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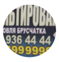

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Evaluation of rutting resistance of rubberized gap-graded asphalt mixtures

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ABSTRACT: The study described in this paper analyzed the rutting resistance of asphalt mixtures containing crumb rubber from end-of-life tires. Different rubberized gap-graded mixtures, both prepared in the laboratory and produced in a hot mix plant, were considered in the investigation. Moreover, a standard dense-graded mixture was used as a reference material. The experimental program included laboratory tests carried out on binders (Multiple Stress Creep Recovery tests) and on compacted mixtures (flow number and wheel tracking tests). In spite of the enhanced stiffness and elasticity of the binder phase, rubberized mixtures showed a lower rutting resistance than the traditional dense-graded mixture both in flow number and wheel-tracking tests. Such an occurrence was explained by referring to the limits of adopted testing protocols and improvements were suggested for future performance-based investigations.

1 INTRODUCTION

Use of crumb rubber derived from end-of-life tires in asphalt mixtures for road paving applications has been known since the 60’s (McDonald, 1981). Since then, it has become popular worldwide due to the fact that it contributes to solve a serious waste management problem and to improve asphalt pavement performance (Santagata & Zanetti, 2012).

Crumb rubber can be incorporated into bitumen by means of the “wet” process (which leads to the production of “asphalt rubber”), or added in the hot mix plant in partial substitution of one or more aggregate fractions by means of the “dry” process (Heitzman, 1992; Epps et al., 1994; Caltrans, 2005). However, it is generally recognized that mixtures containing asphalt rubber generally exhibit a laboratory and field performance which is superior to that of “dry” mixtures (Amirkhanian, 2001; Caltrans, 2005; Way et al., 2012).

In the design and production of asphalt rubber mixtures, adoption of a gap-graded aggregate gradation is commonly recommended since it is assumed to provide sufficient void space to accommodate enough binder and to promote stone-to-stone contact (Caltrans, 2006; Liu et al., 2012). As a consequence of their internal structure and of the enhanced stiffness and elasticity of the binder phase, these mixtures are expected to yield limited permanent strains under repeated loading and may therefore be used for the formation of rut-resistant wearing courses (Lee et al., 2008; Hsu et al., 2011; Pasquini et al., 2011; Kaloush et al., 2012; Moreno et al., 2013).

In contrast with these expectations, in previous laboratory investigations performed by means of wheel tracking tests, the Authors found that in some cases rubberized gap-graded mixtures exhibited poor rutting resistance properties. Thus, further studies were deemed necessary in order to determine whether such a reduced performance can derive from defects in mixture formulation or may be simply due to the ineffectiveness of adopted testing protocols.

Results reported in this paper were obtained in such a context, with the purpose of highlighting the effects of several composition-related factors on the permanent deformation response of gap-graded rubberized mixtures containing asphalt rubber.

Considered mixtures (prepared in the laboratory in controlled conditions and sampled from a hot mix plant) differed in terms of aggregate mineralogy and gradation, and binder dosage. Moreover, a standard dense-graded mixture containing conventional neat bitumen was also considered as a reference.

The experimental program included rheological tests carried out on binders and volumetric and mechanical tests carried out on compacted asphalt mixtures. On the basis of obtained results, rutting properties of the materials were critically analyzed and discussed. Furthermore, limits of the adopted testing protocols were highlighted and improvements were suggested for future performance-based investigations.

2 EXPERIMENTAL INVESTIGATION

2.1 *Materials*

Asphalt mixtures employed in the experimental investigation included two rubberized gap-graded mixtures and one reference dense-graded mixture.

Rubberized mixtures were produced with the same asphalt rubber (AR), a commercially available product containing a nominal amount of crumb rubber equal to 18% by weight of total binder, but different aggregate types, gradation and binder dosage.

