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Use of Municipal Solid Waste Bottom Ashes in Rubberized Asphalt Mixtures

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ABSTRACT

This paper presents the results of an experimental investigation carried out with the aim of evaluating the performance-related properties of rubberized asphalt mixtures containing municipal solid waste bottom ashes in partial substitution of natural aggregates. Performed laboratory tests focused on the determination of workability, visco-elastic characteristics, anti-rutting potential and resistance to crack propagation. Tests were carried out by considering an Ash-Amended Rubberized Asphalt Mixture (AARM) and, for comparison purposes, a standard Gap-Graded Rubberized Mixture (GGRM). Obtained results indicate that the rubberized mixture containing bottom ashes exhibited lower workability, reduced stiffness, and decreased anti-rutting potential with respect to the standard gap-graded rubberized mixture. Conversely, addition of bottom ashes was found to provide beneficial effects in terms of resistance to crack propagation. These outcomes suggest that use of municipal solid waste bottom ashes must be carefully considered, since environmental benefits may be counterbalanced by a lower performance.

Keywords: Municipal Solid Waste, Asphalt Rubber, Viscoelastic properties, Rutting resistance, Crack propagation

1. INTRODUCTION

The continuous growth of Municipal Solid Waste (MSW) produced in urban areas represents a serious concern for local authorities due to waste disposal problems [1]. Incineration of MSW has proven to be of strategic value in the waste management process as it combines the advantage of possible energy production with a significant volume reduction (by 70 to 95% of its original value) and consequent demand for landfill space [2,3]. Moreover, recycling of by-products originated from incineration of MSW in civil engineering applications may lead to additional benefits related to conservation of natural resources.

Several research projects have explored the possible use of Municipal Solid Waste Bottom Ash (MSW-BA) in road pavements, in full or partial replacement of natural aggregates in asphalt mixtures [4-9]. It has been shown that the mechanical behaviour of mixtures is greatly affected by the type and amount of employed MSW-BA. In particular, higher MSW-BA contents generally lead to poorer performance of the mixtures in terms of stiffness and durability.

The use of crumb rubber derived from end-of-life tires (ELTs) in asphalt pavements has become very popular worldwide in the last decades [10, 11]. A prompt to the diffusion of such a technology has been given by increasingly stringent environmental protection regulations (tire stockpiles and landfill disposal is now banned in most Countries). Crumb rubber incorporated in the bitumen leads to the production of asphalt rubber, characterized by enhanced stiffness and elasticity in comparison to traditional binders. As a consequence, rubberized asphalt mixtures may exhibit superior performance in terms of fatigue life, resistance to crack propagation, and anti-rutting potential [12-19].

Moving from the idea of synergistically combining MSW-BA and crumb rubber from ELTs, the experimental study described in this paper focused on the mechanical characterization of innovative Ash-Amended Rubberized Asphalt Mixtures (AARM), in which MSW-BA provided by a local incinerator was used in partial substitution of natural aggregates. A standard Gap-Graded Rubberized Mixture (GGRM) was also considered as a reference. The testing program included the evaluation of workability, viscoelastic characteristics, anti-rutting potential and resistance to crack propagation. Based on obtained results, the possible application of AARM was critically evaluated and discussed.

2. MATERIALS AND METHODS

The AARM considered in the experimental investigation was produced by combining mineral aggregates of different types and sizes with a single MSW-BA. Mineral aggregates included quartzite sand (0/4 mm) and metamorphic crushed gravel, supplied in two size fractions (4/8 and 8/12 mm). MSW-BA was sourced from a local waste-to-energy plant. Since the cooling process of ashes adopted by the plant entails the use of water, MSW-BA was preliminarily dried to completely remove moisture. A visual inspection of MSW-BA showed the presence of few coarse metal residues that were manually removed. The final ash gradation contained particles with sizes up to 16 mm.

Composition of the AARM was defined according to Technical Specifications commonly adopted in Italy for wearing course rubberized gap-graded mixtures [20]. The target particle size distribution was obtained by using the relative percentages of mineral fractions and MSW-BA reported in Table 1. Final gradation of the mixture is graphically represented in Figure 1, which also shows the gradation of a reference GGRM produced by using the same aggregates and sampled in an asphalt production plant.

