Using Sewage-Sludge Ash as Filler in Bituminous Mixes

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Abstract: In this study, the behavior of bituminous mixes made with sewage sludge ash (SSA) as mineral filler was investigated. The behavior of these mixes was evaluated with the Cantabro, indirect tensile strength, water sensitivity, permanent deformation, and resilient modulus tests. The results show that SSA waste may be used in bituminous mixes at approximately 2–3% weight percent, maintaining adequate levels of cohesion and adhesion in the mixtures, which is comparable to mixtures made with active fillers such as hydrated lime and cement. Moreover, its use does not increase permanent deformations. However, the resilient modulus test gave slightly lower results for mixes made with SSA than for mixtures made with other fillers. It may be concluded that SSA waste may be used as a filler for bituminous mixes with better results than for mixes made with limestone fillers and with similar results for mixes made with other fillers such as hydrated lime and cement. **DOI: 10.1061/(ASCE)MT.1943-5533.0001087.** *© 2014 American Society of Civil Engineers.*

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Introduction

The large quantity of sewage sludge generated by major cities has shown significant annual growth because of the processes of urbanization and industrialization. The proportion of waste water that undergoes treatment before its return to rivers or the sea is increasing at a similar rate. Waste water is processed in waste water treatment plants (WWTP). Sewer sludge (SS) is a result of treatment in these plants, and it must be processed correctly, taking into account the contaminants that it contains.

According to the most recent data collected by the Spanish National Sludge Registry, 1,200,000 t of SS were generated in Spain. Part of this waste is incinerated, and at present, 200,000 t of sewer sludge ashes (SSA) are produced annually (Ministerio de Agricultura 2013).

The most common way of disposing of sewer sludge ash is to use it as an organic fertilizer (Antolin et al. 2010; Jayasinghe et al. 2010; Krzywy-Gawronska 2010; Soares et al. 2010; Antil et al. 2011; Lakhdar et al. 2011; Wang et al. 2012) in agricultural regions. However, SS has also been the focus of study as a construction material by a number of investigators. The use of sewer sludge is common in the ceramics industry (Tay 1987; Lin and Weng 2001; Weng et al. 2003, 2011). Recent studies indicate that SS has the potential to be used in the pavement industry (da Christiane de Figueirêdo Lopes Lucena et al. 2013) and can be used to manufacture lightweight aggregate (Huang and Wang 2013). The incorporation of SSA into ceramic materials augments their porosity, reducing the material density which may improve its thermal and acoustic insulating properties. After high temperature incineration of SS, the principle components of the remaining ash are SiO_2, CaO, Al_2O_3, and Fe_2O_3, which are components of ordinary cements. Some research is looking into using SSA as a primary ingredient in the fabrication of cements (Lin et al. 2005; Lin and Lin 2005; Donatello et al. 2010; Mattenberger et al. 2010; Lin et al. 2012), incorporating them into mortars (Bhatty and Reid 1989; Tay and Show 1992; Monzo et al. 1996, 1999, 2003; Cyr et al. 2007; Shen et al. 2009; Chang et al. 2010), precast concrete blocks (Carrion et al. 2013), and even in the fabrication of concrete as a substitute for the fines in the mix (Tay 1987; Khanbilvardi and Afshari 1995).

The addition of filler to a bituminous mix permits optimization of the bitumen properties. Fillers have a complex role in the mixes because on one hand, they serve as an inert, pore-filling material, whereas on the other, they serve as an active material. Their principle function is to modify the viscosity and consistency of the bitumen creating a filler-bitumen mix, called a mastic, of thicker consistency to cover the aggregate and to also improve the cohesion and adhesivity of the combined mix.

A number of studies have investigated the use of wastes as fillers in various types of bituminous mixes. Some fillers have been used with the idea of making the mix more water resistant, whereas others have been used simply as an alternative to natural or commercial fillers if the mix shows good behavior. The utilization of demolition wastes (Chen et al. 2011), wastes from the exploitation of andesites (Uzun and Terzi 2012), which require an increase in bitumen, the partial substitution of filler by urban city waste ash in stone mastic asphalt mixes (Xue et al. 2009), powdered iron (Arabani and Mirabdolazimi 2011), and asphaltite (Yilmaz et al. 2011) have been studied. The addition of SSA in bituminous mixes is also in accordance with existing norms (Al Sayed et al. 1995) when the study was carried out in hot regions.

This study investigates the use of SSA as a mineral filler (grain size smaller than 63 μm) in asphalt concrete for very thin layers, which is one of the most commonly used wearing courses in Spain. The physical and mechanical properties of SSA mixtures and control mixtures (hydrated lime, cement, and limestone) were evaluated with various quantities of bitumen to obtain the optimum bitumen content that complies with the requirements established for a discontinuous wearing course.

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Table 1. Properties of the Coarse and Fine Aggregates

Properties	Standard test	Limit	Coarse aggregate	Fine aggregate
Apparent particle density (kg/m^3)	UNE EN 1097-6	—	2,937	2,719
Dry particle density (kg/m^3)	UNE EN 1097-6	—	2,869	2,641
Saturated surface dry density (kg/m^3)	UNE EN 1097-6	—	2,892	2,669
Water absorption after 24 h (%)	UNE EN 1097-6	—	0.8	1.1
Flakiness index (%)	UNE EN 933-3	≤20–30	13.5	—
Los Angeles abrasion loss (%)	UNE EN 1097-2	≤20–25	10	—
Polished stone value	UNE EN 1097-8	≥56–44	54	—

Materials

The aggregates used in fabrication of the mixes were a coarse porphyrous aggregate and a fine limestone aggregate. The properties of the two are shown in Table 1. Because the main objective was to study the influence of SSA as filler (smaller than 63 μm in size) in discontinuous wearing course, the fine aggregate was washed in the laboratory to remove particles smaller than 63 μm so that fine aggregate particles do not interfere with the filler. Thus, the results are due to the filler used in the mixture.

