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ABSTRACT

The increasing need of environment protection and preservation has been stimulating road agencies to progressively adopt sustainable technologies for the design, construction, and maintenance of their assets, with the consequent increasing use of recycled materials, industrial by-products, and wastes. In such a context, the experimental investigation presented in this paper moved from the idea of synergistically combining the use of bottom ashes originating from incineration of municipal solid waste (MSW) and crumb rubber from end-of-life tires. The performance-related properties of rubberized asphalt mixtures containing MSW bottom ashes in partial substitution of natural aggregates were evaluated by means of laboratory tests focused on the determination of workability, viscoelastic characteristics, anti-rutting potential, and resistance to crack propagation. Tests were carried out by considering an ash-amended rubberized asphalt mixture and, for comparison purposes, a standard gap-graded rubberized mixture (GGRM). Obtained results indicate that the rubberized mixture containing bottom ashes exhibited lower workability (16 % decrease in k parameter), reduced stiffness (decrease of dynamic modulus at 20°C of approximately 40 % and 60 % at 0.1 Hz and 10 Hz, respectively), and decreased anti-rutting potential (17 % decrease in flow number values) with respect to the standard GGRM. Conversely, the addition of bottom ashes was found to provide beneficial effects in terms of resistance to crack propagation (with fracture toughness values five times larger than those of the reference mixture). These outcomes suggest that the use of MSW bottom ashes must be carefully considered because environmental benefits may be counterbalanced by lower performance.

Keywords

municipal solid waste, asphalt rubber, viscoelastic properties, rutting resistance, crack propagation

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Introduction

Management of municipal solid waste (MSW) has become increasingly complex in recent years, especially as a result of its highly diversified composition, which varies greatly from country to country and may also change significantly over time. Its continuous growth in urban areas represents a serious concern for local authorities because of 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 originating from the incineration of MSW in civil engineering applications may lead to additional benefits related to the conservation of natural resources. Residues produced from these incineration plants are traditionally classified as MSW bottom ash (MSW-BA), fly ash, or air pollution control residue, the use of which has proven to be attractive as sustainable construction materials.[4]

Several research projects have explored the possible use of MSW-BA in road pavements, in full or partial replacement of natural aggregates and mineral filler in asphalt mixtures and cement concrete, focusing on either performance properties or environmental features.[5–23] It has been shown that the optimum percentage of MSW-BA employed for aggregate substitution can vary widely (ranging from 10 to 75 % by the total weight of dried aggregates) and seems to depend upon several factors such as the physicochemical treatment that MSW-BA has been subjected to, its chemical composition, and the pavement layer in which it is included.[24–40]

The mechanical behavior of asphalt mixtures was found to be significantly affected by the type and amount of employed MSW-BA. In particular, it is currently well known that higher MSW-BA contents generally lead to poorer performance of the mixtures in terms of stiffness and anti-rutting potential[29–31,35] and to a reduction of their resistance to raveling.[23,26,31] For this reason, several investigators have suggested using MSW-BA in the subgrade, subbase, and base course.[25,30,34,38,40]

The use of crumb rubber derived from end-of-life tires (ELTs) in asphalt pavements has become very popular worldwide in the last decades.[41,42] Increasingly stringent environmental protection regulations have prompted the diffusion of such a technology, given that tire stockpiling and landfill disposal are currently banned in most countries.

Crumb rubber incorporated in bitumen leads to the production of asphalt rubber, characterized by enhanced stiffness and elasticity in comparison to neat binders. Therefore, in comparison with traditional ones, rubberized asphalt mixtures may exhibit a superior performance in terms of fatigue life, resistance to crack propagation, anti-rutting behavior, ageing susceptibility, resistance to moisture damage, skid resistance, and noise absorption.[43–68]

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 (AARMs), in which MSW-BA provided by a local incinerator was used in partial substitution of natural aggregates. A standard gap-graded rubberized mixture (GGRM), sampled from an asphalt plant, 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 use of AARMs in pavement construction and maintenance was critically evaluated and discussed.

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. Because the cooling process of ashes adopted by the plant entails the use of water, MSW-BA was preliminarily dried to completely remove moisture (fig. 1).

