RBEC REVISTA BRASILEIRA ENGENHARIA CIVIL
V.1 N.2

Effect of basalt powder and metakaolin fillers on asphalt mastic behavior

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Abstract

Asphalt mastic is the mix between filler and the asphalt binder that can influence the mixture's compaction characteristics and the optimal asphalt content. Filler is defined as the mineral portion that passes through the sieve nº. 200 and it acts in the asphalt mixture by filling voids and modifying the viscosity, elasticity, and thermal susceptibility of asphalt binders. This study sought to determine the influence of different filler types and amounts on asphalt mastics' behavior. For this, physical tests, such as penetration, softening point, ductility, and elastic recovery were performed to evaluate the characteristics of binder and mastics with filler addition. The filler types used were basalt powder and metakaolin in the proportion of 0.6 and 1.2 filler/asphalt. The fillers' additions significantly influenced the mastic, and metakaolin had a more considerable effect on asphalt binder behavior than basalt powder. It made the mastic more rigid, more viscous, less elastic, and less susceptible to temperature. These changes are strong insights that the filler insertion improves the mixture performance regarding fatigue cracking and permanent deformation.

Keywords: asphalt mastic, filler, binder, asphalt mixture.

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INTRODUCTION

The primary objective of paving a road is to provide an operational improvement of traffic, achieving efficient, safe, and fast flow of vehicles. Pavements are designed for structural and functional purposes. First, the structural aims are to reduce and distribute traffic loads to the subgrade considering the weather and expected traffic. Besides, it is essential that the pavement functionality meet users' needs regarding safety and comfort.

In flexible pavements, dynamic loads caused by traffic generate stresses in the asphalt layer, such as compression, tensile, and shear stresses. The repetition of stresses and deformations caused by compression and shear is responsible for the permanent deformations that, accumulated over time, form the rutting. Simultaneously, bending moments generate stresses and tensile deformations at the bottom of the asphalt surface course, which, when acting repeatedly, cause fatigue cracking of the asphalt concrete.

In this scenario, asphalt layers must be formulated and designed to minimize the main phenomena that contribute to reducing the useful life of asphalt pavements: fatigue cracking and permanent deformation (Bardini, 2013).

Asphalt concrete mixture is a multi-level structure system that is composed of asphalt binder, aggregates, and filler. Formulating the mixture is a complex task that aims to balance asphalt concrete's susceptibility to the two leading causes of defects in asphalt pavements by choosing a design asphalt content for a predefined granulometric distribution. When selecting this asphalt content, the main controlled characteristics are the volume of air voids (Va), the voids filled with asphalt (VFA), and the volume of voids in the mineral aggregate (VMA) (Antunes et al., 2016). In this situation, fillers' association with the available asphalt binder represents the formation of the so-called asphalt mastic. The mastic affects the lubrication between the larger aggregates, the volume of voids in the mineral aggregate mixture, and, consequently, the compaction characteristics and the design asphalt content. The quality of this mastic is dependent on the type and quantity of asphalt and filler.

Filler definition is a fraction of mineral dust that passes the 200-mesh sieve. It fills the voids between the coarse aggregates in the asphalt mixes, increasing its density, stability, and rigidity, and it also changes the properties of the asphalt binders. Particles smaller than 0.020 mm incorporate the asphalt binder and form the mastic. The quality of the mastic is directly related to the quality of the asphalt mixture and its workability. Particles larger than 0.040 mm function is to fill the voids, close the mix, and modify its resistance to water and aging (Bardini, 2013).

However, the relationship between the benefits of adding filler and the amount of asphalt binder available is not linear. The high amount of filler in an asphalt mix negatively affects the mastic workability, flexibility, and durability. The fillers change the mastic's stiffness and, consequently, the asphalt mixture's behavior concerning permanent deformation at high temperatures and fatigue at intermediate temperatures (Bardini et al., 2010). Fatigue occurs due the development and growth of microcracks in the mastic. It is related to the asphalt binder's characteristics, filler's properties, and physical-chemical interaction between these two materials.

Several studies have suggested that the filler proportion on the mastic and its physical properties, such as size, shape, void space, and surface characteristics significantly influence the physical-chemical interaction between asphalt binder and filler (Bardini, 2013; Kavussi and Hicks 1997; Liao et al., 2012; Zhu et al., 2018). Thus, the main purpose of this work is to analyze the effects of the amount of two different filler types in an asphalt mastic formulation and behavior using polymer-modified petroleum asphalt cement.

