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Behavior of asphalt mastics containing different materials as filler

Juan Gabriel Bastidas-Martínez, Hugo Alexander Rondón-Quintana, and Márcio Muniz de Farias

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Abstract: The behavior of the asphalt mixture is mainly attributed to the performance of the asphalt mastic. Several studies have been performed to evaluate the behavior of mastics made with different fillers. Most researchers have added the filler by mass within the bitumen; however, this comparison may be more appropriate by volume. An experimental program was designed to evaluate the behavior of mastics produced with five different fillers (natural limestone, LS; hydrated lime, HL; Portland cement, PC; Linz-Donawitz steel slag, LDSS; and blast furnace slag, BFS), and were dosed by mass and volume. Penetration, softening point, viscosity, multiple stress creep and recovery test, and linear amplitude sweep test were performed. Results showed that analyzed asphalt mastic properties depend on dosage type performed and test type. Furthermore, HL, PC, BFS and LDSS mastics showed better performance compared to control LS mastic.

Key words: asphalt mastic, filler, mass and volume dosage, rheological properties.

Résumé : Le comportement du mélange d'asphalte est principalement attribuable à la performance du mastic d'asphalte. Plusieurs études ont été réalisées afin d'évaluer le comportement des mastics fabriqués avec différents produits de remplissage. La plupart des chercheurs ont ajouté le produit de remplissage par poids dans le bitume; toutefois, cette comparaison peut être plus appropriée par volume. Un programme expérimental a été conçu afin d'évaluer le comportement des mastics produits avec cinq produits de remplissage différents (calcaire naturel, LS; chaux hydratée, HL; ciment de Portland, PC; laitier d'acier de Linz-Donawitz, LDSS et laitier de haut fourneau, BFS) et ont été dosés par poids et par volume. La pénétration, le point de ramollissement, la viscosité, l'essai de fluage et de récupération à contraintes multiples et l'essai de balayage d'amplitude linéaire ont été effectués. Les résultats ont montré que les propriétés analysées du mastic d'asphalte dépendent du type de dosage administré et du type d'essai. En outre, les mastics HL, PC, BFS et LDSS ont montré une meilleure performance par rapport au mastic LS de contrôle. [Traduit par la Rédaction]

Mots-clés : mastic d'asphalte, produit de remplissage, dosage du poids et du volume, propriétés rhéologiques.

Introduction

Asphalt mastic is a composite material consisting of asphalt binder, fillers smaller than 75 μm (Little and Petersen 2005; Zulkati et al. 2012; Kuity et al. 2014; Davis and Castorena 2015; Kuity and Das 2015; Pei et al. 2015; Veytskin et al. 2015; Das and Singh 2017), and in some cases additives (Zhu 2013). The amount of filler in the mineral aggregates of asphalt mixtures is low (approximately 4%–8% by mass); however its surface area is high (70%–90% of total surface of the mineral aggregates (Dan et al. 2014; Veytskin et al. 2015). This discrepancy justifies the present research on dosing filler by mass or by volume.

Several studies have been performed to evaluate the behavior of mastics made with different fillers since the 1930s (Anderson and Goetz 1973), and perhaps the first one to approach the topic was Richardson (1915), who suggested that particle geometry and the asphalt thickness absorbed by the filler affect mastic stiffness. Filler provides mainly volume filling (forming an interconnected network) and cohesion to asphalt mastic increasing stiffness in the asphalt mixture (Richardson 1915; Rigden 1947; Heukelom 1965; Chen and Peng 1998; Yi-qiu et al. 2010; Liao et al. 2012; Davis and Castorena 2015; Pasandín and Pérez 2015; Robati et al. 2015; Tenza-Abril et al. 2015; Al-Khateeb et al. 2017). However, stiff mastics may affect asphalt mixture performance under low temperature conditions due to its brittle behavior, which may result in cracking (Chen and Peng 1998; Yi-qiu et al. 2010). In addition, filler material plays an important role in properties related to mixture compatibility, aggregate bitumen adhesion (Modarres and Rahmanzadeh 2014) and ductility (Pereira et al. 2018). For these reasons, filler is an important component that affects behavior (workability, moisture damage, fatigue and permanent deformation resistance, durability, aging and long-term characteristics) of asphalt mastic and asphalt mixtures (Yi-qiu et al. 2010; Zulkati et al. 2012; Muniandy et al. 2013; Antunes et al. 2015; Davis and Castorena 2015; Pei et al. 2015; Veytskin et al. 2015; Cheng et al. 2016). Nonetheless, a great amount of filler may weaken the asphalt mixture since it would increase the amount of bitumen needed to cover the aggregates, and it may also affect its workability and compatibility (Heukelom 1965; Zulkati et al. 2012). Some of the identified variables that influence mastic properties and performance include: specific surface area (Richardson 1915; Rigden 1947; Cheng et al. 2016; Das and Singh 2017), filler shape, geometry,

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type and mineralogy (Lackner et al. 2005; Antunes et al. 2015), proportions and particle sizes (Richardson 1915; Traxler 1937; Pei et al. 2015), and physical–chemical interactions (Yiqiu et al. 2012; Muniandy et al. 2013; Antunes et al. 2016; Das and Singh 2017). Baker et al. (2018) studied the performance of asphalt mixtures after natural bentonite clay partial replacement of the mineral filler portion of aggregates. Results indicate an increase in flow and indirect tensile strength values, and reduction in hydraulic conductivity compared with control specimens. J. Liu et al. (2018) characterized the rheological properties of mastics comprised of asphalt modified with polyphosphoric acid and three mineral fillers (pulverized limestone filler, Portland cement, and hydrated lime). They used different filler-to-binder (F/A) ratios by mass. The results indicated that the F/A significantly affected stiffness in the modified asphalt mastic regardless of testing temperature but had little effect on m-value at low temperatures. Liu et al. (2018*b*, 2018*c*) used different volcanic ashes (VA) to elaborate asphalt mastics. They concluded that VA filler with the addition of styrene-butadiene-styrene (SBS) modifier can improve high and low temperature performance of asphalt mixtures. Additionally, strength and flexibility of SBS mixes were further improved with VA fine fillers.

Natural powders are the most conventional filler used in asphalt mastics. These materials are obtained as a result of natural degradation or produced after the crushing process of larger natural mineral aggregates, such as crushed limestone, marble or granite materials. Other alternative materials are used as filler and the most studied are lime (Little and Petersen 2005; Sung et al. 2008; Mwanza et al. 2012; Zulkati et al. 2012; Cheng et al. 2016; Lesueur et al. 2016) and Portland cement (Mwanza et al. 2012; Antunes et al. 2016; Lesueur et al. 2016; Nassar et al. 2016). Different types of non-conventional fillers have been used for mastics. Some of them are obtained as byproducts or waste produced in industrial processes. Some examples found in recent literature include: borogypsum (Kütük-Sert and Kütük 2013), recycled brick powder (Chen et al. 2011; Wu et al. 2011), phosphorus (Qian et al. 2013), fly ash (Sharma et al. 2010; Chandra and Choudhary 2013; Muniandy et al. 2013; Cheng et al. 2016; Nassar et al. 2016), phosphate waste (Katamine 2000), coal waste powder (Modarres and Rahmanzadeh 2014), rice husk ash (Sargın et al. 2013), taconite (Moon et al. 2014), waste bleaching clay (Sangiorgi et al. 2016), marble waste dust (Karasahin and Terzi 2007), granite waste dust (Akbulut et al. 2012), steel wool or steel fiber (Liu et al. 2013), sewage sludge ash (Tenza-Abril et al. 2015), zirconium tungstate (Yi et al. 2016), ceramic waste (Muniandy et al. 2013; Nassar et al. 2016), magnetite (Giustozzi et al. 2018), ladle furnace slag (Ortega-López et al. 2016), steel slags and blast furnace slags (Rondón et al. 2018). Using these unconventional fillers, most studies reported improvements in evaluated properties and conclude that these fillers can be used as potential materials for replacing conventional fillers in asphalt mixtures, which additionally produces environmental benefits, saving raw materials (conventional fillers) and reducing waste material volume. Korayem et al. (2018) used amorphous carbon powder as filler material. According to them, AC improved rutting performance and can be used to withstand fatigue cracking in hot mix asphalts. Zhang et al. (2018) replaced natural mineral filler with red mud to prepare asphalt mastic. According to them, this waste filler improved stiffness and rutting parameters in asphalt mastics.