The first one (GG-L) was manufactured in the laboratory by employing siliceous aggregates provided by a local contractor. Composition was defined according to technical specifications commonly adopted in Italy for rubberized gap-graded mixtures (ARI, 2013) with an optimum binder dosage of 8% by weight of dry aggregates. Reconstruction of target gradation was performed by subjecting aggregates to washed sieve separation and by thereafter combining single size fractions (all finer than 16 mm and retained on the 12.5, 8, 4, 2, 0.5, 0.18 and 0.063 mm sieves) in the needed quantities.

The second rubberized mixture (GG-P) was sampled from a hot mix plant which employed basaltic aggregates and the same asphalt rubber used in the laboratory-made blend. Its composition was determined by means of the ignition test (EN 12697-39, 2012), from which a binder content of 7.8% was obtained, and with sieve analysis of recovered aggregates (EN 933-2, 1995).

The dense-graded mixture (DG) was prepared in the laboratory with siliceous aggregates and neat 50/70 penetration grade bitumen (NB), which was employed with a dosage of 5.5%. Target aggregate gradation was defined according to Italian technical specifications for standard wearing courses (CIRS, 2001) and its reconstruction was made by following the same procedure adopted for mixture GG-L.

Composition and aggregate gradations of asphalt mixtures considered in the investigation are summarized in Table 1 and Figure 1.

Table 1. Composition of asphalt mixtures.

Mix code	Aggregate type	Aggregate gradation	Binder type	Binder dosage (%)
GG-L	Siliceous	GG	AR	8.0
GG-P	Basaltic	GG	AR	7.8
DG	Siliceous	DG	NB	5.5

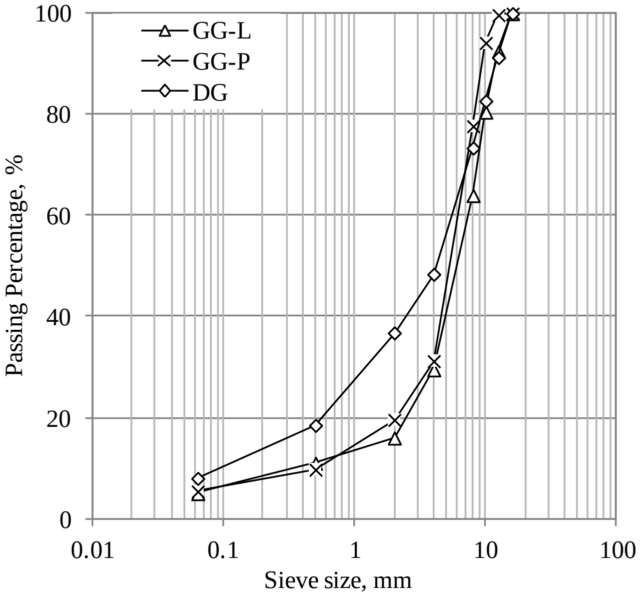

Figure 1. Aggregate size distribution of asphalt mixtures.

2.2 *Testing*

The experimental program included laboratory tests carried out both on binders and mixtures.

Binders were evaluated by means of Multiple Stress Creep Recovery (MSCR) tests, performed with a dynamic shear rheometer in accordance to AASHTO TP 70-10 (2010). The MSCR test protocol consisted in applying 10 cycles of 1 s creep loading and 9 s recovery at two different stress levels (equal to 0.1 and 3.2 kPa). The 25 mm parallel plates geometry was employed for measurements with a 1.0 mm gap between the plates. Test temperature was set at 58°C, which corresponds to the high performance grade temperature commonly used in North-Central Italy.

Binders were tested in short-term aged conditions, simulated by means of the Rolling Thin Film Oven (RTFO) in accordance to AASHTO T 240 (2009).

Asphalt mixtures were subjected to preliminary characterization in order to assess their compaction properties by making use of the Gyratory Shear Compactor (GSC) (EN 12697-31, 2007). Cylindrical specimens (150 mm diameter) were prepared in the laboratory at a fixed number of gyrations, equal to 100, and at a compaction temperature of 175 and 150°C for rubberized mixtures and dense-graded mixture (DG), respectively. Densification curves of the materials were obtained by analyzing variation of sample height as a function of the number of gyrations recorded during the compaction process.

Flow number and wheel-tracking tests were used to determine resistance to permanent deformation of the mixtures.