FILLER

The filler can be defined as a material that has more than 65% of its particles passing through the 200-mesh sieve (DNER-ME, 1997) or as a material derived mainly from coarse and fine aggregates that are used in asphalt mixtures and can improve the rheological, mechanical, thermal and water sensitivity behavior (Santana, 1995. In addition, Santana (1995) points out that the use of filler in the asphalt mixture improves the consistency uniformity and thermal susceptibility.

According to Barra (2005), the filler can act in two different ways in the asphalt mixture due to its granulometry — the larger particles as aggregate and the smaller ones as active filler. The filler working as a fraction of the aggregate is a fine and inert material that acts to fill the voids and promotes the contact between the larger particles, promoting greater resistance of the mixture. The active filler acts in the formation of the mastic because it is a particle in suspension. The mastic is the mixture of the filler with the asphalt binder to form a matrix that involves the coarse aggregates and fills the asphalt mixture's voids (Bardini, 2013). The asphalt mixture's behavior is significantly affected by the rheological characteristics of the asphalt mastic (Bechara et al., 2008).

In the formation of asphalt mastic, the active portion of the filler mixes with the binder, increasing the consistency and cementing the larger parts, which provides changes in the binder's viscosity and elasticity (Traxler, 1937). The filler's function that will predominate depends on several factors: the granulometry of the aggregates, degree of compaction, the thickness of the binder film, and filler/binder ratio.

The filler influences the asphalt mixture's properties by increasing the mastic stiffness, decreasing thermal susceptibility, and increasing its stability. However, as pointed out by Faheem et al. (2008), Kavussi and Hicks (1997), and Zhu et al. (2018), the results of the interaction between the filler and changes in the mixture depend mainly on the type of filler (gradation and texture), its nature (mineralogical composition and physical-chemical activity), and the content of filling material in the mixture.

TYPES OF FILLER

There are different types of materials that have been used as filler in asphalt mixtures. Between them, limestone, cement, and aggregate dust are the most commonly used. In recent years, the replacement of mineral filler by waste materials, such as fly ash, glass powder, slag powder, brick powder, and waste concrete powder, has been studied (Taherkhani and Kamsari, 2020).

Among the sources and types of fillers, there are those derived from the aggregate's larger fractions, such as basalt powder, and industrialized ones such as lime, cement, and metakaolin. Basalt is a fine-grained eruptive igneous rock, known for its hardness between 4.8 to 7. Basalt is rich in magnesium and iron silicates and has a basic characteristic that can improve adhesion to the asphalt binder (Bernucci et al., 2007).

Additionally, the type of filler influences other characteristics of the mixture. According to Bardini (2013), Portland cement used as filler in dense asphalt mixes has a better behavior in terms of tensile strength concerning limestone powder, hydrated lime, and silica. For Barra et al. (2005), fillers' active behavior is not related to the size of the particles but mainly to their shape, surface texture, specific surface area, and mineralogical nature. On the other hand, Motta and Leite (2000) point out that the thinner filler must be associated with a lower filler-binder ratio because it will reduce the aggregate covering's thickness, changing the properties of the mixture.

In this context, metakaolin appears as an alternative for replacing fillers derived from natural rocks. Metakaolin in a very fine powder, characterized by particles with an average diameter of 12.4 µm. However, this material has a pozzolanic characteristic, consisting basically of silica (SiO2) and alumina (Al2O3) in the amorphous phase, which can impair the adhesion characteristics of the mixture with asphalt binders.

FILLER'S INFLUENCE ON THE PERFORMANCE OF THE MIXTURE PERFORMANCE

The presence of filler in the asphalt mixture modifies some physical-chemical properties of the mixture, affects the workability and flexibility during the mixing and compaction process and increases the optimal asphalt content due to the dust higher surface area and absorption potential (Zulkati et al., 2012). The addition of filler to the asphalt mix can affect the mastic response to the pavement's main defects, such as fatigue cracking and rutting (Taherkhani and Kamsari, 2020).

According to Liao et al. (2012), the addition of filler to asphalt concrete makes it stiffer and the filler particles interrupt the crack growth in the mastic, influencing the fatigue life of the mixture. Besides, the filling material fills the voids in the mixture and promotes the best interaction between the mastic and the aggregates, leading to longer fatigue life Bardini (2013).