Much research work has been conducted to evaluate asphalt mastic properties. Most researchers added filler by mass within the bitumen, given that it is simpler and more practical. Additionally, many standard fillers present small variations in their physical properties, and because of that reason, dosage is carried out by mass. However, fillers could have different specific gravities or densities and for that reason, their comparison would be more appropriate through volume. Few studies have evaluated the effect of dosing filler by volume within asphalt mastic. Kuity et al. (2014) for example, used five different types of fillers (brick dust, fly-ash, hydrated lime dust, recycled concrete waste aggregates dust, and stone dust) within an asphalt mix using volume proportioning; however, they did not evaluate asphalt mastic performance. Gundla et al. (2016) evaluated the effectiveness of employing hydrated lime (HL) and Portland cement (PC) in mastics (dosed by volume) to mitigate the aging effects of asphaltic mixtures.

In this study, an experimental program was designed to evaluate the conventional and rheological properties of five asphalt mastics when fillers are added to asphalt by mass and volume. Rheological characterization was carried out for high and intermediate service temperatures, considering their application in tropical countries such as Brazil. Mastics were produced with an asphalt cement AC 50/70 (penetration grade) and the five types of fillers: limestone (LS, as natural mineral and control filler), HL, PC, blast furnace slag (BFS), and a Linz-Donawitz steel slag (LDSS). HL and PC are the most studied, and both tend to increase asphalt mastic stiffness (Taha et al. 2002; Little and Petersen 2005; Mwanza et al. 2012; Movilla-Quesada et al. 2015; Gundla et al. 2016; Nassar et al. 2016; Das and Singh 2018; Diab and You 2018). In spite that other researchers have brought up the importance of volume over mass in mastics (e.g., Rigden 1947; Gundla et al. 2016), no comparison reporting the effect of dosage by mass and volume was found in the literature consulted. Despite that multiple researches have been carried out in relation to the topic of study, the response of different mastics when they are dosed by mass and volume, is something that has not yet been fully understood. Thus, the foregoing study helps to deepen the discussion, contributing with results of an experimental phase designed for such purpose.

The main applications of LDSS and BFS in asphalt mixtures are utilizing them as substitutes for the coarse fraction of natural granular aggregates, maybe because of the fact that the size of particles is predominantly coarse. Using these slags as filler or blended with other types of fillers, LDSS and BFS have been studied in the analysis of hot, cold, porous asphalt mixtures and stone mastic asphalt mixtures (Muniandy et al. 2013; Nassar et al. 2016; Al-Hdabi and Al-Nageim 2017; Diab and You 2018; Rondón et al. 2018). Used as fillers in asphalt mastic, both materials (LDSS and BFS) have been less studied. Cosme et al. (2016) evaluated a LDSS residue as filler in mastic. They performed physical, chemical, mineralogical, and rheological characterization of asphalt mastic produced with different filler proportions by mass. According to them, LDSS residues improved binder rheological behavior, especially contributing to the increase of mastic stiffness, and also showed better results for recovery and creep compliance. A similar conclusion is reported by Li et al. (2017) using three different steel slag fillers. The results of this conducted and reviewed research encourage further studies, mainly in relation to the use of fillers in asphalt mastics, and in relation to adding them to asphalt by mass and volume proportions.

Materials and methods

General characterization

Asphalt mastics were produced using a 50/70 penetration grade asphalt cement that meets Brazilian specification requirements (DNIT 2006) for hot mix asphalts (HMA) (see general properties in Table 1) and five filler materials passing sieve No. 200: (1) a natural aggregate (Fig. 1*a*), used as control filler in this study, which is a limestone material (LS) widely used in the construction of HMA in Brasilia (Brazil) and was obtained from a local quarry; (2) hydrated lime (HL) (Fig. 1*b*) was selected because of its calcium content and because it is the most widely used anti-stripping agent in asphalt mixtures; (3) Portland cement (Fig. 1*c*), which is a conventional CP I type according to DNIT (2004) specification and also is used as

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Table 1. General properties of AC 50-70.

Test	Method	Unit	Requirement Min	Requirement Max	Value
Test on the original AC					
Penetration (25 °C, 100 g, 5 s)	ASTM D5-13	0.1 mm	60	70	51.1
Penetration index	NLT 181-88	—	–1.5	+0.7	–0.67
Softening point	ASTM D36-06	°C	46	—	52.0
Specific gravity	AASHTO T228-04	—	—	—	1.022
Viscosity to 135 °C	AASHTO T316-13	cP	274	—	337
Viscosity to 150 °C	AASHTO T316-13	cP	112	—	177
Viscosity to 177 °C	AASHTO T316-13	cP	57	285	66
Flashpoint	ASTM D3143-08	°C	235	—	338
Ductility (25 °C, 5 cm/min)	ASTM D113-99	cm	100	—	>105
Tests on the residue of AC after the RTFOT					
Mass loss	ASTM D2872-12	%	—	0.5	0.1
Penetration, in % of the original penetration	ASTM D5-13	%	55	—	81
Increase of the softening point	ASTM D36-06	°C	—	8	7.5

Fig. 1 Samples of (*a*) LS, (*b*) HL, (*c*) PC, (*d*) LDSS, and (*e*) BFS. [Colour online.]

anti-stripping agent; (4) LD Linz-Donawitz steel slag (LDSS) (Fig. 1*d*), which is produced when pig iron is processed into crude steel; (5) BFS, which is ACBFS (air-cooled blast furnace slag) type (Fig. 1*e*). LDSS and BFS slags produced by the company ArcelorMittal (Brazil). These last two fillers were chosen because their use can provide social, economic, and environment benefits.

For the case of LS, LDSS, and BFS, after drying, the coarse fraction of each raw material was crushed for 2 h using a Los Angeles (LA) abrasion machine, and then it was sieved using mesh No. 200. Each material was washed and dried in the oven for 24 h at 105 °C to blend with the bitumen. For the asphalt mastic production, asphalt and fillers were blended at a temperature of 150 °C for 5 min. To avoid problems associated to filler sedimentation, we manufactured small samples (samples of approximately 50 g) and tests on said samples were performed as soon as these reached room temperature. The specific gravities (SG, ASTM C188-17) of LS, HL, PC, LDSS, and BFS are 2.719, 2.688, 3.064, 3.390, and 2.640, respectively. Attention should be given to the high specific gravity value of LDSS.

HMA mixture designed using the LS as aggregate and AC 50/70 as binder show an optimum asphalt content (OAC) in average of 4.8% in relation to mass (Muniz de Farias et al. 2019; Rondón et al. 2019). Likewise, ES 031/2006 specifies 6% as average filler content by mass (DNIT 2006). Considering the above mentioned, for the case of mass analysis, 44.4 g of AC 50/70 were blended with 55.6 g of each filler to produce 100 g of each asphalt mastic. This mix corresponds to a filler-to-asphalt ratio F/A = 1.25. For volume analysis, the new mass of each filler necessary to produce the same volume of particles in relation to the control LS was calculated using the specific gravity of materials. The required mass of LS (55.6 g) was multiplied by the ratio of specific gravities between each filler and the LS to obtain the new filler mass that would replace LS by volume. Thus, 44.4 g of AC 50/70 was blended with 54.9, 62.6, 69.3, and 53.9 g of HL, PC, LDSS, and BFS fillers, respectively.

Table 2. XRF results for filler samples.