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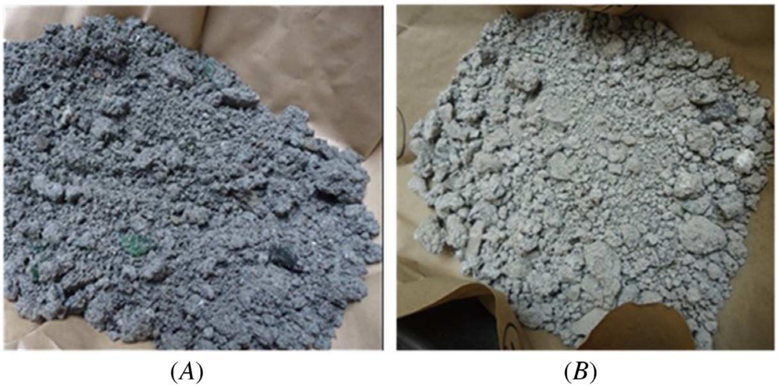
FIG. 1

MSW-BA before (*A*) and after (*B*) drying at 105°C.



The MSW-BA employed in the investigation consisted mainly of particles having different dimensions and shapes, including glass and ceramic-based grains. A visual inspection of MSW-BA showed a 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 coarse rubberized gap-graded mixtures.[69] 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 2**, which also shows the gradation of a reference GGRM that was sampled

TABLE 1

Composition of asphalt mixtures

	Percentage, %	
Fractions	AARM	*GGRM*
0/4	17	26
4/8	37	32
8/12	25	42
MSW-BA	21	

FIG. 2

Gradation of asphalt mixtures.

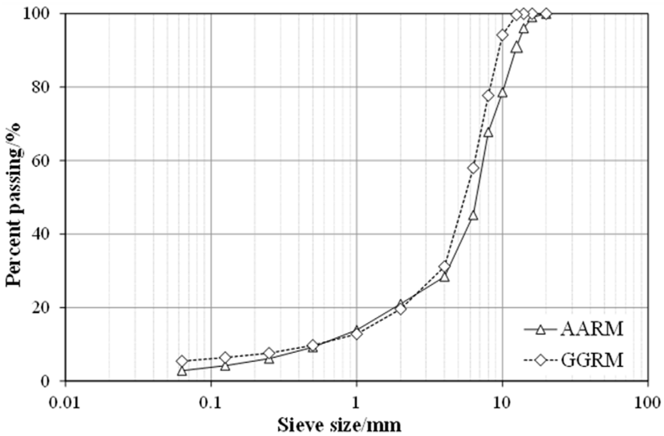


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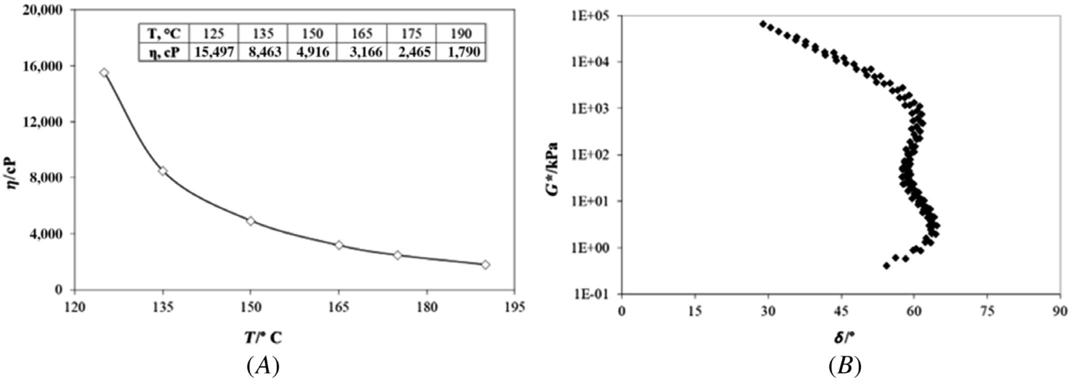
FIG. 3 (*A*) Asphalt rubber viscosity and (*B*) Black diagram.



in an asphalt plant and produced by using the same aggregates and asphalt rubber employed for the AARM. The target binder dosage set during plant production was equal to 8.5 % (by total weight of dry aggregates).