The resistance of asphalt mixture to permanent deformation is related to the stiffness of asphalt binder, mixture volumetrics, and the bonding interaction between asphalt binders and aggregate. The addition of filler, increases the stiffness of the mixture and improves it density and strength, consequently improving rutting resistance (Wang et al., 2011). Besides, the presence of filler decreases the mastic temperature susceptibility, which is an important characteristic for preventing rutting in hot regions pavements (Taherkhani and Kamsari, 2020).

MATERIALS AND METHODS

A modified 65/90 petroleum asphalt concrete (CAP) and two types of fillers were used to carry out this work, derived from basalt powder and the other metakaolin. The first was obtained in a quarry in the city of Uberlandia, Brazil, and is a common material in road paving. Metakaolin is an industrialized product and was supplied by the company Metacaulim do Brasil, located in the city of Jundiai, Brazil. Table 1 shows the chemical characterization of this product according to the manufacturer's information. Note, from the analysis of Table 1 and 2, that metakaolin is a product consisting essentially of silicon oxide and aluminum oxide with high pozzolanic activity.

Table 1 - Characteristics of metakaolin: chemical composition

Element	%
SiO2	51.57
Al2O3	40.5
Fe2O3	2.8
Na2O	0.08
K2O	0.18
Moisture	0.6
PF	2.62
Total	97.8
Alkaline equivalent	0.2
SiO2+Al2O3+Fe2O3	94.87

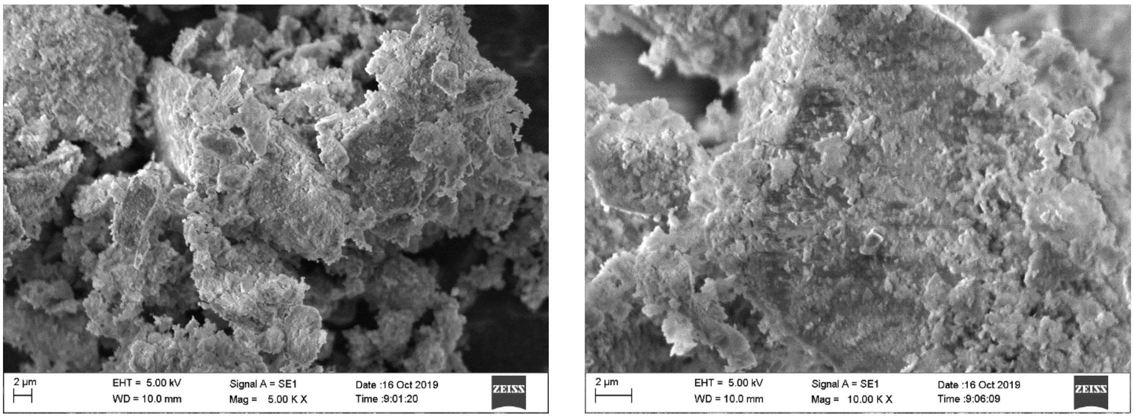
Source: Adapted from Metacaulim do Brasil (2003).

Table 2 - Characteristics of metakaolin: physical characterization and pozzolanic activity

Average diameter (μm)	12.4
Specific gravity (g/m^3)	2.650
Pozzolanic activity at 90 ± 5 °C (mg CaO/g sample)	771.2

Source: Adapted from Metacaulim do Brasil (2003).

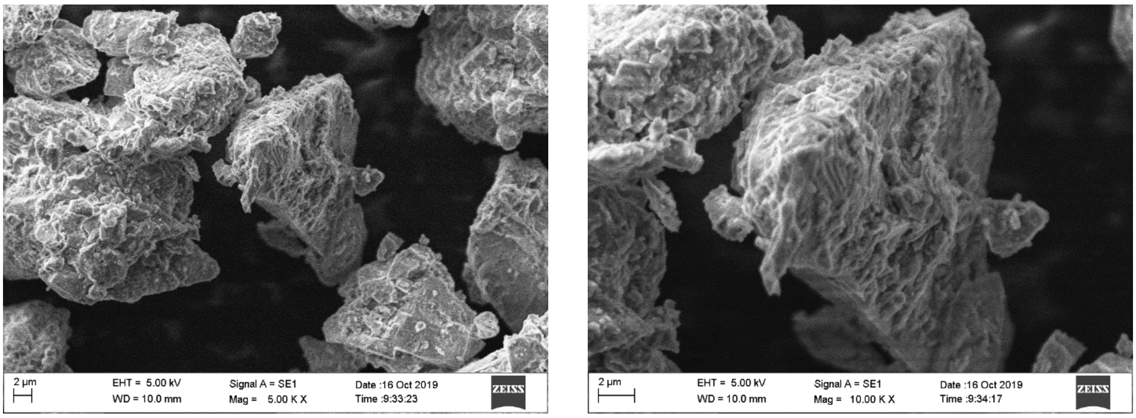
As for the characterization of metakaolin by the Scanning Electron Microscopy (SEM), it appears that the material does not have a well-defined shape (Figure 1). Dispersive energy spectroscopy (EDS) was also performed on metakaolin. Results showed that the main chemical elements present in the material were predominantly silica and aluminum. Alves (2018) carried out in her work the metakaolin's diffraction characterization. The results indicated a crystalline kaolinite peak, and quartz appeared as the main mineral phase.