Material	Chemical compound, % in mass: CaO	SiO_2	Fe_2O_3	Al_2O_3	K_2O	MgO	P_2O_5	TiO_2	Na_2O	SO_3
LS	72.8	14.4	3.1	3.0	3.0	2.3	0.9	0.3	—	—
HL	91.3	1.22	0.11	0.72	0.23	0.65	0.03	0.01	0.17	0.82
PC	63.7	22.8	2.9	4.8	—	2.8	—	—	—	2.4
LDSS	38.2	10.4	36.6	4.8	0.1	4.1	1.8	0.6	0.3	—
BFS	47.9	32.9	2.4	8.9	0.4	5.7	0.6	0.5	—	—

On each mastic, the following tests were performed: (*a*) penetration (ASTM D5-13, 0.1 mm at 100 g, 5 s and 25 °C); (*b*) softening point (ring and ball, ASTM D36-06); and (*c*) viscosity measured in a temperature range of 135 °C to 177 °C using a Brookfield viscometer (ASTM D4402-15) with #27 spindle at 20 rpm. Five replicate samples were prepared and tested to evaluate each property.

Mineralogical characterization and chemical composition of fillers

To analyze chemical composition of fillers, X-ray fluorescence (XRF) tests were performed (Table 2). In addition, for the LS, LDSS, and BFS, screening tests based on X-ray diffractometry (XRD) were performed for the evaluation of mineralogical composition (Table 3). A detailed description regarding the execution of these tests can be found in Zhang et al. (2003) and Beckhoff et al. (2006). It is possible to observe that the predominant mineral in LS is calcite. Normally, calcite is not a mineral of high hardness. However, microcline and quartz are, which together, along with the strong adhesion of particles produced by the high CaO content, could increase abrasion resistance of LS particles. CaO is alkaline, which contributes to increase aggregate–asphalt adhesion, and improves resistance to moisture damage and stripping (Muniandy et al. 2013; Modarres and Rahmanzadeh 2014; Pasandín and Pérez 2015). For the case of BFS, its predominant minerals are akermanite and gehlenite, both of which result from the recrystallization of

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Table 3. Mineral percentages in filler samples analyzed (XRD test).

Material	Mineral	Chemical composition	%, in mass	Material	Mineral	Chemical composition	%, in mass
LS	Calcite	$CaCO_3$	77.36	HL	Calcium oxide	CaO	84.8
	Microcline	$KAlSi_3O_8$	12.90		Magnesia	MgO	14.11
	Quartz	SiO_2	6.22		Quartz	SiO_2	0.64
	Dolomite	$CaMg(CO_3)_2$	3.52		Kalium	K_2O	0.45
PC	Quartz	SiO_2	22.80	LDSS	Belite	Ca_2SiO_4	27.99
	Aluminum Oxide	Al_2O_3	4.75		Brownmillerite	$Ca_2(Al,Fe_3+)_2O_5$	24.59
	Iron Oxide	Fe_2O_3	0.25		Wüstite	FeO	23.42
	Calcium oxide	CaO	69.75		Calcium oxide	CaO	14.02
	Magnesia	MgO	0.56	BFS	Akermanite	$Ca_2Mg(Si_2O_7)$	54.88
	Sulfur oxide	SO_3	1.36		Gehlenite	$Ca_2Al(AlSiO_7)$	38.87
	Fluorine	F	0.39		Marcasite	FeS_2	3.99
	Kalium	K_2O	0.14		Rutile	TiO_2	2.26

BFS. Akermanite and gehlenite are minerals that develop high hardness. In addition, these minerals are considered as ideal pozzolanic phases in cement manufacture, mainly due to their good hydraulic activity (Baptista et al. 2011). Mineralogical results are consistent with those obtained in the XRF test (Table 2) where the predominant chemical component in LS is calcium oxide (CaO), and for BFS, CaO and silica (SiO_2) respectively. Both oxides are pozzolanic compounds and can improve asphalt–aggregate surface adhesion and internal cohesion in the asphalt mixture (Modarres and Rahmanzadeh 2014), increasing its resistance to moisture damage (Nassar et al. 2016). However, a high siliceous content can induce poor moisture damage performance due to a lower adhesion between asphalt and this mineral (Pasandín and Pérez 2015). In addition, it is possible to observe that BFS has a greater quantity of Al_2O_3 than LS. Normally, Al_2O_3 is associated with good adhesion between aggregate and asphalt, increasing rutting resistance for mixtures (Muniandy et al. 2013). LDSS shows similar minerals found in Portland cement. Belite is an industrial mineral with a density of approximately of 3.3 g/cm^3, and it is responsible for development of late strength in concrete. Brownmillerite is the ferrite phase of cement clinker (Hassaan et al. 2004), it appears during the agglomeration of iron ores, and it is one of four main components (>30% by volume) of Portland cements and cement clinkers (Sharygin et al. 2008). This mineral is a material of high density (SG of 3.8, approximately). According to Brand and Roesler (2015), Wüstite (FeO) is a mineral form of iron oxide found in meteorites and native iron, and it is a mineral of high density (5.88 g/cm^3) and hardness. All the minerals reported in Table 3 explain the high density of LDSS. Dehydrated lime was found in LDSS, and this compound can generate volumetric instability and expansion after hydration in presence of moisture (Kuo and Shu 2014; Hesami et al. 2015; Li et al. 2017).

Rheological properties

Multiple stress creep and recovery test

According to FHWA (2008), the multiple stress creep recovery (MSCR) test is an improvement to the Superpave performance graded (PG) asphalt binder specification. The MSCR test specification may be found in ASTM D7405-15, and it is used to identify the presence of elastic response in a binder and change in elastic response at two different shear stress levels. According to ASTM D7405-15, the MSCR test is also useful as a substitute for other test methods used to measure elasticity in asphalt binders, such as ASTM D5801-17, Toughness and Tenacity), ASTM D6084-04 (Elastic Recovery), and ASTM D7175-08 (DSR phase angle). Some of these procedures were specifically designed to indicate polymer modification of asphalt binders. A single MSCR test can provide information about both performance and formulation of the asphalt binder.

Table 4. Penetration and softening point values of asphalt mastics.

	Penetration (mm/10)		Softening point (°C)	
Filler	Mass	Volume	Mass	Volume
LS	28.0	28.0	59.7	59.7
PC	27.8	23.2	64.0	61.8
HL	20.6	17.8	81.0	79.0
LDSS	27.6	24.8	62.0	58.0
BFS	20.8	24.6	62.5	60.3

The potential for permanent deformation of a binder sample is evaluated by subjecting it to cycles of creep and recovery under constant shear stress (τ) levels, using the same DSR apparatus as the one used for PG specification. For each stress level, 10 creep–recovery cycles are applied, each cycle comprising a creep load of 1 s followed by 9 s of creep recovery. The test starts with the application of a low stress (τ = 0.1 kPa) for 10 creep–recovery cycles, and then this stress is increased to τ = 3.2 kPa and repeated for 10 additional cycles. Aside from the prescribed stress levels, an intermediate stress stage of τ = 1.6 kPa was also applied. For each load level and load/recovery cycle, a parameter called nonrecoverable compliance (J_{nr}) is defined as

$$J_{nr}(\tau, N) = \frac{\gamma_r - \gamma_0}{\tau} \tag{1}$$

in which τ is the stress level, N in the cycle index (N = 1, . . ., 10), γ_0 and γ_r are shear strains at the beginning and end of each cycle, respectively.

Another useful parameter obtained from the MSCR test is recovery percentage (R), defined as

$$R(\tau, N) = \frac{\gamma_1 - \gamma_N}{\gamma_1} \times 100 \tag{2}$$

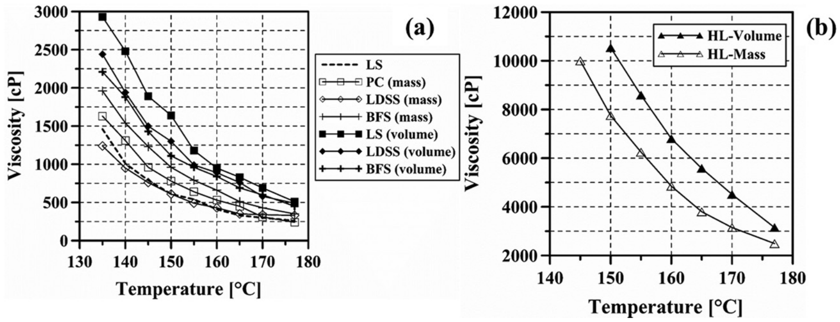
in which γ_1 is the shear strain recorded at the end of 1 s and γ_N is the shear strain recorded at the end of the 10 s creep phase.