Table 2 shows the properties of the bitumen used in the bituminous mixtures. The bitumen used in this study was a polymer-modified bitumen of type BM-3c (PG 76-28). This bitumen is the most widely used in high traffic discontinuous wearing courses in Spain.

In this study, four types of filler were selected for the mastic: (1) hydrated lime (HL), (2) cement (CEM), (3) limestone filler (LM), and (4) SSA from the waste water treatment plant located in Zaragoza (Spain). The chemical composition of the SSA is shown in Table 3.

The Spanish regulations given in PG-3 (Ministerio de Fomento 2009) require the use of fillers with bulk densities from 500 to 800 kg/m^3. From this range, the critical concentration of each of the fillers was computed to find the appropriate volumetric dose. The critical concentration corresponds to the dispersion of filler particles in the bitumen with free movement but in contact with one another (Recasens et al. 2005). This parameter is determined by the Argentinean IRAM 1542 (IRAM 1983) norm according to Eq. (1). The test consists in filling a graduated test tube with 20 cm^3 of kerosene along with the filler, placing the tube in a double boiler at 100°C, and stirring the mixture for at least 1 h to remove the air. The settled volume of the filler as obtained after 24 h may be seen in Fig. 1. This procedure determines the maximum volume of filler that the bitumen membrane can accommodate in its interior

$$C_s = \frac{P}{V \cdot \gamma} \tag{1}$$

where C_s is the critical concentration; P is the filler mass (g); V is the volume occupied after sedimentation of the filler in anhydrous kerosene after a 24-h period (cm^3); and γ is the specific weight of the filler (g/cm^3).

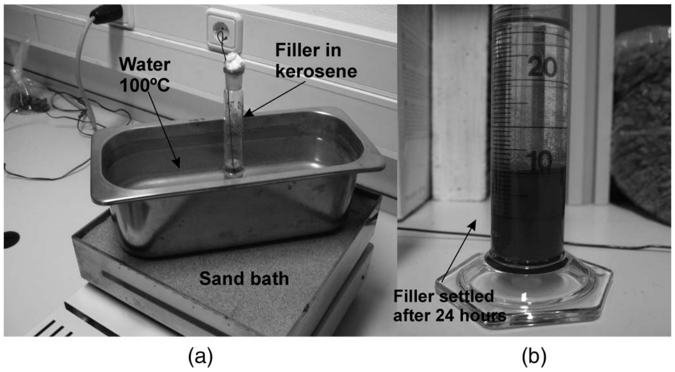
The properties of bulk density, particle density, and critical concentration are given in Table 4. The particle size distribution of the fillers used for the mixes was obtained with a laser diffraction analyzer (Fig. 2).

Table 2. Properties of the Bitumen (BM-3c) Used in this Study

Standard test	Units	Results
Penetration (25°C)	mm/10	58.0
Softening point	°C	70.9
Penetration index	—	2.7
Specific weight	kg/m^3	1,028
Elastic recovery	%	75.0

Mix Design

The selected mixture type was the type associated with an open-graded wearing course (BBTM 11B). The maximum aggregate size for this mixture was 11 mm. The BBTM 11B mixtures are discon-



(a) (b)

Fig. 1. Critical concentration test to determine the maximum volume of filler

Table 3. Chemical Composition of the SSA Used as Filler

Component	Concentration (%)	Component	Concentration (%)	Component	Concentration (%)
Na_2O	0.822	TiO_2	1.075	SrO	0.23
MgO	3.136	Cr_2O_3	0.193	Nb_2O_5	0.356
Al_2O_3	9.475	MnO	0.044	SnO_2	0.026
SiO_2	17.208	Fe_2O_3	8.551	BaO	0.139
P_2O_5	12.574	CuO	0.17	PbO	0.037
SO_3	8.437	ZnO	0.303	Cl	0.136
K_2O	1.24	As_2O_3	0.004	—	—
CaO	29.879	Rb_2O	0.004	—	—

Table 4. Characteristics of the Fillers Used for the Bituminous Mixes

Test	Standard	HL	CEM	LM	SSA
Bulk density (kg/m^3)	UNE-EN 1097-3	169	648	623	476
Particle density (kg/m^3)	UNE EN 1097-7	2,316	2,960	2,776	2,780
Critical concentration	IRAM 1542	0.074	0.261	0.286	0.148