(a) (b)

Figure 1 – Metakaolin SEM: (a) image magnified 5,000 times e (b) image magnified10,000 times.

The filler's characterization derived from the basalt powder was made through SEM and a specific gravity test. The basalt powder specific gravity was 2.985 g/cm^3. The SEM test results indicated that the basalt powder grain has a definite shape that resembles an angular aggregate. Figure 2 shows the image of a sample of basalt powder magnified 5,000 and 10,000 times. From the EDS test, it was possible to observe silica as the material's mainchemical element.



(a) (b)

Figure 2 – Basalt powder SEM: (a) image magnified 5,000 times, (b) image magnified 10,000 times.

Dutra and Leandro (2020) performed X-ray diffraction tests (XRD) in the basalt powder and indicated an outstanding amount of silicon dioxide ($\mathrm{Si}O2$), anorthite ($CaAl2Si2O8$), and the presence of albite ($NaAlSi3O8$) and quartz. Anorthite and albite belong to the group of feldspar minerals called plagioclase. This group of minerals constitutesa complete isomorphic series.

Comparing Figure 1 and 2, it is possible to infer that the basalt powder filler particles are larger and have a smoother surface than the metakaolin's. Besides, the metakaolin particles had sharp angles, different from the basalt powder ones that had round angles.

The asphalt binder was characterized in penetration, softening point, ductility, and elastic recovery, using ASTM standards. The supplier performed the asphalt binder viscosityand density tests, and the results are shown in Table 3.

Table 3 – Results of the CAP viscosity and density tests performed by the product supplier

Test	Unit	Result	Specification (ANP Resolution No. 32, 2010)
Softening point, minimum	°C	69,5	
Elastic recovery at 25ºC, 20 cm, minimum	%	92,67	
Penetration (100 g, 5s, 25ºC)	0,1 mm	51,67	
Ductility	cm	73	
Brookfield Viscosity at 135°C, spindle 21, 20 rpm, max	cP	1883	≤ 3000
Brookfield Viscosity at 150°C, spindle 21, 50 rpm	cP	566	≤ 2000
Brookfield Viscosity at 177°C, spindle 21, 100 rpm	cP	220	≤ 1000
Density		1,006	

Following the recommended filler-to-binder mass ratio of 0.6–1.2 by Superpave volumetric mix design method, the proportions of filler/asphalt to produce asphalt mastic were 0.6 and 1.2. The mixtures of each type of filler with the CAP were carried out by homogenization in the laboratory. Initially, the asphalt reached a temperature sufficient to allow its workability in an oven. The mix between the binder and dust occurred for 30 minutes in a mixing container, maintaining the temperature between 180 and 185 ° C. The mixing speed needs to be sufficient to create a central vortex without generating bubbles during the process, so it is important to control it. The introduction of filler was gradually ata rate of 10g/min.

RESULTS AND DISCUSSION

In order to analyze and evaluate the impact of the filler type and amount in the mixture, characterizations tests were made. Table 4 shows the results for CAP and mastics made withthe two types of fillers. Table 5 shows the percentage changes in mastic results concerning pure CAP.

Table 4 - Test results on CAP and mastics made with filler derived from basalt powder andmetakaolin.