Here, the MSCR test was applied to the five types of asphalt binders, using the same setting of 25 mm samples and 1 mm plate gap as for the G^* tests. Tests were performed for the following temperatures: 40, 46, 52, 58, 64, and 70 °C. Prescribed stress levels were τ = 0.1, 1.6, and 3.2 kPa. Five replicates of each binder were tested, and the average values are reported in the results and analysis section.

Complex shear modulus

The complex shear moduli (G^*) of each asphalt mastic was measured under strain-controlled mode using a dynamic shear

Fig. 2. Viscosity results of mastics with (*a*) LS, PC, LDSS and BFS, and (*b*) HL.



rheometer (DSR) (AASHTO T 315). The strain level was 1% and frequency range used was 1–100 rad/s under temperatures of 15, 25, 35, 58, and 64 °C. Samples of 25 mm of diameter and parallel plate of DSR with 1 mm gap were tested. Five duplicate specimens were tested for each individual asphalt mastic, and the average value was reported.

Linear amplitude sweep test

To evaluate fatigue performance and damage tolerance of asphalt mastics at intermediate pavement temperature, linear amplitude sweep (LAS) tests were performed (AASHTO TP 101-14) using a DSR, and RTFOT+PAV (rolling thin film oven test + pressure aging vessel) aged samples of 8 mm parallel plate of DSR and 2 mm gap setting. Tests were performed following the two typical steps recommended: (1) during frequency sweep, samples were subjected to constant shear loading of 0.1% varying loading frequency from 0.2 to 30 Hz, and (2) during amplitude sweep, strain level increased linearly from 0.1% to 30% using a loading frequency of 10 Hz checking the extension of the linear viscoelastic domain. LAS tests were performed under a temperature of 25 °C. Five duplicate specimens were tested by individual asphalt mastic, and the average value was reported.

Results and analysis

Penetration, softening point, and viscosity

Penetration is an empirical test used to measure consistency in asphalt binders, and in some cases, it is indirectly correlated to stiffness. Softening point indicates the temperature at which asphalts reach an arbitrary degree of softening (Mwanza et al. 2012), and it is widely used to evaluate the high temperature susceptibility of asphalts. Furthermore, an increase in this property is generally denoted as an indicator of greater stiffness. Viscosity is used to evaluate the shearing deformation resistance of asphalt at high temperature (Cheng et al. 2016) and also could be correlated with stiffness. Table 4 shows the results of penetration and softening point tests, while the viscosity–temperature curves are illustrated in Fig. 2. Mastics with PC, HL, LDSS, and BFS have lower penetration compared to LS. This could be an indicator of greater mastic stiffness when using PC, HL, LDSS, and BFS as fillers. However, the following observations must be taken into account:

(*i*) By volume, the lowest penetration is observed when the mastic uses HL and PC. This is because increase in stiffness is mainly due to the physical–chemical interactions of these active fillers with asphalt (Little and Petersen 2005; Lesueur et al. 2016) and also due to the adsorption of some of the lighter bitumen components in mineral pores (Wu and Airey 2011).

(*ii*) Contrary to the above, by mass, PC does not significantly influence mastic penetration, since it tends to have less particles compared to the mastic with LS, and therefore, the needle can pass through it easier during the test. A similar behavior and conclusion can be drawn for the mastic with LDSS.

(*iii*) For the case of mastic with BFS, the lowest penetration occurs when analysis is performed by mass, mainly due to the tendency of this mastic to have a greater number of particles, generating greater needle penetration difficulty during the test.

(*iv*) The above described shows that penetration results are influenced by the volume of particles that comprise the mastic.

As in the penetration test, the most evident increases related to softening point occur when the mastic uses HL due to a stiffness increase mainly because of the physical–chemical interactions with the asphalt. Table 4 shows that some softening point results do not agree with penetration results, as for example, for the case of mastic with LDSS by volume, the softening point is lower in comparison to the LS. This can be explained by the fact that during test, LDSS particles tend to separate from asphalt because they are heavier than those of LS, allowing the steel ball to cross the asphalt mastic more easily. A similar trend is reported for the case of mastic with PC. For the case of mastic with BFS and HL, when analysis is performed by mass, the softening point is higher compared to the one analyzed by volume. This is due to the fact that by mass, these two fillers have a greater volume of particles and surface area to be coated with asphalt, which induces the formation of an asphalt mastic with less resistance to allow the passage of the steel ball during the test. The above described shows that softening point results are influenced by the number and weight of particles that comprise the mastic.

As in the previous tests, a higher viscosity (Fig. 2) is obtained when the mastic is made with HL, and changes in the results are observed when analysis is carried out by mass or volume. When analysis is performed by mass, the high viscosity observed in the BFS mastic is explained by the greater number of particles to be displaced to generate torque through the cylindrical spindle during the test, while in the LDSS the lower viscosity is explained through the lower number of particles. For the analysis by volume, it is possible to observe that LDSS and PC mastics have higher viscosity, which can be explained by a greater weight in particles which requires a higher spindle torque. Likewise, it can be seen that by volume, the BFS mastic decreases viscosity in comparison to the analysis performed by mass because the particles are lighter and therefore easier to be displaced by the cylindrical spindle during the test.

Multiple stress creep and recovery test

Figure 3 and Fig. 4 respectively show R and J_{nr} results of an MSCR test performed on asphalt mastics. The asphalt with a lower J_{nr} value and higher R percentages is expected to perform better against rutting. Using HL, BFS, and PC as fillers produced asphalt mastics with higher R percentages and lower J_{nr} than LS under all evaluated temperatures and stresses, which shows an

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Fig. 3. Recovery percentages of asphalt mastics for stress of (*a*) 0.1 kPa, (*b*) 1.6 kPa, and (*c*) 3.2 kPa.

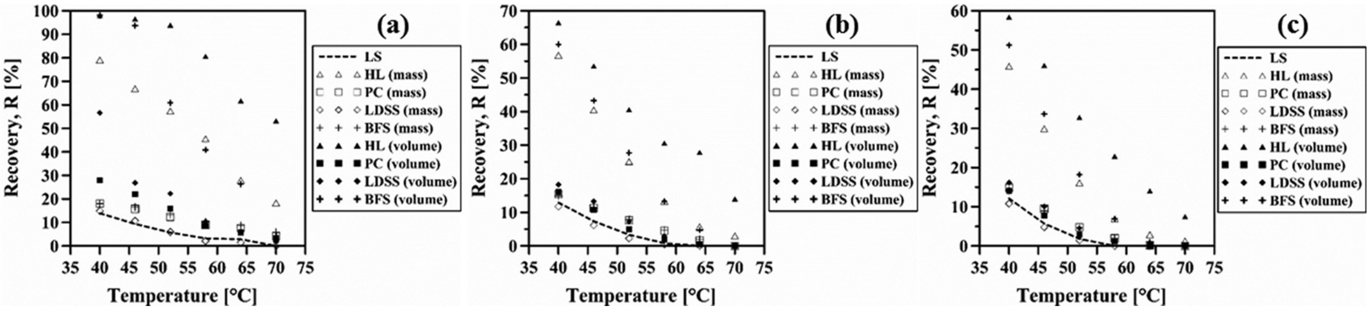
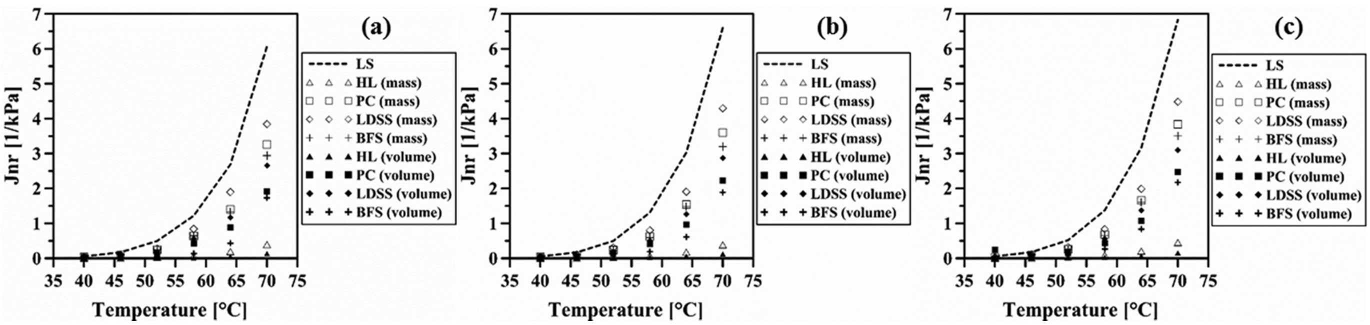