Flow number tests were performed by means of the Asphalt Mixture Performance Tester (AMPT) in accordance to AASHTO TP 79 (2009). The adopted testing protocol consisted in applying repeated compressive stresses (equal to 600 kPa) to slender GSC specimens (100 m diameter, 150 mm height) at a given temperature (equal to 58°C, chosen in accordance with the previously described MSCR tests). Cumulative permanent deformation developed in specimens was recorded as a function of loading cycles. GSC test specimens were obtained from larger ones (150 mm diameter, 170 mm) by following the instructions provided by AASHTO PP 60 (2011). In particular, over-height specimens were prepared by compacting the mass of mixture needed to reach target air voids content, which in this study was set equal to 6.8±0.5%. Cores with 100 mm diameter were then extracted from the center of the gyratory samples using a diamond coring stand and thereafter subjected to trimming by means of a masonry saw in order to obtain smooth and parallel end surfaces.

Volumetric properties of compacted mixtures (voids content, voids in mineral aggregates, voids filled with asphalt, according to EN 12697-8, 2003) were calculated based on the theoretical maximum density measured on loose blends with the pycnometer method according to EN 12697-5 (2009).

Wheel tracking tests were performed by means of the Wheel Tracking Device (WTD) in accordance to EN 12697-22 (2007). Rectangular slabs were subjected to 30,000 passes of a loaded rubber wheel (700 N vertical load) at a single test temperature (set at 60°C). Rut depth produced by wheel loading was measured at regular intervals in 15 points distributed on the slab surface. Slabs (50 cm length, 18 cm width, 4 cm thickness) were prepared by means of a large-size roller compactor, operated according to EN 12697-33 (2007), at a geometric air voids content defined in order to reach an actual air voids content equal to that employed in GSC compaction (6.8±0.5%). In order to prevent the occurrence of internal thermal gradients which may bias experimental results, both AMPT specimens and WTD slabs were conditioned in an environmental chamber for 6 hours before testing.

Two replicates were performed for each material and test type, and average data were used in the analysis.

3 RESULTS AND DISCUSSION

3.1 *MSCR tests*

Experimental data retrieved from MSCR tests were analyzed in order to determine non-recoverable creep compliances ($J_{nr0.1}$ and $J_{nr3.2}$), given by the average non-recovered strains occurring in the 10 creep and recovery cycles divided by the corresponding applied stress. Obtained results are listed in Table 2.

As expected, asphalt rubber AR showed significantly lower non-recoverable creep compliance values than neat binder NB, revealing a higher anti-rutting potential due to the combined effects of higher stiffness and enhanced degree of elasticity.

For both binders, $J_{nr3.2}$ exceeded $J_{nr0.1}$, indicating a transition from linear to non-linear domain when passing from 0.1 to 3.2 kPa applied shear stress. However, the relative increase in non-recoverable creep compliance was higher in the case of binder AR, which proved to be characterized by a more pronounced non-linear behavior.

Table 2. Non-recoverable creep compliance values obtained from MSCR tests.

	AR	NB
$J_{nr0.1}$ (kPa^{-1})	0.748	0.013
$J_{nr3.2}$ (kPa^{-1})	0.814	0.008

3.2 *GSC compaction*

From specimen height progressively recorded during GSC compaction, mixture densification curves were obtained by back-calculating percent compaction (C) values and by fitting them to the following relationship:

$$C = C_1 + k \cdot \log(N_g) \tag{1}$$

where C is compaction (%), C_1 is the self-compaction parameter corresponding to compaction at 1 gyration (%), k is the workability parameter, N_g is the number of progressive gyrations during the densification process.

Compaction curves and corresponding regression parameters are shown in Figure 2 and Table 3, respectively.

It was observed that rubberized mixtures exhibited higher self-compaction (C_1) and workability (k) values than those of the reference mixture. In particular, the gap in behavior appeared to be more pronounced when comparing mixtures GG-L and DG, the curves of which could be clearly distinguished from each other. Such a result is not fully coherent with expectations, since the use of AR was believed to increase resistance to compaction due to its high viscosity. Thus, it was inferred that the higher C_1 and k values of rubberized mixtures resulted from the combined effects of non-uniform aggregate skeleton (gap-graded) and high binder dosage, which overcame the counter effects of high binder viscosity.