			Mastic with metakaolin		Mastic with basalt powder	
Test	Unit	CAP	Filler/asphaltratio		Filler/asphaltratio	
			0,6	1,2	0,6	1,2
Softening point, minimum	°C	69,5	76,25	89,5	73,1	79,5
Elastic recovery at 25ºC, 20 cm, minimum	%	92,67	73,5	62,4	84	77,75
Penetration (100 g, 5s, 25ºC)	0,1 mm	51,67	20,6	8,25	26,9	22,15
Ductility	Cm	73	27,5	7,15	33,2	21,5
Temperature susceptibility index		2,85	1,77	1,82	1,87	2,36

Table 4 shows that the insertion of the different types of fillers increased the hardnessof the asphalt and reduced the elastic recovery, resulting in higher temperatures of softeningpoint and less ductility of the mixtures. These effects were most evident for the most considerable amounts of filler. The temperature susceptibility index results were also significantly influenced by the insertions of different types of fillers in the CAP, mainly for the basaltic filler/asphalt ratio of 1.2, but without compromising the degree of sensitivity of the mixtures to high temperatures. Table 4 also indicated that doubling the metakaolin amount resulted in a variation of about 4% in the temperature susceptibility index from the smallest to the most considerable dust amount. Besides, there was no significant difference between the two types of filler for the filler/asphalt ratio of 0.6. However, the more significantproportion of the basaltic filler resulted in a greater influence on the mastic's temperature susceptibility.

Table 5 - Percentage variations of the test results in mastics made with filler derived frombasalt powder and metakaolin comparing to the modified CAP.

Test	Mastic with metakaolin		Mastic with basalt powder	
	Filler/asphalt ratio		Filler/asphalt ratio	
	0,6	1,2	0,6	1,2
Softening point, minimum	9,7%	28,8%	5,2%	14,4%
Elastic recovery	-20,7%	-32,7%	-9,4%	-16,1%
Penetration	-60,1%	-84,0%	-47,9%	-57,1%
Ductility	-62,3%	-90,2%	-54,5%	-70,5%
Temperature susceptibilityindex	-37,9%	-36,3%	-34,6%	-17,3%

Tables 4 and 5 also show that the fillers' insertion promoted a more significant effecton the CAP's ductility and penetration than on the softening point results. It is also evident that metakaolin was more efficient in altering the properties of asphalt than basaltic filler. Ingeneral, the mastic produced with metakaolin results in a more rigid, less elastic, and less ductile mixture. Also, when molding the specimens and handling the mastics, it was noticedthe loss of workability and increased viscosity of the mastics in comparison with CAP, especially for the mastic made with metakaolin. The more efficient absorption of this dust can explain the lower workability of metakaolin mixtures by the asphalt, which increases theeffects of the filler in the mixture. This greater absorption occurs because of metakaolin's fineness and the fact that the proportions were made by weight. The basalt powder's actual specific mass is greater than that of metakaolin, which in volume is about 13% greater than that of the natural filler. The cementation reaction of metakaolin could not explain this behavior given the unavailability of calcium hydroxide and moisture in the mixture, which activates the pozzolanic characteristic's activating elements. Figures 3, 4, 5, and 6 show the results of penetration, softening point, elastic recovery, and ductility as the filler/asphalt ratiofunction.

The results from Tables 4 and 5 and Figures 3, 4, 5, and 6 give insights into the mixture's improvement regarding the main pavement distresses. With the addition of filler, the penetration test results decreased, as shown in Figure 3, indicating that the mastic stiffnessincreased. The increased stiffness and the high amount of filler particles that can prevent cracking growth in the mastic improve the fatigue life of the mixture. The softening point increased for both mixtures with metakaolin and basalt powder compared to the virgin binder (Figure 4). That indicates that the filler improved the thermal susceptibility of the mixture.

Thus, a stiffer mastic and less susceptible to temperature is ideal for preventing permanent deformation, especially in regions of a hot climate. However, there was a slight decrease in elastic recovery (Figure 5), which can be a problem if the deformations become nonreversible and increase permanent deformation. The ductility also decreased as filler is incorporated into the mixture (Figure 6), making the mastic more brittle.