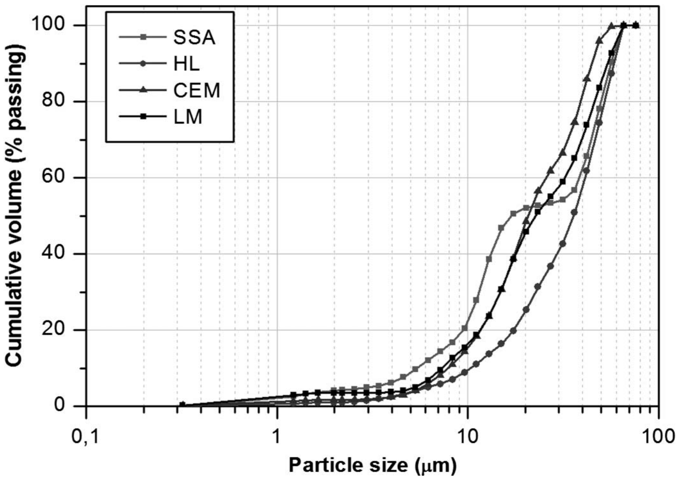


Fig. 2. Particle size distribution of sewage sludge ash (SSA), hydrated lime (HL), cement (CEM), and limestone filler (LM)

tinuous bituminous mixtures that are applied in very thin layers (asphalt concrete for very thin layers) of 2–3 cm thick. The size distribution is shown in Table 5. These layers provide a texture with high slip resistance, good drainage, and durability. Modified bitumen is used in these layers to enhance cohesion.

The mixes were designed according to the recommendations of reference (PG-3). The BBTM 11B mixes were fabricated using the grain size distribution given in Table 5, with various fillers. Specifically, hydrated lime (BBTM-HL), cement (BBTM-CEM), limestone (BBTM-LM), and treated sewage sludge ash (BBTM-SSA) were used.

The quantity of bitumen was calculated to be 4–5.5% for the theoretical amount of filler of 5% corresponding to a 63-μm sieve size in Table 5. With the quantity of bitumen and the value of the critical concentration given in Table 4, the amount of filler for each bitumen content was calculated according to Eq. (2) by setting the ratio $C_v/C_s = 1$. The maximum cohesion in the mixture is expected at this ratio. The addition of filler was made by volume and not by weight. The volume occupied by the filler in the mastic was constant for the mixes

$$C_v = \frac{\frac{P_f}{\gamma_f}}{\frac{P_f}{\gamma_f}+\frac{P_b}{\gamma_b}} \qquad (2)$$

where C_v is the volume concentration; P_f is the filler weight; P_b is the bitumen weight; γ_f is the filler specific weight; and γ_b is the bitumen specific weight.

Mixes with bitumen content of 4–5.5% were studied. In Table 6, the weight percentage of filler as a function of bitumen content is shown for each mix. The percentages of filler were calculated from the critical concentrations given in Table 4.

Because the quantities of the critical concentration of the filler CEM and LM are similar, the quantities of filler, by weight, of the grain size distributions of these mixes are also similar. Furthermore, these two fillers comply with the apparent density established in Ministerio de Fomento (2009), so that their weight percentage is also in the 4–6% range as established in the specifications. In any case, only a small quantity of HL and SSA fillers are necessary to fabricate the mixes. In the case of the HL filler, only approximately 1% by weight is necessary, which is in agreement with the values stated by some previous authors (1–2% of lime in the mix) (Akili 1993; Sengul et al. 2012).

Physical Parameters

The apparent density was computed according to UNE EN 12697-6 and the percentage of void content, percentage of voids in the mineral aggregate (VMA), and the percentage of voids filled with bitumen (VFB) (UNE EN 12697-8) for each of the different types of filler. To evaluate the physical parameters of the different mixes, nine Marshall specimens of each mix were compacted by applying 50 blows to each side of the sample.

Cantabro Test

To test the cohesion and adhesivity of the mixes, a Cantabro test was used according to the NLT-352 Spanish norm for the dry samples, and according to the NLT-362 Spanish norm for the wet samples. Six samples were prepared for each bitumen mix that was studied. The samples were compacted with an automatic Marshall compactor that applied 50 blows to each sample side.

Three samples were placed under controlled dry conditions at 25°C for 24 h, another three samples were immersed in water and maintained at 60°C for 24 h, and finally all of the samples were placed in a controlled environment at 25°C for another 24 h. Afterwards, the samples were tested in the Cantabro tester for evaluation.

Table 5. Design Gradation Limits for the BBTM 11B Mixes and the Associated Grain Size Distributions

Sieve sizes (mm)	Upper and lower limits	Passing (%)
16	100	100
11.2	100–90	96
8	80–60	74
4	27–17	24
2	25–15	20.5
0.500	16–8	11.1
0.063	6–4	5 (theoretical)

Table 6. Percentage, by Weight, of Filler as a Function of Bitumen Content

Bitumen content (%)	Percentages of filler			
	BBTM-HL	BBTM-CEM	BBTM-LM	BBTM-SSA
4	0.78	4.26	4.54	2.03
4.5	0.88	4.79	4.73	2.29
5	0.98	5.32	5.25	2.55
5.5	1.08	5.85	5.77	2.82