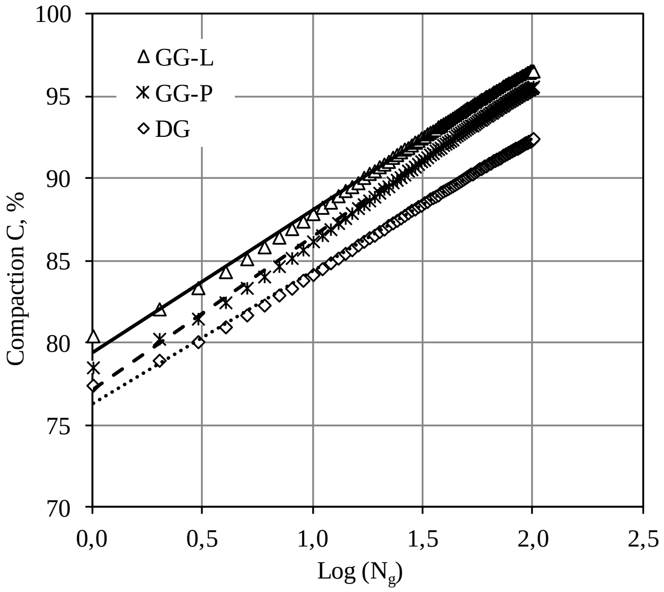

Figure 2. GSC compaction curves of asphalt mixtures.

Table 3. GSC compaction parameters of asphalt mixtures.

	GG-L	GG-P	DG
Self-compaction, C_1 (%)	79.4	77.2	76.3
Workability, k (-)	8.7	9.3	8.1

3.3 *Flow number tests*

Typical results obtained from a flow number test are shown in Figure 3, where accumulated axial strains are plotted as a function of number of loading cycles. Three portions of the curve, corresponding to different stages of flow, can be clearly distinguished: a primary stage, in which rate of strain decreases as the number of loading cycles increases; a secondary stage, characterized by a rate of strain that remains almost constant with load repetitions; and a third stage (tertiary flow), in which strain rate rises dramatically, leading to failure.

The number of loading cycles corresponding to the point at which tertiary flow starts to take place is known as the flow number (FN) and is adopted for the evaluation of the anti-rutting potential of asphalt mixtures (NCHRP 9-33, 2011).

Franken's model recently introduced in AMPT data analysis (Biligiri et al., 2007; Dongrè et al., 2009) was used to calculate FN values, due to its effectiveness and consistency in fitting experimental data (Bonaquist, 2008). Obtained results are summarized in Table 4 which also contains the values of volumetric parameters (air voids, v, voids in mineral aggregate, VMA, and voids filled with asphalt, VFA) determined on test specimens.

Air voids of all the mixtures were very similar to each other and within acceptance limits. However, mixtures GG-L and GG-P were characterized by higher VMA and VFA values than mixture DG as a consequence of the gap-graded aggregate distribution and higher binder content.

Referring to FN values, a first observation was drawn by comparing the rubberized mixtures to each other. The use of though basaltic stone aggregates in mixture GG-P was expected to produce enhanced rutting performance with respect to mixture GG-L, which is characterized by a very similar composition (aggregate gradation, binder type and binder content) but different aggregate mineralogy (siliceous). However, in contrast with expectations, the FN value of mixture GG-P was found to be slightly lower than that of GG-L, thus indicating a negligible influence on permanent deformation response produced by aggregate source.

Interpretation of results should also take into account the different conditions in which the two mixtures were manufactured (laboratory versus hot mix plant).