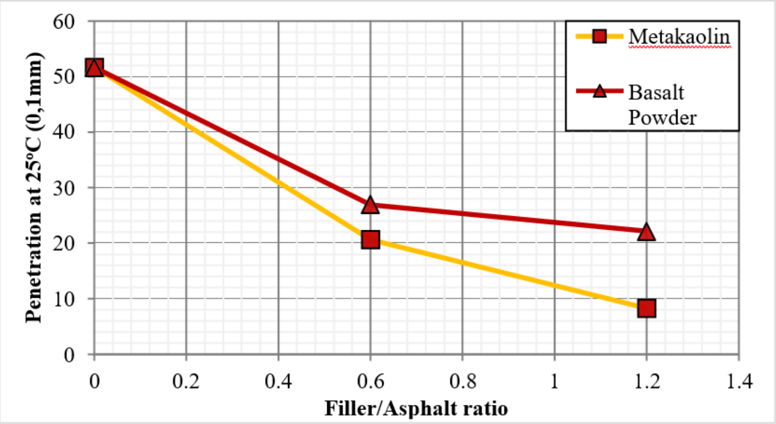


Figure 3 – Penetration results as a function of filer/asphalt ratio

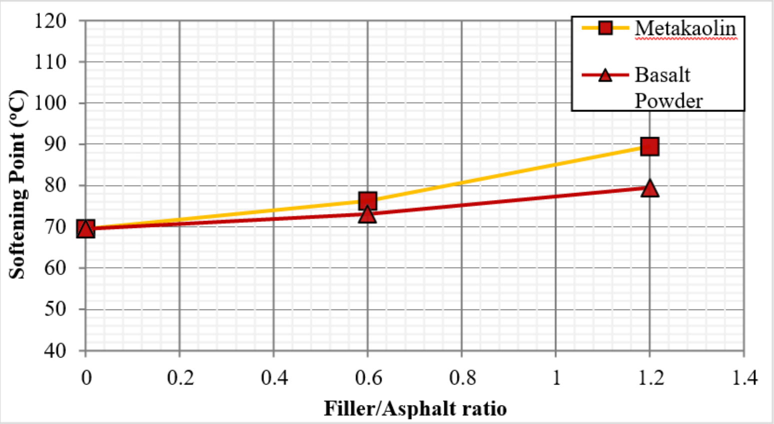


Figure 4 – Softening point results as a function of filer/asphalt ratio

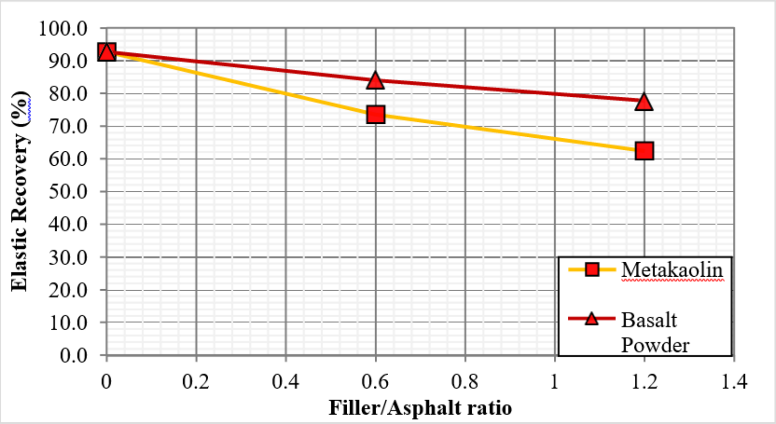


Figure 5 – Elastic recovery results as a function of filer/asphalt ratio

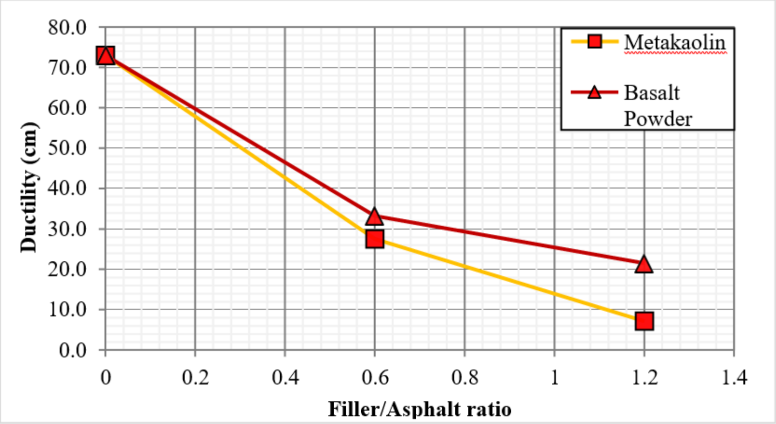
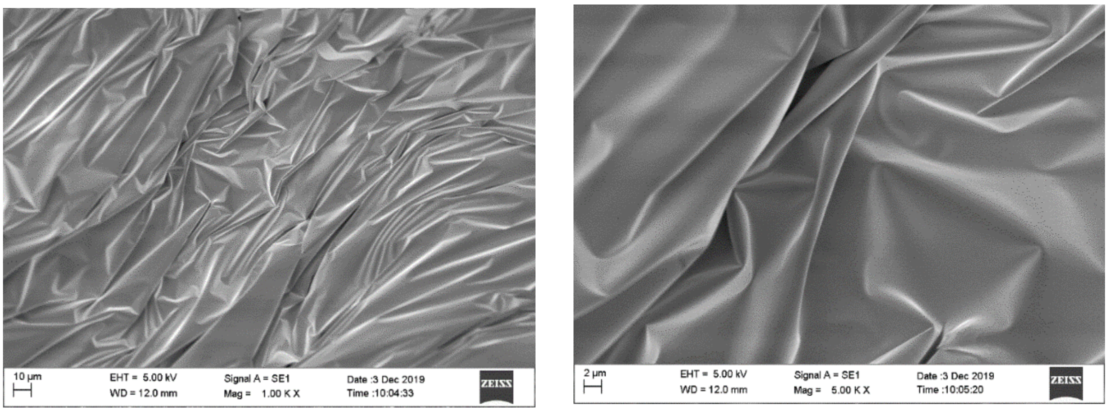