The employed asphalt rubber binder was a commercially available product with a nominal crumb rubber content equal to 18 % (by weight of base bitumen). It was subjected to a preliminary rheological characterization that included determination of viscosity, complex modulus, and phase angle. Viscosity tests were carried out by using a rotational Brookfield viscometer equipped with a SC4-27 spindle and by adopting a shear rate that was adjusted as a function of temperature (variable between 125°C and 190°C). Results obtained at the reference shear gradient of 6.8 s^{-1} are reported in **figure 3*A***. The complex modulus G^* and the phase angle δ were evaluated by means of frequency sweep tests performed using a dynamic shear rheometer operating at frequencies between 1 rad/s and 100 rad/s, while the temperature was varied between 4°C and 82°C (with increment steps of 6°C). Recorded data are synthetically displayed in the Black diagram shown in **figure 3*B***, which is consistent with the typical behavior expected for asphalt rubber.

MIX DESIGN OF AARM

According to the adopted technical specification[69] and in agreement with the approach adopted in the experimental investigations presented in the literature on the reuse of MSW-BA,[24–40] mix design of the AARM was carried out by means of the Marshall method. To identify its optimum value, binder content was varied between 7.0 % and 9.0 %. Because of the specific nature of MSW-BA,[70] which tends to absorb a large amount of bitumen, mixtures with lower binder contents exhibited an unsatisfactory degree of coating of aggregate particles. For this reason, after initial trials, mixtures prepared with 7 % and 7.5 % asphalt rubber were not considered further in the experimental investigation. Four specimens were compacted for each of the remaining mixtures by using the Marshall hammer with the application of 75 blows per face.[71] Results obtained from the consequent volumetric and Marshall tests led to the identification of the optimum binder dosage, equal to 9.0 % (by weight of dry aggregates).

Average results of volumetric and Marshall tests obtained on the design AARM and on the reference GGRM are listed in **Table 2**. They are expressed in terms of theoretical maximum density (*TMD*), voids content (*v*), voids

TABLE 2

Results of volumetric and Marshall tests (mean values) performed on asphalt mixtures

Blend	Binder Content, %	*TMD*, kg/m^3	*v*, %	*VMA*, %	*VFB*, %	*S*, kN	*f*, mm	*MQ*, kN/mm
AARM	9.0	2,378	6.0	24.0	75.4	9.8	3.8	2.6
GGRM	8.5	2,540	6.9	24.5	71.9	7.1	2.7	2.6

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in mineral aggregate (*VMA*), voids filled with bitumen (*VFB*), Marshall stability (*S*), Marshall flow (*f*), and Marshall quotient (*MQ*).[72–75]

As expected, as a consequence of the higher binder dosage, in comparison with the GGRM, the AARM was compacted to a lower voids content and higher *VFB* value. Because of the higher binder dosage and the presence of MSW-BA particles, which are lighter in nature, the *TMD* of the AARM decreased. The AARM mixture also showed a significantly higher Marshall stability that can be explained by referring to the combined effects originating from the interaction of the finest MSW-BA particles with the binder matrix and from the presence of MSW-BA coarse grains characterized by a very rough surface that can improve the interlocking among particles, thus enhancing the stiffness of the mixture. Moreover, as indicated by the values of Marshall flow, the presence of the fine particles of the MSW-BA that intimately interact with the asphalt rubber binder seemed to enhance the ductility properties of the AARM.

TEST METHODS

Following the preliminary design and characterization phase, the optimized AARM and the reference GGRM were subjected to an extended laboratory investigation focused on the evaluation of their workability, viscoelastic properties, anti-rutting potential, and resistance to crack propagation.

Workability was assessed by making use of the gyratory shear compactor (GSC), according to EN 12697-31:2019, *Bituminous Mixtures - Test Methods - Part 31: Specimen Preparation by Gyratory Compactor*.[76] Cylindrical specimens with a 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, selected based on the recommendations of the asphalt rubber producer. For both mixtures, the workability assessment was performed by referring to four independent replicates.

Viscoelastic properties were determined by means of dynamic modulus tests performed at three temperatures (4°C, 20°C, and 35°C) and multiple loading frequencies (from 25 to 0.01 Hz), according to AASHTO T 378-17, *Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)*.[77] Measurements were carried out by means of the AMPT on cylindrical specimens of 100-mm diameter and 150-mm height that were obtained by coring and sawing larger gyratory specimens.