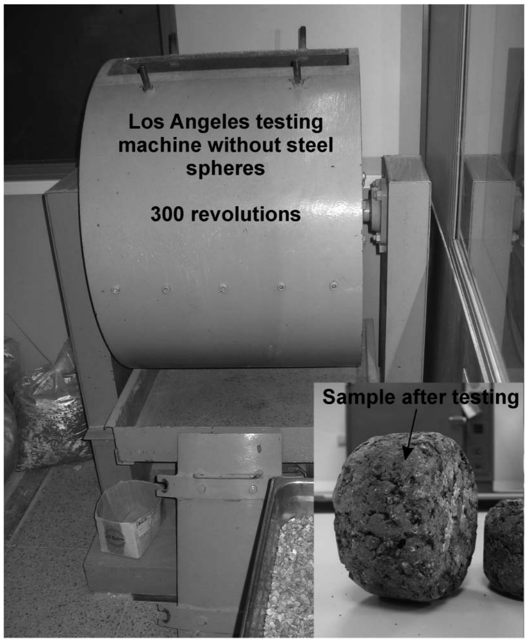


Fig. 3. Cantabro test machine and bituminous mix after testing

For this test, a Marshall test-sized cylindrical sample is placed in the Los Angeles testing machine without steel spheres (Fig. 3) and the drum is rotated for 300 revolutions at 30 rpm and at 25°C. The weight lost from the specimen is recorded as a percentage of the original weight using the Eq. (3)

$$\mathrm{CL} = \frac{(A - B)}{A} \cdot 100 \qquad (3)$$

where CL is the Cantabro loss (%); A is the initial weight of test specimen (g); and B the final weight of test specimen (g).

This test measures the sliding resistance between the aggregate and mastic in dry (CL_d) and wet conditions (CL_w).

Water Sensitivity

Water sensitivity tests were conducted according to the UNE EN 12607-12 norm. The object of this test is to determine the effect of saturation on the sample because water produces a loss of adhesion between the mastic and the surface of the aggregate. The test consists of measuring the indirect tensile strength (ITS) in cylindrical samples compacted at 50 blows per side. For each level of bitumen concentration, three samples were tested under dry conditions and three samples were wet tested. The temperature for the dry sample group was set at 15°C. The wet samples were submerged in water and then vacuum-sealed for 30 min. Subsequently, they were submerged in a warm water bath at 40°C for 72 h. Both groups of samples were tested at 15°C. The indirect tensile strength ratio (ITSR) was calculated according to Eq. (4). The minimum ITSR value recommended by Spanish technical specifications is 90%

$$\mathrm{ITSR} = 100 \cdot \frac{\mathrm{ITS}_w}{\mathrm{ITS}_d} \qquad (4)$$

where ITSR is the indirect tensile strength ratio; ITS_w is the indirect tensile strength of the wet samples; and ITS_d is the indirect tensile strength of the dry samples.

Permanent Deformation

The permanent deformation measurement was carried out using the Wheel Tracking test according to the UNE EN 12697-22 norm. Three samples were prepared for each bitumen content of dimensions of 300 × 400 × 40 mm. The samples were compacted using a plate. The air voids of each sample were fixed at the air voids obtained previously for the Marshall specimens. The test was carried out at a temperature of 60°C with a back-and-forth frequency of 26.5 passes/min with a 700-N loaded wheel for 10,000 load cycles. The Wheel tracking slope was determined from Eq. (5)

$$\mathrm{WTS}_{\mathrm{air}} = \frac{d_{10{,}000} - d_{5{,}000}}{5} \qquad (5)$$

where $\mathrm{WTS}_{\mathrm{air}}$ ($\mathrm{mm}/10^3$ load cycles) is the slope of the rutting curve after 1,000 load cycles; $d_{5{,}000}$ and $d_{10{,}000}$ are the depths of the rutting curve (mm) after 5,000 and 10,000 load cycles, respectively.

The Spanish technical specifications recommend a maximum $\mathrm{WTS}_{\mathrm{air}}$ value of 0.07–0.1 $\mathrm{mm}/10^3$ load cycles for heavy and light traffic, respectively, in accordance with the temperature of the zone where the bituminous layer is emplaced.

Resilient Modulus

The resilient modulus was measured with the configuration used to measure the indirect tensile strength. This is the most popular method because of its simplicity and because it may be applied to cores extracted from the road surface (Kok and Yilmaz 2009). Many factors affect the resilient modulus, among them are the following: (1) the intensity of the applied force, (2) the load frequency, (3) the bitumen content, (4) the type of aggregate, (5) the void content, (6) additives, and (7) temperature.

The test was conducted on cylindrical samples at a controlled temperature of 15°C in accordance with Appendix C of the UNE EN 12697-26 norm using the resilient modulus test apparatus (IT-CY). Five samples of each mix were fabricated with a diameter of 100 mm with 4–5% bitumen using a gyratory compactor according to UNE EN 12697-31 norm. The air voids of each sample were fixed at the air voids obtained previously on the Marshall specimens.

Results and Discussion

The results obtained for the apparent density, void content, VMA, and VFB are shown in Table 7.

As shown in Table 7, the BBTM-HL mix had the least apparent density followed by the BBTM-SSA mix. This is because of the low density and proportion of the HL and SSA fillers used in fabricating these mixes. The Spanish regulations recommend a void content greater than 12% in the mix. As shown in Table 7, all mixes at each studied percentage of bitumen are in compliance with this requirement.

Table 8 shows the measured weight loss as a function of bitumen content for the dry and wet Cantabro tests for each of the studied mixes. A drop in the percentage of weight loss with increasing bitumen content is observed for most bitumen content levels. This indicates an improvement in the cohesion of the mixes. The percent weight losses measured in the wet tests were greater than those measured in the dry tests, which indicates a loss of adhesivity after conditioning of the mixes in water. The loss of adhesivity is reduced as the amount of bitumen in the mix is increased.

