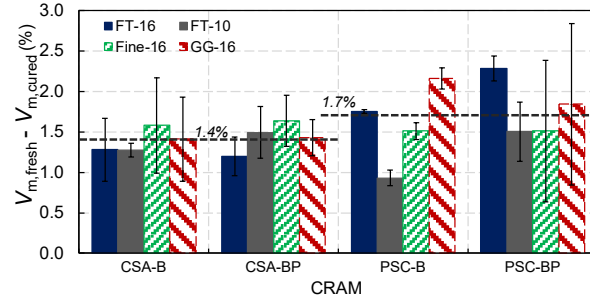


Fig. 4. Reduction of voids in the mixture after curing (error bars are the standard error of mean)

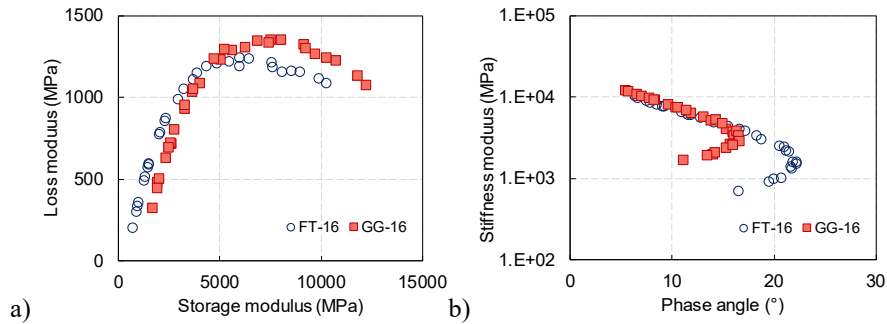


Fig. 5. Complex modulus measurement, CSA mixtures: a) Cole-Cole plan, b) Black diagram

4 Conclusions

This paper evaluates the effect of different grading distribution on physical and mechanical properties of CRAM produced with bitumen emulsion and high strength cement. The Fuller-Thompson distribution does not confer better compactability to CRAM. The increase of fines or a gap-graded distribution allow the reduction of voids. At the end of curing, voids of CRAM are further reduced because of the increase in the volume of cement. Compared to mixtures produced with Fuller-Thompson grading, CRAM produced with a gap-graded distribution showed, in the long-term, higher stiffness modulus and smaller phase angles at all temperatures.

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