The same equipment and gyratory sample geometry were adopted in flow number tests, conducted in accordance with AASHTO T 378-17[77] for the evaluation of the anti-rutting potential. The employed testing protocol entailed the application of repeated compressive stresses (600 kPa) at a fixed temperature of 58°C and in confined conditions (with a confining pressure of 25.6 kPa, corresponding to 4 psi).

Resistance to crack propagation was finally investigated through semicircular bending (SCB) tests, carried out on notched samples and at a temperature of 20°C, according to EN 12697-44, *Bituminous Mixtures - Test Methods - Part 44: Crack Propagation by Semi-circular Bending Test*.[78] Test specimens (50-mm thickness) were obtained by sawing from gyratory samples, which were subsequently notched in their center (0.35-mm width, 10-mm depth). Tests were performed by imposing a displacement rate of 5 mm/min.

Four replicates were considered for both mixtures and for all the mechanical characterization tests described earlier, thereby referring to average results in the subsequent analyses. Test specimens were prepared with a target void content of 7.0±0.5 % (as recommended for flow number tests by NCHRP project 9–33 and in AASHTO T 378-17[77]).

Results and Discussion

WORKABILITY

Data recorded during GSC compaction were processed to determine mixture densification curves, which describe the variation of percent compaction (*C*) as a function of the number of gyrations (*N*) and can be modeled according to the relationship reported in equation (1):

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FIG. 4

Densification curves of asphalt mixtures.

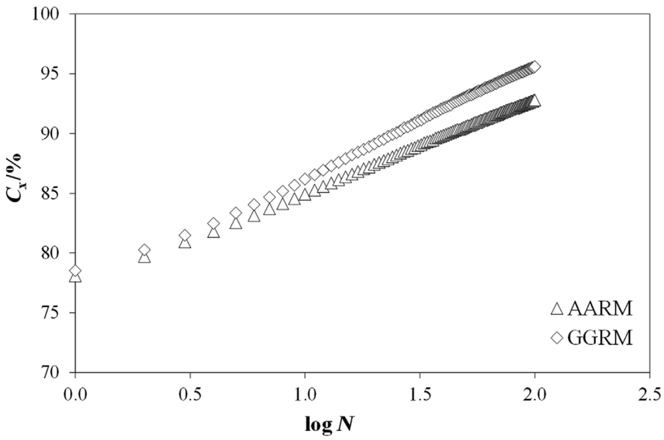

TABLE 3

Voids at 100 gyrations and regression parameters C_1 and k derived from densification curves

Mixture	v_{100}, %	k, %/log(N)	C_1, %
AARM	7.2	7.8	77.3
GGRM	4.4	9.3	77.2

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

where C_1 and k are regression parameters obtained from data fitting.

Average densification curves and regression parameters C_1 and k are provided in **figure 4** and **Table 3**, respectively. **Table 3** also shows the void contents of the two mixtures at 100 gyrations (v_{100}).

Parameter C_1 is commonly considered as an indicator of the self-compaction properties of an asphalt mixture. Because 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 with 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 binder absorption of MSW-BA that results in a reduction of the effective binder and the second one being associated with the stiffening of the filler-binder mastic caused by the MSW-BA. As a result of the significant difference in k, at 100 gyrations the two mixtures achieved completely different levels of compaction with voids contents equal to 7.2 % and 4.4 % for the AARM and GGRM, respectively.

VISCOELASTIC PROPERTIES

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.[79,80] Raw data were modeled by means of a sigmoidal function (equation (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[81] (equation (3)):

$$\log|E^*| = \kappa + \frac{\mu - \kappa}{1 + e^{\gamma + \delta \log f_R}} \tag{2}$$

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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

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

In equations (2) and (3), $|E^*|$ is the dynamic modulus; γ, δ, κ, and μ are regression constants; f_R is reduced frequency (calculated as the product of physical frequency f and shift factor $a(T)$); $a(T)$ is the shift factor at the generic test temperature T; E_a is activation energy; and T_r is reference temperature.

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

Activation energy E_a can be interpreted as a resisting barrier to viscous flow,[82–84] thus providing a measure of the thermal susceptibility of the binder phase included in a mixture. Binders with a higher E_a value typically exhibit a higher sensitivity to temperature changes.[84–86] Obtained results indicate that inclusion of MSW-BA led to an asphalt mixture that was more sensitive to temperature changes, probably because of the interactions occurring between the MSW-BA particles and the binder matrix. As discussed in the literature,[84] it was also confirmed that a higher value of E_a was found for the mixture (AARM), which required higher compaction efforts to achieve a given level of densification (or, equivalently, with a lower value of workability parameter k).