The BBTM-SSA mixes show good cohesion. The percent weight loss in these mixes in the dry tests was less than 10%, which

Table 7. Mean Values of Apparent Density, Void Content, VMA, and VFB as a Function of the Percentage of Bitumen for the Studied Mixes

Mix	Bitumen content (%)	Apparent density (kg/m3)	Void content (%)	VMA (%)	VFB (%)
BBTM-HL	4	2,110	21.36	29.92	28.62
BBTM-HL	4.5	2,147	19.27	29.06	33.68
BBTM-HL	5	2,163	17.98	28.92	37.84
BBTM-HL	5.5	2,136	18.28	30.16	39.39
BBTM-CEM	4	2,201	18.39	27.01	31.96
BBTM-CEM	4.5	2,229	16.71	26.49	36.92
BBTM-CEM	5	2,223	16.27	27.05	39.85
BBTM-CEM	5.5	2,192	16.80	28.43	40.93
BBTM-LM	4	2,168	19.44	27.92	30.38
BBTM-LM	4.5	2,224	16.65	26.41	36.97
BBTM-LM	5	2,217	16.24	26.99	39.86
BBTM-LM	5.5	2,197	16.33	27.99	41.69
BBTM-SSA	4	2,149	20.09	28.70	30.01
BBTM-SSA	4.5	2,165	18.82	28.55	34.10
BBTM-SSA	5	2,178	17.64	28.49	38.09
BBTM-SSA	5.5	2,181	16.82	28.74	41.50

Table 9. Mean Tensile Strength Values of Each Mixture

Mix	Bitumen content (%)	ITS$_d$ (%)	ITS$_w$ (%)
BBTM-HL	4	899.81 ± 20.75	851.90 ± 50.05
BBTM-HL	4.5	978.80 ± 15.30	928.48 ± 30.45
BBTM-HL	5	1,019.62 ± 17.26	968.61 ± 18.85
BBTM-HL	5.5	931.11 ± 67.00	903.28 ± 37.17
BBTM-CEM	4	1,347.29 ± 19.92	1,105.67 ± 57.38
BBTM-CEM	4.5	1,434.04 ± 60.92	1,360.35 ± 30.06
BBTM-CEM	5	1,186.21 ± 24.01	1,145.53 ± 37.74
BBTM-CEM	5.5	1,157.61 ± 59.77	1,153.03 ± 29.37
BBTM-LM	4	1,171.80 ± 60.25	1,042.89 ± 36.69
BBTM-LM	4.5	1,313.73 ± 76.74	1,210.26 ± 37.21
BBTM-LM	5	1,158.25 ± 37.85	1,067.48 ± 5.76
BBTM-LM	5.5	979.81 ± 24.25	907.36 ± 41.70
BBTM-SSA	4	1,225.39 ± 34.85	1,096.52 ± 8.30
BBTM-SSA	4.5	1,213.74 ± 5.98	1,120.11 ± 38.08
BBTM-SSA	5	1,178.97 ± 15.13	1,114.40 ± 10.46
BBTM-SSA	5.5	1,159.62 ± 60.56	1,123.54 ± 29.46

Note: ITS$_d$ is the indirect tensile strength of the dry specimens and ITS$_w$ is that of the wet specimens ± one standard deviation.

is similar to the other mixes. The dry weight loss stayed relatively constant with respect to the bitumen content.

The results from the wet tests show that the percent weight loss is pronounced at low bitumen content (4–4.5%) in the mixes but tends to converge to the dry test weight loss as the bitumen content is increased (5–5.5%) and were approximately the same at one bitumen content of the BBTM-HL mix.

Table 9 shows the measured tensile strength (ITS$_d$ and ITS$_w$) and Fig. 4 shows the ITSR as a function of bitumen content for each of the studied mixes. In spite of the low values of ITS for the BBTM-HL mix, the samples showed good adhesivity at all of the studied bitumen contents, retaining more than 90% of their tensile strength after wet conditioning, as recommended by the Spanish PG-3 norm. This may be due to the fact that in mixtures with HL and polymer-modified bitumen, the ratio $C_v/C_s = 1.3$ (increasing HL content in the mixture) may be achieved (Bianchetto et al. 2007) with better results than $C_v/C_s = 1$. The BBTM-CEM mix exhibited a very high tensile strength. The BBTM-HL mix had ITSR values above 94% for all studied bitumen contents, which demonstrated the good behavior of this filler under wet conditions, as has been shown by numerous authors (Movilla-Quesada et al. 2012; Perez et al. 2012).

Table 8. Mean Percent Weight Loss Measured in Mixes with Cantabro Dry and Wet Tests ± One Standard Deviation

Mix	Bitumen content (%)	CL in dry conditions (%)	CL in wet conditions (%)
BBTM-HL	4	10.45 ± 1.38	17.15 ± 3.56
BBTM-HL	4.5	7.88 ± 0.48	7.33 ± 0.16
BBTM-HL	5	7.62 ± 0.11	8.37 ± 0.08
BBTM-HL	5.5	6.33 ± 0.38	9.79 ± 0.34
BBTM-CEM	4	10.36 ± 1.35	12.43 ± 1.07
BBTM-CEM	4.5	7.87 ± 0.62	8.97 ± 1.46
BBTM-CEM	5	6.13 ± 1.76	8.00 ± 2.09
BBTM-CEM	5.5	5.68 ± 0.70	8.24 ± 1.06
BBTM-LM	4	7.98 ± 0.67	18.37 ± 0.43
BBTM-LM	4.5	6.65 ± 0.87	7.79 ± 1.59
BBTM-LM	5	4.88 ± 0.08	7.40 ± 1.49
BBTM-LM	5.5	4.18 ± 0.82	5.30 ± 1.36
BBTM-SSA	4	8.10 ± 0.87	16.08 ± 1.38
BBTM-SSA	4.5	6.70 ± 0.64	11.85 ± 0.89
BBTM-SSA	5	6.59 ± 0.52	9.00 ± 0.75
BBTM-SSA	5.5	6.86 ± 0.90	8.65 ± 0.64