Fig. 4. J_{nr} of asphalt mastics for stresses of (*a*) 0.1 kPa, (*b*) 1.6 kPa, and (c) 3.2 kPa.



increase in permanent deformation resistance. According to the results, HL and BFS mastics have the lowest permanent deformation and highest elastic recovery values in overall deformation for any stress level. On the other hand, by mass, LS mastic showed the lowest resistance to permanent deformation followed by LDSS mastic, while by volume both show similar resistance to deformation. A greater resistance to permanent deformation is observed in mastics when they are analyzed by volume. These results are consistent with those presented previously for softening point and viscosity. However, there is no clear explanation proposed in this regard, since mastic response must be influenced by the number, weight, shape, and porosity of filler particles, as well as their physical–chemical interactions with asphalt.

Complex shear modulus

Figure 5 shows that the G^* increases with the rise of frequency. G^* is related with strength and overall stiffness of asphalt mastics (Cheng et al. 2016). Using HL, PC, LDSS, and BFS as filler resulted in increased stiffness of asphalt mastics compared to LS, as shown by the increment of G^*. At high temperatures (58 and 64 °C), the results of G^* are consistent with those of MSCR. Based on the results, it is possible to observe that

- HL mastic is stiffer for any temperature, and this is more evident when temperature increases. This result is consistent with all those presented previously (MSCR, viscosity, softening point and penetration). Furthermore, by volume, HL mastic presents higher G^* values than by mass and this was more evident at high temperatures (58 to 64 °C).
- BFS mastic is stiffer than LS by volume, especially at intermediate temperatures (15 to 35 °C). For high temperatures (58 to 64 °C), the increase in G^* is less noticeable. By mass, G^* values are also higher than those of LS; however, it is lower when compared to the volume dosage and its magnitude is similar to that of PC and LDSS mastics.
- PC and LDSS mastics present similar G^* values. When performing volume analysis, they have higher G^* values under temperatures of 15 and 25 °C if compared to LS mastic; however, with increasing temperature (35, 58, and 64 °C), stiffness tends to be similar to that of LS. Contrary to HL and BFS, PC and LDSS mastics tend to reach higher stiffness values by mass than by volume at intermediate temperatures (15 to 35 °C). For high temperatures, G^* does not undergo significant changes when analysis is performed by mass or volume.

Linear amplitude sweep test - LAS

Figure 6 represents load cycle number variation in relation to failure against the applied strain level amplitude obtained from LAS data analysis. Using HL, PC, LDSS, and BFS as filler resulted in an increase of fatigue resistance compared to LS. By mass, LDSS and HL mastics present the highest fatigue strengths. For the case of LDSS, this behavior is perhaps due to the smaller number of particles, which generate a more ductile mastic with a higher concentration of asphalt. A similar conclusion can be reported for BFS mastic since, by volume, it has less particles and for such reason perhaps greater fatigue resistance is observed. For the case of PC mastics, their behavior should be similar to LDSS mastic due to its high SG, but in this case, the observed behavior changed perhaps due to physical–chemical reactions, which were not measured in the present study. By volume, HL mastic tends to noticeably decrease its fatigue resistance as deformation level increases due to its high stiffness (brittle behavior).

Conclusions

Most of the research conducted on asphalt mastics evaluates their properties comparing and dosing by mass since it is simpler and more practical. However, fillers can have different volumetric and gravimetric properties, and in this case, the number, volume, and weight of particles can differ significantly and affect results. Therefore, to make a better comparison of filler effects on asphalt mastic properties, analysis and dosage are more appropriate by volume. Based on the results obtained in this

Fig. 5. Evolution of G^* with load frequency for (*a*) 15 °C, (*b*) 25 °C, (*c*) 35 °C, (*d*) 58 °C, and (*e*) 64 °C.

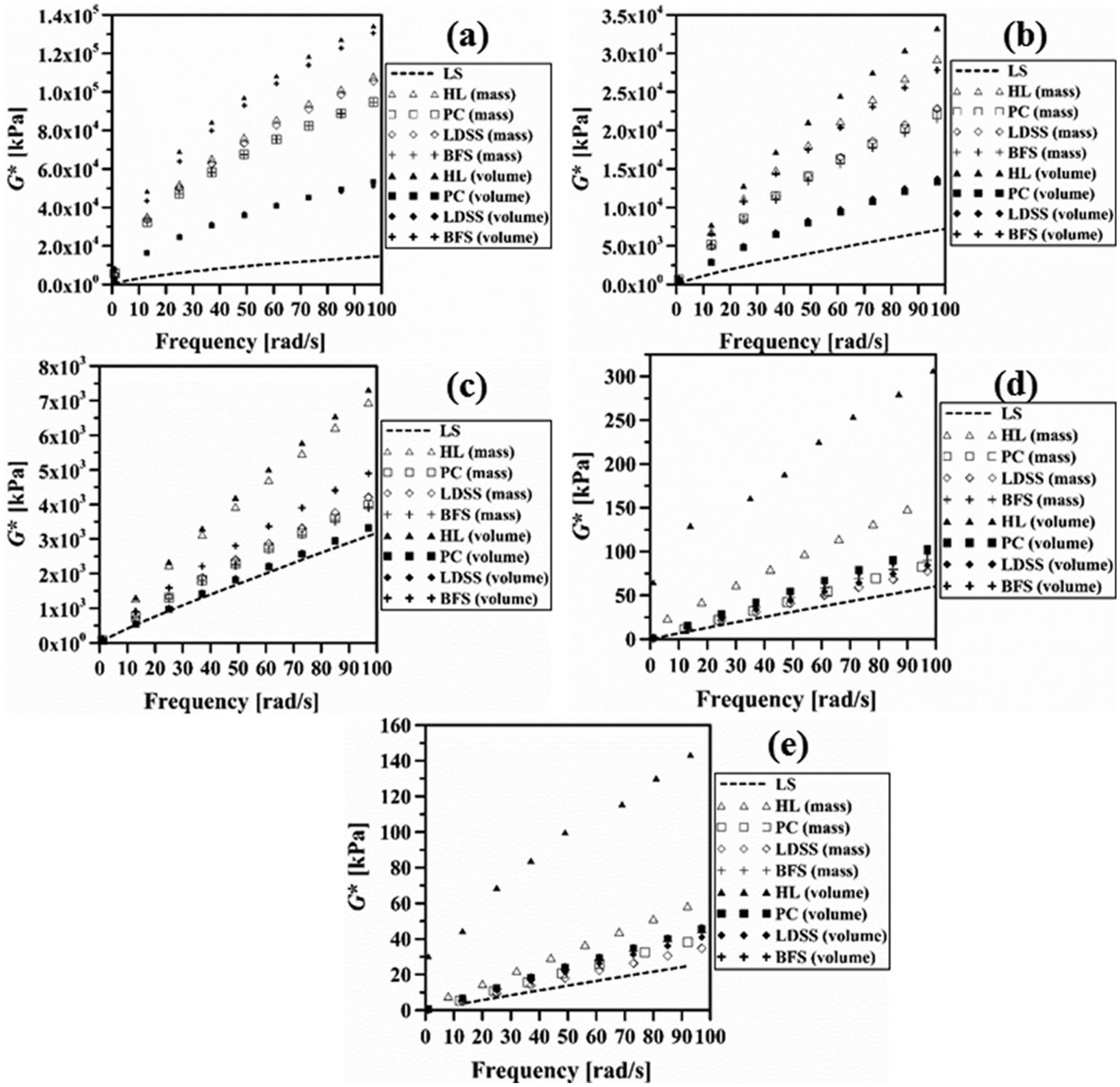
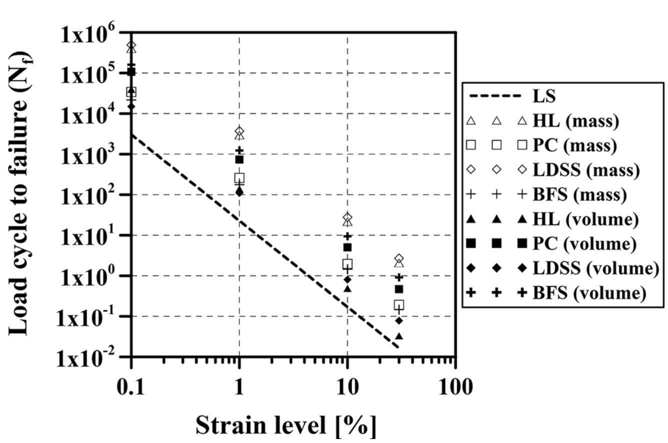