TABLE 1 Composition of the AARM

Fractions	Percentage [%]
0/4	17
4/8	37
8/12	25
MSW-BA	21

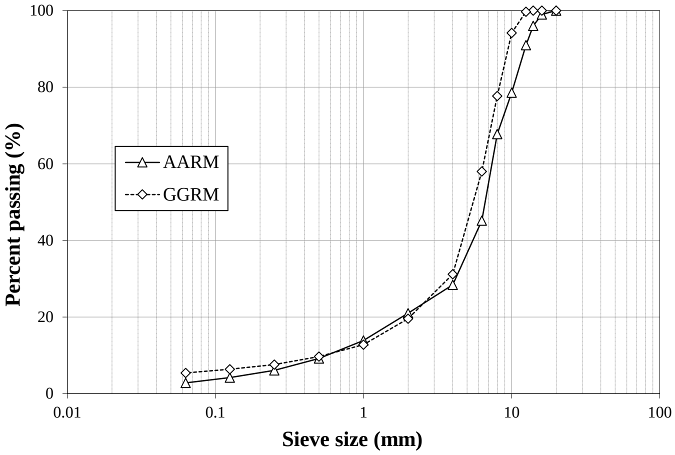

FIGURE 1 Gradation of asphalt mixtures

The employed asphalt rubber binder was a commercially available product with a nominal crumb rubber content equal to 18% (by weight of base bitumen). The design binder dosage was set equal of 9% by weight of dry aggregates. This value was selected based on the analysis of volumetric properties of mixtures, including voids content (v), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA), along with their mechanical parameters, including stability (S), flow (f) and S/f ratio, determined from classical Marshall tests (Table 2).

TABLE 2 Volumetric and Marshall properties of asphalt mixtures

Mixture	v [%]	VMA [%]	VFA [%]	S [kN]	f [mm]	S/f [kN/mm]
AARM	6,0	24,0	75,4	9,8	3,8	2,8
GGRM	6,9	24,5	71,9	7,1	2,7	2,6

The optimized AARM and GGRM were subjected to an extended laboratory characterization aimed at evaluating their workability, visco-elastic properties, anti-rutting potential, and resistance to crack propagation.

Workability was assessed by making use of the Gyratory Shear Compactor (GSC), according to EN 12697-31. Cylindrical specimens with 150 mm diameter were prepared in the laboratory at a fixed number of gyrations, equal to 100, and at a compaction temperature of 175 °C.

Visco-elastic properties were determined by means of dynamic modulus tests performed at three temperatures (4, 20 and 35 °C) and multiple loading frequencies according to AASHTO T 378-17. Measurements were carried out by means of the Asphalt Mixture Performance Tester (AMPT) on cylindrical specimens of 100 mm diameter and 150 mm height obtained by coring from larger gyratory samples.

The same equipment and gyratory sample geometry was adopted in flow number tests, conducted in accordance with AASHTO TP 79 for the evaluation of the anti-rutting potential. The employed testing protocol entailed the application of repeated compressive stresses at a fixed temperature of 58°C and with a confining pressure of 25.6 kPa (corresponding to 4 psi).

Resistance to crack propagation was finally determined through semi-circular bending tests, carried out according to EN 12697-44 on notched samples at a temperature of 20°C.

3. RESULTS AND DISCUSSION

Data recorded during GSC compaction were processed to determine mixture densification curves, which describe the variation of percent compaction (C) as a function of number of gyrations (N) according to the following relationship (Eq.1):

$$C = C_1 + k \cdot \log(N) \qquad (1)$$

Regression parameters C_1 and k, obtained from data fitting, are reported in Table 3.

TABLE 3 Regression parameters C_1 and k

Mixture	k [%/logN]	C_1 [%]
AARM	7,8	77,3
GGRM	9,3	77,2

Parameter C_1 is commonly considered as an indicator of the self-compaction properties of a mixture. Since it is mainly dependent upon the nominal maximum diameter of aggregates and on the density of component materials, coherently with expectations no differences were observed between the two mixtures. Parameter k is associated to the intrinsic workability of a mixture, which depends upon the reorganization of the internal aggregate structure under loading while approaching progressively higher density levels. The lower value of k observed for the AARM with respect to the GGRM can be attributed to two concurrent factors: the first one being related to the high absorption of MSW-BA, that results in a reduction of the effective binder covering the aggregate particles, and the second one being related to a higher stiffening effect of MSW-BA, that results in a higher viscosity of the filler-binder mastic.

Results of dynamic modulus tests obtained at various temperatures were shifted to the reference temperature of 20°C based on the time-temperature superposition principle [21]. Raw data were modelled by a sigmoidal function (Eq.2), used to mathematically describe the evolution of the dynamic modulus |E*| in the frequency domain, and by simultaneously fitting shift factors a(T) to the Arrhenius equation (Eq.3), used to model temperature dependency:

$$\log\left|E^*\right| = \kappa + \frac{\mu - \kappa}{1 + e^{\gamma + \delta \log f_R}} \quad (2)$$

$$\log a(T) = \frac{E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (3)$$

In the equations reported above, γ, δ, κ and μ are regression constants, f_R is reduced frequency, E_a is activation energy, T_r is reference temperature.