The ITS values for the BBTM-SSA mix were not very dependent upon the bitumen content and were higher than those of the BBTM-HL and BBTM-LM mixes, which indicates better cohesion in the BBTM-SSA mix. Furthermore, the ITSR values show good adhesivity at bitumen percentages in excess of 4.5%, which is in compliance with the Spanish norm for this type of mix. The adhesivity of mixes fabricated with SSA is comparable to that of mixes made with active fillers such as HL and CEM. Additionally, the SSA mix showed better adhesivity than mixes containing LM. The LM is usually used in Spain as filler for bituminous mixes.

Fig. 5 shows the slope of the rutting curve after 10,000 load cycles as a function of the bitumen content for each of the studied mixes and the low and high heavy goods traffic limits. The results show the trends obtained from the permanent deformation tests. All the studied mixes are in compliance with the Spanish norms.

The deformations of the BBTM-HL mixes are the least of the four studied. The BBTM-CEM and BBTM-LM mixes had similar deformations with respect to bitumen content. The BBTM-LM mix had the maximum deformation at a bitumen content of 5.5%.

The BBTM-SSA mixes showed the minimal plastic deformation with respect to bitumen content at 4.5% bitumen content. As may be observed, the rutting curve test deformations produced in the BBTM-SSA mixes were similar to those produced in the CEM and LM tests.

As established in the PG-3 norm, the BBTM 11B mixes should contain a minimum bitumen content of at least 4.75%. This value may be corrected if the aggregates have a density other than 2,650 kg/m^3 using the Eq. (6)

$$\alpha = \frac{2{,}650}{\rho_d} \tag{6}$$

where α is the correction factor; and ρ_d is the particle density (kg/m^3) of the aggregates used in the bituminous mixes.

As reflected by the data of Table 10, the BBTM-SSA mix shows a behavior similar to the rest of the studied mixes. The optimal percentage of bitumen is higher than 4.5% for this mix to meet the ITSR value required by Spanish norms, similar to that of the BBTM-CEM and BBTM-LM mixes.

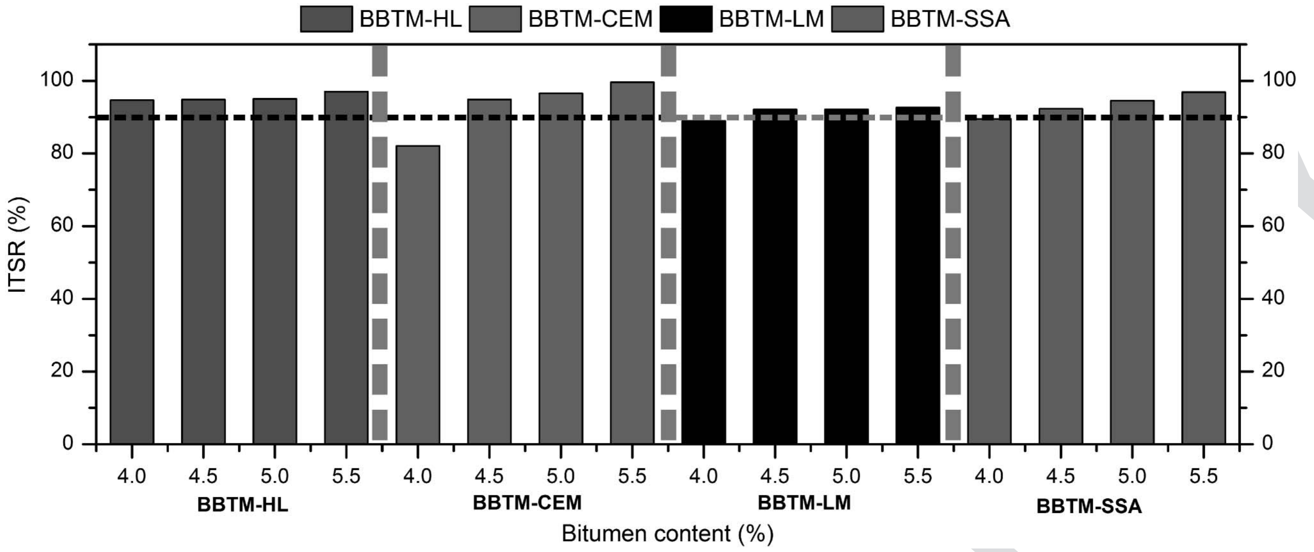


Fig. 4. Indirect tensile strength ratio (ITSR) and the minimum established by Spanish specifications is given by the dotted line