Fig. 6. Variation of fatigue life for the different mastics.



research, it is possible to conclude that the properties of analyzed asphalt mastics depend on dosage type performed (by mass or by volume). Furthermore, the way that some tests are conducted influenced results. For example, on the penetration test, the needle will have greater resistance in puncturing the asphalt mastic when particle volume is greater; for the case of softening point, steel balls tend to go through the asphalt mastic more easily during testing when filler weight is greater; and for the viscosity test, a greater volume and weight of particles requires a higher torque to rotate the cylindrical spindle in the asphalt mastic.

Some conclusions obtained from rheological characterization are:

(*i*) In general terms, mastics produced with hydrated lime (HL), Portland cement (PC), blast furnace slag (BFS), and Linz-Donawitz steel slag (LDSS) showed better performance (greater resistance to rutting at high temperatures and fatigue) compared to the control mastic, using natural limestone aggregate;

(*ii*) Hydrated lime and blast furnace slag mastics (particles with lower specific gravity, G_s) tended to generate greater G^* by volume in comparison to mass analysis. Contrary to the above, for the case of blast furnace slag and Linz-Donawitz steel slag mastics (particles with greater G_s), higher values of stiffness G^* were obtained when dosage was performed by mass;

(*iii*) In the MSCR test, it was observed that asphalt mastics were more resistant to rutting when analysis was performed by volume (higher recovery R and lower J_{nr}).

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(*iv*) In the linear amplitude sweep (LAS) test, the highest fatigue strengths were observed when the asphalt mastics tended to have lower particle contents (LDSS mastic by mass and BFS mastic by volume), greater amount of asphalt and more ductile behavior, except for the PC mastic where some physical–chemical interactions may have occurred but were not measured.

(*v*) Future studies must be carried out, with the purpose of evaluating and comparing results obtained in the foregoing research on mastics, along with the mechanical performance of asphaltic mixtures.

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References

Akbulut, H., Gürer, C., Çetin, S., and Elmacı, A. 2012. Investigation of using granite sludge as filler in bituminous hot mixtures. Construction and Building Materials, **36**: 430–436. doi:10.1016/j.conbuildmat.2012.04.069.

Al-Hdabi, A., and Al-Nageim, H. 2017. Improving asphalt emulsion mixtures properties containing cementitious filler by adding GGBS. Journal of Materials in Civil Engineering, **29**(5): 04016297. doi:10.1061/(ASCE)MT.1943-5533.0001859.

Al-Khateeb, G.G., Irfaeya, M.F., and Khedaywi, T.S. 2017. A new simplified micromechanical model for asphalt mastic behavior. Construction and Building Materials, **149**: 587–598. doi:10.1016/j.conbuildmat.2017.05.129.

Anderson, D.A., and Goetz, W.H. 1973. Mechanical behavior and reinforcement of mineral filler-asphalt mixtures. Proceedings of the Association of Asphalt Paving Technologists, **42**: 37–66.

Antunes, V., Freire, A.C., Quaresma, L., and Micaelo, R. 2015. Influence of the geometrical and physical properties of filler in the filler–bitumen interaction. Construction and Building Materials, **76**: 322–329. doi:10.1016/j.conbuildmat.2014.12.008.

Antunes, V., Freire, A.C., Quaresma, L., and Micaelo, R. 2016. Effect of the chemical composition of fillers in the filler–bitumen interaction. Construction and Building Materials, **104**: 85–91. doi:10.1016/j.conbuildmat.2015.12.042.

Baker, M.I.B., Abendeh, R.M., and Obaidat, T.A. 2018. Employing natural bentonite clay as partial replacement of mineral filler in asphalt mixtures. Journal of Materials in Civil Engineering, **30**(8): 04018167. doi:10.1061/(ASCE)MT.1943-5533.0002375.

Baptista, L.A., Aparecido, E., Soares, J.A., Fiorotti, R.A., and de Oliveira, J.R. 2011. Characterization of mixed waste of granite and LD slag. Metallurgy and Materials, **64**(2): 169–174. doi:10.1590/S0370-44672011000200006.

Beckhoff, B., Kanngießer, B., Langhoff, N., Wedell, R., and Wolff, H. 2006. Handbook of practical X-Ray fluorescence analysis. Springer, New York.

Brand, A.S., and Roesler, J.R. 2015. Steel furnace slag aggregate expansion and hardened concrete properties. Cement and Concrete Composites, **60**: 1–9. doi:10.1016/j.cemconcomp.2015.04.006.

Chandra, S., and Choudhary, R. 2013. Performance characteristics of bituminous concrete with industrial wastes as filler. Journal of Materials in Civil Engineering, **25**(11): 1666–1673. doi:10.1061/(ASCE)MT.1943-5533.0000730.

Chen, J., and Peng, C. 1998. Analyses of tensile failure properties of asphalt-mineral filler mastics. Journal of Materials in Civil Engineering, **10**(4): 256–262. doi:10.1061/(ASCE)0899-1561(1998)10:4(256).

Chen, M., Lin, J., Wu, S., and Liu, C. 2011. Utilization of recycled brick powder as alternative filler in asphalt mixture. Construction and Building Materials, **25**(4): 1532–1536. doi:10.1016/j.conbuildmat.2010.08.005.

Cheng, Y., Tao, J., Jiao, Y., Tan, G., Guo, Q., Wang, S., and Ni, P. 2016. Influence of the properties of filler on high and medium temperature performances of asphalt mastic. Construction and Building Materials, **118**: 268–275. doi:10.1016/j.conbuildmat.2016.05.041.

Cosme, R.L., Teixeira, J., and Calmon, J.L. 2016. Use of frequency sweep and MSCR tests to characterize asphalt mastics containing ornamental stone residues and LD steel slag. Construction and Building Materials, **122**: 556–566. doi:10.1016/j.conbuildmat.2016.06.126.

Dan, L., Chuanfeng, Z., Yong, Q., Heng, B., Keyao, L., and Junfei, H. 2014. Analysing the effects of the mesoscopic characteristics of mineral powder fillers on the cohesive strength of asphalt mortars at low temperatures. Construction and Building Materials, **65**: 330–337. doi:10.1016/j.conbuildmat.2014.04.123.

Das, A.K., and Singh, D. 2017. Investigation of rutting, fracture and thermal cracking behavior of asphalt mastic containing basalt and hydrated lime fillers. Construction and Building Materials, **141**: 442–452. doi:10.1016/j.conbuildmat.2017.03.032.

Das, A.K., and Singh, D. 2018. Effects of basalt and hydrated lime fillers on rheological and fracture cracking behavior of polymer modified asphalt mastic. Journal of Materials in Civil Engineering, **30**(3): 04018011. doi:10.1061/(ASCE)MT.1943-5533.0002196.

Davis, C., and Castorena, C. 2015. Implications of physico–chemical interactions in asphalt mastics on asphalt microstructure. Construction and Building Materials, **94**: 83–89. doi:10.1016/j.conbuildmat.2015.06.026.