Table 4 lists the values of model parameters obtained for the two mixtures from non-linear regression analysis.

TABLE 4 Fitting coefficients of sigmoidal and Arrhenius functions

Mixture	E_a (J/mol)	κ	μ	γ	δ
AARM	195,921	1.919	7.014	-1.307	-0.376
GGRM	151,732	4.653	7.344	-0.315	-0.572

Activation energy E_a provides a measure of the thermal susceptibility of the binder phase included in a mixture [22-24]. Obtained results indicate that inclusion of MSW-BA presumably altered the thermal properties of asphalt rubber, making the AARM more sensitive to temperature changes. Moreover, higher values of E_a are usually exhibited by mixtures which require higher compaction efforts [22] and this was confirmed by the lower workability exhibited during GSC compaction by the AARM. κ and μ coefficients correspond to the lower and upper asymptotes of the sigmoidal equation, respectively. Comparison of the results obtained for the two mixtures indicate that the AARM is characterized by reduced dynamic moduli with respect to the GGRM at both low and high frequencies. The effects of MSW-BA on the visco-elastic properties of the mixture are also reflected by the observed change in the shape of the sigmoidal function, described in terms of the position (γ parameter) and slope (δ parameter) of the master curve at its inflection point (Figure 2).

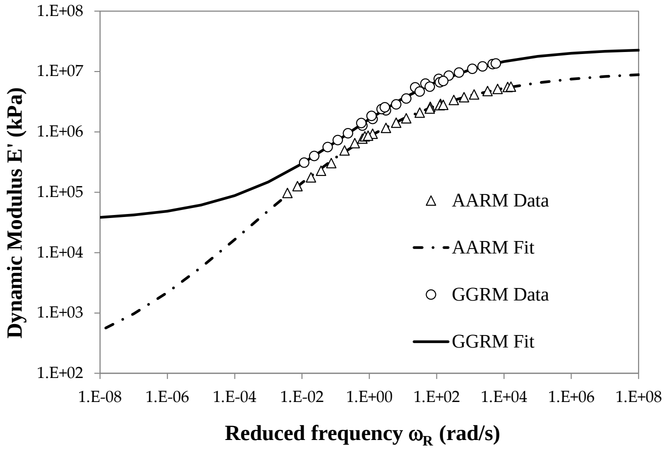

FIGURE 2 Master curves of asphalt mixtures at 20 °C

The experimental data retrieved from flow number tests and semi-circular bending tests were expressed in terms of Flow Number (FN) and Fracture Toughness (K_{IC}), respectively. Obtained values are summarized in Table 5.

TABLE 5 Flow Number and Fracture Toughness of asphalt mixtures

Mixture	FN@25.6 kPa [-]	K_{IC} [N/mm$^{3/2}$]
AARM	2942	7.3
GGRM	3552	1.4

Contrasting observations are drawn when comparing the performance of the mixtures based on the two parameters listed in Table 5.

In the case of FN, a lower value was exhibited by the AARM with respect to the GGRM, thus indicating that partial replacement of mineral aggregates with MSW-BA resulted in a reduced anti-rutting potential. This is probably due to a lower stiffening effect produced by the finer portion of MSW-BA as compared to that produced by a standard mineral filler.

Conversely, the K_{IC} value of the AARM was found to be significantly higher than that recorded for the reference mixture, thus revealing an improved ability to dissipate energy and to control crack propagation phenomena. This behaviour may be due to the presence of unburned particles inside MSW-BA, such as glass, ceramic materials, plastic or metallic fibres, which may induce a “sewing action” on cracks, thus hindering their propagation.

4. CONCLUSIONS

The study presented in this paper focused on the experimental characterization of rubberized asphalt mixtures containing Municipal Solid Waste Bottom Ash (MSW-BA) in partial replacement of mineral aggregates. Results obtained from laboratory testing indicate that the environmental advantages associated to the recycling of ashes may be counterbalanced by a lower performance of the mixture. In fact, the Ash-Amended Rubberized Asphalt Mixture (AARM) exhibited lower workability, reduced stiffness, and decreased anti-rutting potential with respect to the standard Gap-Graded Rubberized Mixture (GGRM) assumed as a reference. Conversely, addition of MSW-BA was found to provide beneficial effects in terms of resistance to crack propagation.

The outcomes of the investigation suggest that use of MSW-BA must be carefully evaluated and limited to those applications in which fracture properties of mixtures are expected to have a prominent role. Nevertheless, findings of this preliminary study need to be corroborated by further research involving a wider array of asphalt binders, formulations, and volumetric conditions.

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