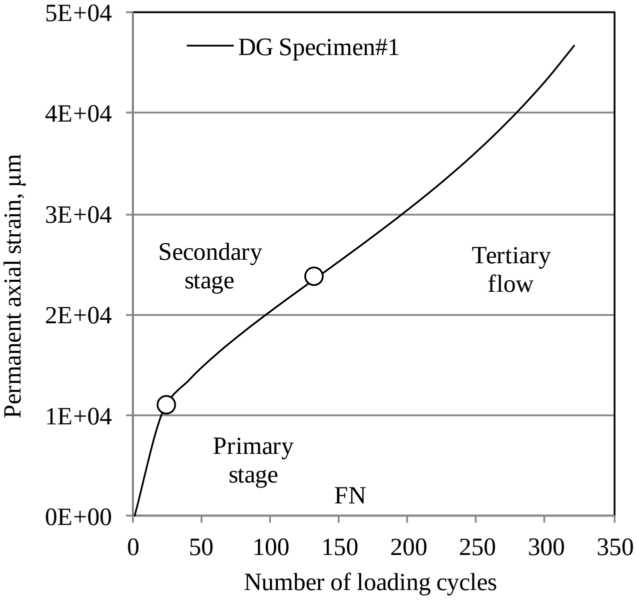

Figure 3. Typical results obtained from a flow number test (mixture DG)

Table 4. Volumetric properties and FN values of asphalt mixtures.

	GG-L	GG-P	DG
v (%)	6.9	6.6	6.8
VMA (%)	22.1	22.9	20.0
VFA (%)	69.0	71.2	66.0
FN (-)	76	69	134

In fact, asphalt binders modified with crumb rubber are extremely sensitive to mixing time and temperature, due to different phenomena (swelling, devulcanization, depolymerisation) that may occur after long interaction periods and/or at high interaction temperatures (Abdelrahman and Carpenter, 1999). As a consequence, control of these factors appears to be crucial in order to obtain a final high-quality material.

Following the experience of previous research works (Santagata et al., 2012), a mixing time of 6 minutes and a mixing temperature of 190°C were adopted in this investigation for the preparation of the laboratory-made mixture. On the contrary, due to constraints that are inherent in the production process, a full control of mixing parameters could not be achieved in the hot mix plant, possibly resulting in the observed decay of material properties when passing from laboratory to full-scale conditions.

A second important consideration is related to the fact that both rubberized gap-graded mixtures showed significantly lower rutting resistance than reference mixture DG. In particular, the FN value obtained for the standard mixture was about 1.8-1.9 times those of mixtures containing asphalt rubber. This result is clearly in contrast with those obtained from MSCR tests discussed above. Contradiction between the response of binders and mixtures may due in part to different mixture formulations (aggregate gradation and binder content) which result in different internal structures of bulk materials (Cooper et al., 1985; Monismith et al., 1985; Sousa et al., 1991). However, it may also be due to the ineffectiveness of testing protocols. For example, in their study conducted on gap-graded and open-graded asphalt rubber mixtures, Zeiada et al. (2011) found that dynamic modulus of these materials measured in triaxial testing configuration may be significantly affected by the level of lateral confinement imposed to the specimens.

In this study, the use of unconfined conditions in flow number tests, as recommended by AASHTO TP 79 (2009), probably led to an underestimate of actual performance of rubberized gap-graded mixtures. In particular, given the non-uniform aggregate size distribution of such type of materials, a lateral confinement may be necessary to better evaluate their rutting properties simulating the real conditions occurring in the field.

3.4 *Wheel tracking tests*

Results of wheel tracking tests were expressed in terms of proportional rut depth values (Pi) determined at predefined loading intervals and thereafter fitted to the power law equation indicated below:

$$P_i = P_{100} \cdot \left(\frac{N}{100} \right)^{\beta} \tag{2}$$

where P_{100} and β are regression constants depending upon material characteristics and testing conditions.

P_{100} is the proportional rut depth after 100 loading cycles and provides a measure of the early response of the mixture under repeated loading, while β is related to the rate of strain accumulation exhibited throughout the test up to 30,000 cycles.