The 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 at a reference temperature of 20°C highlights the fact that the AARM showed reduced dynamic moduli at both low and high frequencies with respect to the GGRM, with a difference of the order of 40 % and 60 % for testing frequencies of 0.1 Hz and 10 Hz, respectively. This is presumably related not only to the higher binder content and higher *VFB* value but also to the effective stiffness of ashes (lower than that of virgin aggregates) and to their interaction with asphalt rubber.

Finally, the effects of MSW-BA on the viscoelastic properties of the mixture were 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 (**fig. 5**).

FIG. 5

Master curves of asphalt mixtures at 20°C.

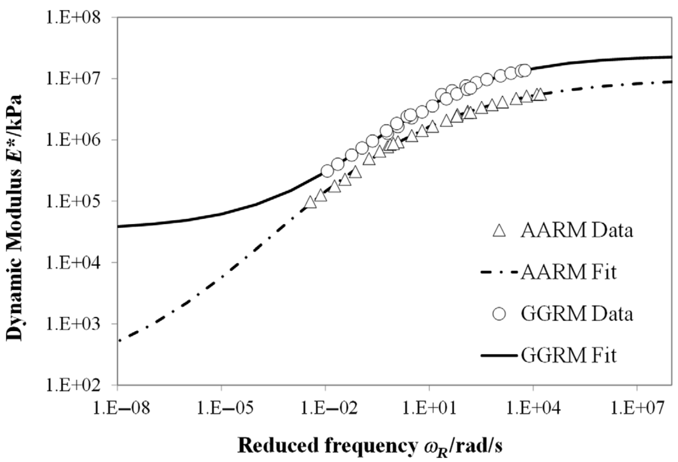

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TABLE 5

Flow number and fracture toughness of asphalt mixtures (and their relative coefficient of variation [CoV])

Mixture	*FN*	CoV_{FN}, %	K_{IC}, N/mm$^{3/2}$	CoV_{KIC}, %
AARM	2,942	6.6	7.3	25.6
GGRM	3,552	4.1	1.4	9.2

PERFORMANCE-RELATED PROPERTIES

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

Contrasting observations can be drawn from the experimental results when comparing the potential and expected performance of the mixtures based on the two parameters listed in **Table 5**.

In the case of *FN* (calculated by using the Francken model[77]), 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 because of the lower stiffening effect produced by the finer portion of the MSW-BA in comparison to that associated with the use of a standard mineral filler. Such an outcome is consistent with the results obtained from dynamic modulus tests, which highlighted a significant difference in stiffness between the two mixtures, especially at low frequencies.

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 behavior may be because of the presence in the MSW-BA of unburned particles such as elongated glass spikes, ceramic residues, and plastic or metallic fibers, which may induce a "sewing action" on cracks, thus hindering their propagation. To prove such an assumption, two samples of AARM, previously subjected to the SCB test, were subjected to ignition at 540°C with the subsequent recovery of the resulting residue. As expected, metallic fibers were clearly detected in the unburned residue, thus confirming the possibility that they may have contributed to the recorded increase of the resistance to crack propagation.

Conclusions

The study presented in this paper focused on the experimental characterization of rubberized asphalt mixtures containing MSW-BA in partial replacement of mineral aggregates.

Results obtained from laboratory testing indicate that the environmental advantages associated with the recycling of ashes may be counterbalanced by the slightly lower performance of the mixture. In fact, the AARM considered in this study exhibited reduced workability, lower stiffness, and decreased resistance to rutting when compared to the standard 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 the use of MSW-BA must be carefully evaluated and limited to pavement construction and maintenance projects in which fracture properties of rubberized asphalt mixtures are expected to have a prominent role. Nevertheless, the findings of this preliminary study need to be corroborated by further research involving a wider and more comprehensive array of asphalt binders, formulations, and volumetric conditions. Furthermore, understanding the effect of the potential variability of MSW-BA composition on mixtures' behavior is of utmost importance because this factor can limit the future applications of this technology. A comprehensive evaluation of the potential environmental impact of the use of MSW-BA (e.g., leachate effects) also deserves consideration in future research.

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