Departamento Nacional de Infraestrutura de Transportes (DNIT). 2004. Pavimento rígido – Pavimento de concreto de cimento Portland - Especificação de serviço. NORMA DNIT 059/2004—ES. DNIT, Rio de Janeiro, Brazil.

Departamento Nacional de Infraestrutura de Transportes (DNIT). 2006. Pavimentos flexíveis—Concreto asfáltico—Especificação de service. NORMA DNIT 031/2006—ES. DNIT, Rio de Janeiro, Brazil.

Diab, A., and You, Z. 2018. Linear and nonlinear rheological properties of bituminous mastics under large amplitude oscillatory shear testing. Journal of Materials in Civil Engineering, **30**(3): 04017303. doi:10.1061/(ASCE)MT.1943-5533.0002179.

Federal Highway Administration (FHWA). 2008. Coordinating, developing, and delivering highway transportation innovations—User guidelines for waste and byproduct materials in pavement construction. Rep. Publication No. FHWA-RD-97-148. FHWA, Washington, D.C.

Giustozzi, F., Mansour, K., Patti, F., Pannirselvam, M., and Fiori, F. 2018. Shear rheology and microstructure of mining material-bitumen composites as filler replacement in asphalt mastics. Construction and Building Materials, **171**: 726–735. doi:10.1016/j.conbuildmat.2018.03.190.

Gundla, A., Medina, J., Gudipudi, P., Stevens, R., Salim, R., Zeiada, W., and Underwood, B.S. 2016. Investigation of aging in hydrated lime and Portland cement modified asphalt concrete at multiple length scales. Journal of Materials in Civil Engineering, **28**(5): 04015205. doi:10.1061/(ASCE)MT.1943-5533.0001501.

Hassaan, M.Y., Ebrahim, F.M., and Salah, S.H. 2004. Variation of some physical properties of Brownmillerite doped with a transition metal oxide. Hyperfine Interactions, **156**/**157**(1–4): 459–464. doi:10.1023/B:HYPE.0000043297.21256.73.

Hesami, S., Ameri, M., Goli, H., and Akbari, A. 2015. Laboratory investigation of moisture susceptibility of warm-mix asphalt mixtures containing steel slag aggregates. International Journal of Pavement Engineering, **16**(8): 745–759. doi:10.1080/10298436.2014.953502.

Heukelom, W. 1965. The role of filler in bituminous mixes. Proceedings of the Association of Asphalt Paving Technologists Technical Sessions, **34**: 396–429.

Karasahin, M., and Terzi, S. 2007. Evaluation of marble waste dust in the mixture of asphaltic concrete. Construction and Building Materials, **21**(3): 616–620. doi:10.1016/j.conbuildmat.2005.12.001.

Katamine, N.M. 2000. Phosphate waste in mixtures to improve their deformation. Journal of Transportation Engineering, **126**: 382–389. doi:10.1061/(ASCE)0733-947X(2000)126:5(382).

Korayem, A.H., Ziari, H., Hajiloo, M., and Moniri, A. 2018. Rutting and fatigue performance of asphalt mixtures containing amorphous carbon as filler and binder modifier. Construction and Building Materials, **188**: 905–914. doi:10.1016/j.conbuildmat.2018.08.179.

Kuity, A., and Das, A. 2015. Homogeneity of filler distribution within asphalt mix – A microscopic Study. Construction and Building Materials, **95**: 497–505. doi:10.1016/j.conbuildmat.2015.07.043.

Kuity, A., Jayaprakasan, S., and Das, A. 2014. Laboratory investigation on volume proportioning scheme of mineral fillers in asphalt mixture. Construction and Building Materials, **68**: 637–643. doi:10.1016/j.conbuildmat.2014.07.012.

Kuo, W.T., and Shu, C.Y. 2014. Application of high-temperature rapid catalytic technology to forecast the volumetric stability behavior of containing steel slag mixtures. Construction and Building Materials, **50**: 463–470. doi:10.1016/j.conbuildmat.2013.09.030.

Kütük-Sert, T., and Kütük, S. 2013. Physical and Marshall properties of borogypsum used as filler aggregate in asphalt concrete. Journal of Materials in Civil Engineering, **25**(2): 266–273. doi:10.1061/(ASCE)MT.1943-5533.0000580.

Lackner, R., Spiegl, M., Blab, R., and Eberhardsteiner, J. 2005. Is low-temperature creep of asphalt mastic independent of filler shape and mineralogy?—Arguments from multiscale analysis. Journal of Materials in Civil Engineering, **17**(5): 485–491. doi:10.1061/(ASCE)0899-1561(2005)17:5(485).

Lesueur, D., Teixeira, A., Lázaro, M.M., Andaluz, D., and Ruiz, A. 2016. A simple test method in order to assess the effect of mineral fillers on bitumen ageing. Construction and Building Materials, **117**: 182–189. doi:10.1016/j.conbuildmat.2016.05.003.

Li, C., Chen, Z., Wu, S., Li, B., Xie, J., and Xiao, Y. 2017. Effects of steel slag fillers on the rheological properties of asphalt mastic. Construction and Building Materials, **145**: 383–391. doi:10.1016/j.conbuildmat.2017.04.034.

Liao, M., Chen, J., and Tsou, K. 2012. Fatigue characteristics of bitumen-filler mastics and asphalt mixtures. Journal of Materials in Civil Engineering, **24**(7): 916–923. doi:10.1061/(ASCE)MT.1943-5533.0000450.

Little, D.N., and Petersen, J.C. 2005. Unique effects of hydrated lime filler on the performance-related properties of asphalt cements: physical and chemical interactions revisited. Journal of Materials in Civil Engineering, **17**(2): 207–218. doi:10.1061/(ASCE)0899-1561(2005)17:2(207).

Liu, J., Yan, K., and Liu, J. 2018. Rheological characteristics of polyphosphoric acid–modified asphalt mastic. Journal of Materials in Civil Engineering, **30**(12): 06018021. doi:10.1061/(ASCE)MT.1943-5533.0002555.

Liu, Q., Wu, S., and Schlangen, E. 2013. Induction heating of asphalt mastic for crack control. Construction and Building Materials, **41**: 345–351. doi:10.1016/j.conbuildmat.2012.11.075.

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Liu, X., Liu, W., Wang, S., and Wang, Z. 2018*b*. Performance evaluation of asphalt mixture with nanosized volcanic ash filler. Journal of Transportation Engineering, Part B: Pavements, **144**(3): 04018028. doi:10.1061/JPEODX.0000060.

Liu, X., Zhang, M., Shao, L., and Chen, Z. 2018*c*. Effect of volcanic ash filler on thermal viscoelastic property of SBS modified asphalt mastic. Construction and Building Materials, **190**: 495–507. doi:10.1016/j.conbuildmat.2018.09.101.

Modarres, A., and Rahmanzadeh, M. 2014. Application of coal waste powder as filler in hot mix asphalt. Construction and Building Materials, **66**: 476–483. doi:10.1016/j.conbuildmat.2014.06.002.

Moon, K.H., Falchetto, A.C., Park, J.Y., and Jeong, J.H. 2014. Development of high performance asphalt mastic using fine taconite filler. KSCE Journal of Civil Engineering, **18**(6): 1679–1687. doi:10.1007/s12205-014-1207-6.

Movilla-Quesada, D., Raposeiras, A.C., Castro-Fresno, D., and Peña-Mansilla, D. 2015. Experimental study on stiffness development of asphalt mixture containing cement and $Ca(OH)_2$ as contribution filler. Materials and Design, **74**: 157–163. doi:10.1016/j.matdes.2015.02.026.

Muniandy, R., Aburkaba, E., and Mahdi, L. 2013. Effect of mineral filler type and particle size on asphalt-filler mastic and stone mastic asphalt laboratory measured properties. Australian Journal of Basic and Applied Sciences, **7**(11): 475–487.

Muniz de Farias, M., Quiñonez Sinisterra, F., and Rondón Quintana, H.A. 2019. Behavior of a hot mix asphalt made with recycled concrete aggregate and crumb rubber. Canadian Journal of Civil Engineering, **46**(6): 544–551. doi:10.1139/cjce-2018-0443.