Comparative evaluation of the rutting performance of mixtures was based on the analysis of regression curves. Due to the fact that in the first part of the test permanent deformation response was characterized by a significant variability, fitting was performed by considering only data starting from the 300th loading cycle. Obtained curves and regression parameters are reported in Figure 4 and Table 5, respectively.

It was observed that curves corresponding to rubberized gap-graded mixtures were quite close to each other, whereas the curve corresponding to reference mixture DG was clearly different. In particular, mixture DG exhibited proportional rut depth values significantly lower than those of the other materials for any given number of wheel passes. This seemed to confirm the superior rutting performance of the traditional mixture with respect to the rubberized ones.

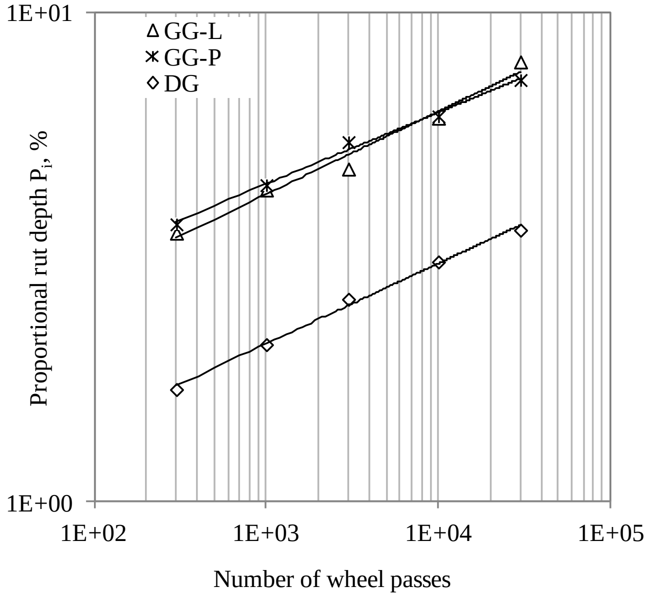

Figure 4. Wheel tracking curves of asphalt mixtures.

Table 5. Wheel tracking regression parameters of asphalt mixtures.

	GG-L	GG-P	DG
P_{100} (%)	2.9	3.2	1.4
β (-)	0.169	0.146	0.164

However, analysis of regression parameters revealed very similar results in terms of β values (especially when comparing GG-L to DG), thus indicating a similar aptitude in accumulating permanent deformation under repeated loading. It was therefore concluded that the gap observed between the curves was mainly due to the difference in P_{100} values. This was explained by hypothesizing the occurrence of initial settlement phenomena under loading in the case of rubberized mixtures as a consequence of their gap-graded structure. Such a biasing effect should be taken into account when carrying out a performance-related comparison between mixtures of different type, possibly by focusing on permanent deformation rates rather than on proportional rut depth values.

4 CONCLUSIONS

In the study presented in this paper rutting properties of rubberized gap-graded mixtures were investigated and compared with those of a reference dense-graded mixture containing neat bitumen. The experimental program included rheological tests carried out on binders (asphalt rubber and neat bitumen) and volumetric and mechanical tests carried out on asphalt mixtures (gap-graded and dense-graded).

Analysis of obtained results revealed the existence of a substantial discordance between rutting performance of binders and that of corresponding mixtures.

In particular, while asphalt rubber showed significantly lower non-recoverable creep compliance values measured by means of MSCR tests with respect to neat binder, flow number and wheel tracking test results indicated a lower rutting resistance for rubberized mixtures as compared to that of the traditional dense-graded one.

Such a discrepancy was explained in terms of asphalt mix formulation, mainly related to the use of gap-graded aggregate size distributions and higher binder contents in rubberized mixtures. However, the possible ineffectiveness of adopted standard protocols was also highlighted.

More research is certainly needed to further investigate rutting properties of rubberized mixtures, by considering a wider array of binders, formulations and volumetric conditions. The use of alternative test protocols in addition to or in replacement of standard methods should also be explored. In particular, the use of repeated compressive loading in confined conditions is recommended for flow number tests, while the analysis of permanent strain rates from wheel tracking tests should be considered as an alternative to the simple assessment of proportional rut depth values.

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