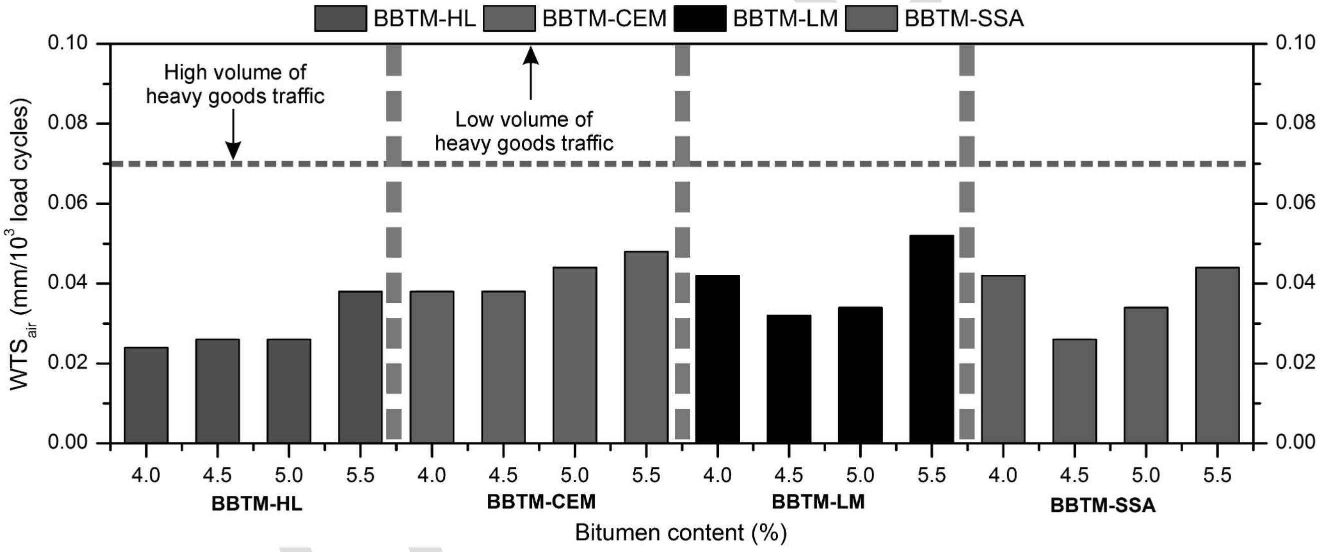


Fig. 5. Results of deformation because of rutting curve test after 10,000 load cycles. The maximum permitted deformation for a high volume of heavy goods traffic is given by the dotted line, whereas the maximum permitted deformation given for a low volume of heavy goods traffic is given by the solid line

Table 10. Particle Densities of Aggregates, Correction Coefficient for Obtaining the Minimum Content of Bitumen (A), Percentage of Bitumen Needed to Comply with the Spanish Requirement for the Void Percentage in the Mixes, Indirect Tensile Strength Ratio (ITSR), and the Slope of the Rutting Curve after 10,000 Cycles

Mix	BBTM-HL	BBTM-CEM	BBTM-LM	BBTM-SSA
ρ_d(kg/m^3)	2,880	2,860	2,850	2,870
A	0.92	0.93	0.93	0.92
Minimum bitumen content (%)	4.36	4.41	4.41	4.38
Vh($\geq 12\%$)	4–5.5	4–5.5	4–5.5	4–5.5
ITSR($\geq 90\%$)	≥4	≥4.5	≥4.5	≥4.5
WTS$_{air}$(≤ 0.07 mm)	4–5.5	4–5.5	4–5.5	4–5.5
Optimum bitumen content (%)	4.36–5.5	4.5–5.5	4.5–5.5	4.5–5.5

Table 11 gives the resilient modulus and the phase angle obtained from tensile strength tests as a function of bitumen content for each of the studied mixes. Some authors have observed a loss in the resilient modulus with increasing bitumen content, making the pavement more flexible (Arabani et al. 2010; Nejad et al. 2010). Examining the results of Table 11, the BBTM-HL and BBTM-CEM mixes appear to be most affected by the reduction of the resilient modulus, with an approximate loss of 50% from the initial value of bitumen content to the final value of 5%. The BBTM-LM and BBTM-SSA mixes also showed a loss in the resilient modulus with increasing bitumen content, although to a lesser degree. For the BBTM-SSA mixes, the resilient modulus was least dependent on bitumen content, only decreasing approximately 10% over the entire range of bitumen content. Although rigid pavements may be more resistant to permanent deformation, they also

Table 11. Resilient Modulus and Phase Angle Obtained for Each of the Mixes and Filler Types

Mix	Bitumen content (%)	Resilient modulus (MPa)	Phase angle (degrees)
BBTM-HL	4	5,121	20.18
BBTM-HL	4.5	4,717	23.08
BBTM-HL	5	2,642	28.31
BBTM-CEM	4	6,654	19.45
BBTM-CEM	4.5	3,769	27.00
BBTM-CEM	5	3,230	28.60
BBTM-LM	4	6,159	20.032
BBTM-LM	4.5	4,645	23.81
BBTM-LM	5	4,091	25.69
BBTM-SSA	4	4,630	21.05
BBTM-SSA	4.5	4,176	22.065
BBTM-SSA	5	3,570	27.15

tend to crack at low temperatures more readily than more flexible pavements.

The behavior of bituminous mixes is not perfectly elastic, but rather viscoelastic, which gives rise to a delay in the deformation response to applied loads that are described by the phase angle (δ). The phase angles for the studied mixes were calculated with Eq. (7) and are shown in Table 11

$$\delta = \omega \cdot \Delta t \tag{7}$$

where δ is the phase angle; ω is the angular frequency; and Δt is the delay in the maximum deformation response time to the applied load.