Mwanza, A.D., Hao, P., and Wang, H. 2012. Effects of type and content of mineral fillers on the consistency properties of asphalt mastic. Journal of Testing and Evaluation, **40**(7): 1094–1102. doi:10.1520/JTE20120140.

Nassar, A.I., Mohammed, M.K., Thom, N., and Parry, T. 2016. Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler. Construction and Building Materials, **114**: 352–363. doi:10.1016/j.conbuildmat.2016.03.112.

Ortega-López, V., Fuente-Alonso, J.A., Santamaría, A., and Manso, J.M. 2016. Ladle furnace slag in asphalt mixes. Construction and Building Materials, **122**: 488–495. doi:10.1016/j.conbuildmat.2016.06.085.

Pasandín, A.R., and Pérez, I. 2015. The influence of the mineral filler on the adhesion between aggregates and bitumen. International Journal of Adhesion and Adhesives, **58**: 53–58. doi:10.1016/j.ijadhadh.2015.01.005.

Pei, J., Fan, Z., Wang, P., Zhang, J., Xue, B., and Li, R. 2015. Micromechanics prediction of effective modulus for asphalt mastic considering inter-particle interaction. Construction and Building Materials, **101**: 209–216. doi:10.1016/j.conbuildmat.2015.10.053.

Pereira, L., Freire, A.C., Sá da Costa, M., Antunes, V., Quaresma, L., and Micaelo, R. 2018. Experimental study of the effect of filler on the ductility of filler-bitumen mastics. Construction and Building Materials, **189**: 1045–1053. doi:10.1016/j.conbuildmat.2018.09.063.

Qian, G., Bai, S., Ju, S., and Huang, T. 2013. Laboratory evaluation on recycling waste phosphorus slag as the mineral filler in hot-mix asphalt. Journal of Materials in Civil Engineering, **25**(7): 846–850. doi:10.1061/(ASCE)MT.1943-5533.0000770.

Richardson, C. 1915. The theory of the perfect sheet asphalt surface. Journal of Industrial Engineering and Chemistry, **7**: 463–465.

Rigden, P.J. 1947. The use of fillers in bituminous road surfacings: A study of filler-binder systems in relation to filler characteristics. Journal of the Society of Chemical Industry, **66**(9): 299–309. doi:10.1002/jctb.5000660902.

Robati, M., Carter, A., and Perraton, D. 2015. New conceptual model for filler stiffening effect on asphalt mastic of microsurfacing. Journal of Materials in Civil Engineering, **27**(11): 04015033. doi:10.1061/(ASCE)MT.1943-5533.0001264.

Rondón, H.A., Ruge, J.C., and Muniz de Farias, M. 2019. Behavior of a hot mix asphalt containing blast furnace slag as aggregate: evaluation by mass and volume substitution. Journal of Materials in Civil Engineering, **31**(2): 04018364. doi:10.1061/(ASCE)MT.1943-5533.0002574.

Rondón, H.A., Ruge, J.C., Patiño, D.F., Vacca, H.A., Reyes, F.A., and Farias, M.M. 2018. Use of blast furnace slag as a substitute for the fine fraction of aggregates in an asphalt mixture. Journal of Materials in Civil Engineering, **30**(10): 04018244. doi:10.1061/(ASCE)MT.1943-5533.0002409.

Sangiorgi, C., Tataranni, P., Simone, A., Vignali, V., Lantieri, C., and Dondi, G. 2016. Assessment of waste bleaching clay as alternative filler for the production of porous asphalts. Construction and Building Materials, **109**: 1–7. doi:10.1016/j.conbuildmat.2016.01.052.

Sargın, S., Saltan, M., Morova, N., Serin, S., and Terzi, S. 2013. Evaluation of rice husk ash as filler in hot mix asphalt concrete. Construction and Building Materials, **48**: 390–397. doi:10.1016/j.conbuildmat.2013.06.029.

Sharma, V., Chandra, S., and Choudhary, R. 2010. Characterization of fly ash bituminous concrete mixes. Journal of Materials in Civil Engineering, **22**(12): 1209–1216. doi:10.1061/(ASCE)MT.1943-5533.0000125.

Sharygin, V.V., Sokol, E.V., and Vapnik, Y. 2008. Minerals of the pseudobinary perovskite-brownmillerite series from combustion metamorphic larnite rocks of the Hatrurim Formation (Israel). Russian Geology and Geophysics, **49**(10): 709–726. doi:10.1016/j.rgg.2008.03.001.

Sung, D.H., Mun, P.H., and Keun, P.S. 2008. A study on engineering characteristics of asphalt concrete using filler with recycled waste lime. Waste Management, **28**(1): 191–200. doi:10.1016/j.wasman.2006.11.011.

Taha, R., Al-Rawas, A., Al-Harthy, A., and Qatan, A. 2002. Use of cement bypass dust as filler in asphalt concrete mixtures. Journal of Materials in Civil Engineering, **14**(4): 338–343. doi:10.1061/(ASCE)0899-1561(2002)14:4(338).

Tenza-Abril, A.J., Saval, J.M., and Cuenca, A. 2015. Using sewage-sludge ash as filler in bituminous mixes. Journal of Materials in Civil Engineering, **27**(4): 04014141. doi:10.1061/(ASCE)MT.1943-5533.0001087.

Traxler, R.N. 1937. The evaluation of mineral powders as fillers for asphalt. Proceedings of the Association of Asphalt Paving Technologists, **8**: 60–68.

Veytskin, Y., Bobko, C., Castorena, C., and Kim, Y.R. 2015. Nanoindentation investigation of asphalt binder and mastic cohesion. Construction and Building Materials, **100**: 163–171. doi:10.1016/j.conbuildmat.2015.09.053.

Wu, S., Zhu, J., Zhong, J., and Wang, D. 2011. Experimental investigation on related properties of asphalt mastic containing recycled red brick powder. Construction and Building Materials, **25**(6): 2883–2887. doi:10.1016/j.conbuildmat.2010.12.040.

Wu, J., and Airey, G. 2011. The influence of mineral fillers on mastic aging properties. *In* Proceedings of the 11th International Conference of Chinese Transportation Professionals (ICCTP 2011). ASCE, Nanjing, China, pp. 3450–3461. doi:10.1061/41186(421)342.

Yi, J., Cao, Y., Feng, D., and Huang, Y. 2016. Characterization of zirconium tungstate filler and performance investigation on asphalt mastic made with zirconium tungstate filler. Construction and Building Materials, **125**: 387–397. doi:10.1016/j.conbuildmat.2016.08.074.

Yi-Qiu, T., Li, Z., Zhang, X., and Dong, Z. 2010. Research on high- and low-temperature properties of asphalt-mineral filler mastic. Journal of Materials in Civil Engineering, **22**(8): 811–819. doi:10.1061/(ASCE)MT.1943-5533.0000015.

Yiqiu, T., Xiaolin, L., and Jiantao, W. 2012. Internal influence factors of asphalt-aggregate filler interactions based on rheological characteristics. Journal of Materials in Civil Engineering, **24**(12): 1520–1528. doi:10.1061/(ASCE)MT.1943-5533.0000506.

Zhang, G., Germaine, J., Torrence, M., and Whittle, A.A. 2003. A simple sample-mounting method for random powder X-RAY diffraction. Clays and Clay Minerals, **51**(2): 218–255. doi:10.1346/CCMN.2003.0510212.

Zhang, J., Liu, S., Yao, Z., Wu, S., Jiang, H., Liang, M., and Qiao, Y. 2018. Environmental aspects and pavement properties of red mud waste as the replacement of mineral filler in asphalt mixture. Construction and Building Materials, **180**: 605–613. doi:10.1016/j.conbuildmat.2018.05.268.

Zhu, X. 2013. Influence of interfacial zone between asphalt mastic and aggregate on the elastic behavior of asphalt concrete. Construction and Building Materials, **49**: 797–806. doi:10.1016/j.conbuildmat.2013.08.072.

Zulkati, A., Diew, W.Y., and Delai, D.S. 2012. Effects of fillers on properties of asphalt-concrete mixture. Journal of Transportation Engineering, **138**(7): 902–910. doi:10.1061/(ASCE)TE.1943-5436.0000395.