The phase angle increases whereas the resilient modulus decreases with increasing bitumen content in the mixes. This points to a predominance of a viscous response in the deformations with increasing bitumen, that is, an increase of permanent deformations.

The main purpose of two-factor ANOVA was to determine the effect of the type of filler (A) and the bitumen content (B) in the properties tested in the mixtures. The level of significance was assumed to be 0.05. The dependent variables used were apparent density, void content, ITS_d, ITS_w, CL_d, CL_w, WTS_{air}, and resilient modulus. The effect of the single factor and each pair of combined factors (interaction effect) was obtained and summarized in the Table 12.

The statistical study reveals that the type of filler and the bitumen content influence the apparent density, voids content, ITS_d, ITS_w, CL_d, CL_w, WTS_{air}, and resilient modulus as single

Table 12. Two-Factor ANOVAs for Each Laboratory Test for the Type of Filler (A) and Bitumen Content (B)

Test	Source of variation	Sum of squares	Degrees of freedom	Mean square	F	Significance
Apparent density	A	1.554×10^5	3	5.180×10^4	250.346	0.000
	B	4.279×10^4	3	1.426×10^4	68.932	0.000
	$A \times B$	1.637×10^4	9	1.819×10^3	8.789	0.000
	Error	3.641×10^4	176	2.069×10^2	—	—
	Total	9.126×10^8	192	—	—	—
Void content	A	1.545×10^2	3	5.151×10^1	175.622	0.000
	B	2.467×10^2	3	8.224×10^1	280.415	0.000
	$A \times B$	2.519×10^1	9	2.799	9.544	0.000
	Error	5.162×10^1	176	2.930×10^1	—	—
	Total	6.229×10^4	192	—	—	—
ITS_d	A	6.760×10^5	3	2.253×10^5	118.614	0.000
	B	1.941×10^5	3	6.470×10^4	34.058	0.000
	$A \times B$	1.639×10^5	9	1.821×10^4	9.584	0.000
	Error	6.079×10^4	32	1.900×10^3	—	—
	Total	6.427×10^7	48	—	—	—
ITS_w	A	4.965×10^5	3	1.655×10^5	141.976	0.000
	B	1.394×10^5	3	4.647×10^4	39.867	0.000
	$A \times B$	1.404×10^5	9	1.560×10^4	13.38	0.000
	Error	3.730×10^4	32	1.166×10^3	—	—
	Total	5.564×10^7	48	—	—	—
CL_d	A	2.992×10^1	3	9.974	14.007	0.000
	B	8.346×10^1	3	2.782×10^1	39.072	0.000
	$A \times B$	1.502×10^1	9	1.669	2.344	0.037
	Error	2.279×10^1	32	7.120×10^1	—	—
	Total	2.600×10^3	48	—	—	—
CL_w	A	2.955×10^1	3	9.851	4.925	0.006
	B	5.286×10^2	3	1.762×10^2	88.089	0.000
	$A \times B$	1.037×10^2	9	1.152×10^1	5.76	0.000
	Error	6.401×10^1	32	2.000	—	—
	Total	5.815×10^3	48	—	—	—
WTS_{air}	A	1.275×10^3	3	4.250×10^4	12.252	0.000
	B	1.449×10^3	3	4.830×10^4	13.924	0.000
	$A \times B$	4.890×10^4	9	5.433×10^5	1.566	0.168
	Error	1.110×10^3	32	3.469×10^5	—	—
	Total	6.900×10^2	48	—	—	—
Resilient modulus	A	6.973×10^6	3	2.324×10^6	22.521	0.000
	B	5.144×10^7	2	2.572×10^7	249.198	0.000
	$A \times B$	1.445×10^7	6	2.408×10^6	23.328	0.000
	Error	4.954×10^6	48	1.032×10^5	—	—
	Total	1.266×10^9	60	—	—	—

factors (significance < 0.05). For these tests, the interaction between the two independent variables ($A \times B$, type of filler, and the bitumen content) also proved to be significant (significance < 0.05) on each of the dependent variables except in the case of the parameter $\mathrm{WTS}_{\mathrm{air}}$ (significance $= 0.168$). This indicates that the interaction between the type of filler and the bitumen content is not significant for the permanent deformation in the mixtures studied.

Conclusions

In this study, the properties of the BBTM 11B mixes made both with SSA and with other fillers normally used in the fabrication of pavements are compared. The principle conclusions are as follows:

- Given the apparent density of the SSA filler, the mixes have been fabricated with a weight percentage of 2–3% with respect to the total weight of the aggregates in the BBTM 11B mix.
- The mixes made with SSA have shown adequate values of cohesion and adhesivity. The values of the ITS parameter were better than the mixes using HL and LM fillers, indicating an improvement in cohesion for SSA when compared to these fillers.
- The ITSR for the SSA mixes were greater than 90% at bitumen content greater than 4.5%, being comparable to that of CEM or HL.
- The permanent deformations in the mixes made with SSA were similar to those produced in mixes made with CEM or LM.

The resilient modulus of mixes made with SSA was slightly less than mixes made with other types of filler. The loss in the resilient modulus with increasing bitumen is principally because of an increase in the phase angle.

The results of this study show that sewage sludge ash has properties that make it an adequate filler material for BBTM 11B mixes.

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