Figure 6 – Ductility results as a function of filer/asphalt ratio

The metakaolin additions' greater effectiveness as fillers is evident from the analysisof Figures 3, 4, 5, and 6. The rate of change in physical characteristics is always more remarkable than for the cases in which basalt powder is dust in the mastic. The highest variation rates occur for the lowest filler/asphalt ratio, regardless of the type of filler except for the softening point results.

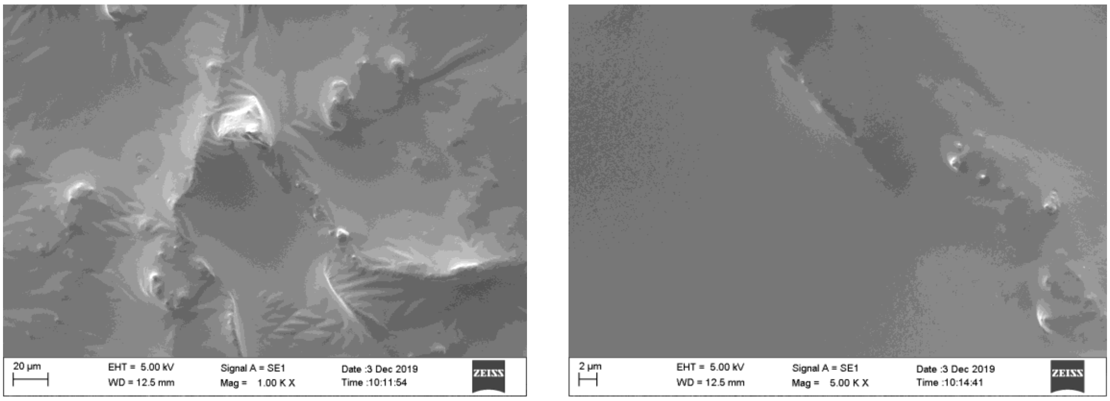
From the SEM test, the visual changes that occurred in the binder were evaluated withthe addition of metakaolin and basalt powder in the 1.2 filler/asphalt ratio. The CAP, shownin Figure 7, has a plastic aspect because a polymer modifies it. Also, the surface is very irregular.



(a) (b)

Figure 7 – CAP 65/90 sample SEM: (a) image magnified 1,000 times, (b) imagemagnified 5,000 times

Figure 8 shows the SEM images for the mastic made with metakaolin with a 1.2 filler/asphalt ratio. The mixture is heterogeneous, and the matrix is more regular than that ofthe asphalt binder. There are some irregularities in the matrix that may have occurred due to particle agglomeration.



(a) (b)

Figure 8 – Mastic with metakaolin sample SEM (filler/asphalt ratio = 1,2): (a) imagemagnified 1,000 times, (b) image magnified 5,000 times

The mastic made with filler derived from basalt powder in the 1.2 filler/asphalt ratio presents a more regular and more homogeneous matrix (Figure 9) than the metakaolin mastic. Some irregularities in the matrix may have occurred due to the particles' agglomeration, butin lesser quantities than in the mastic samples with metakaolin.

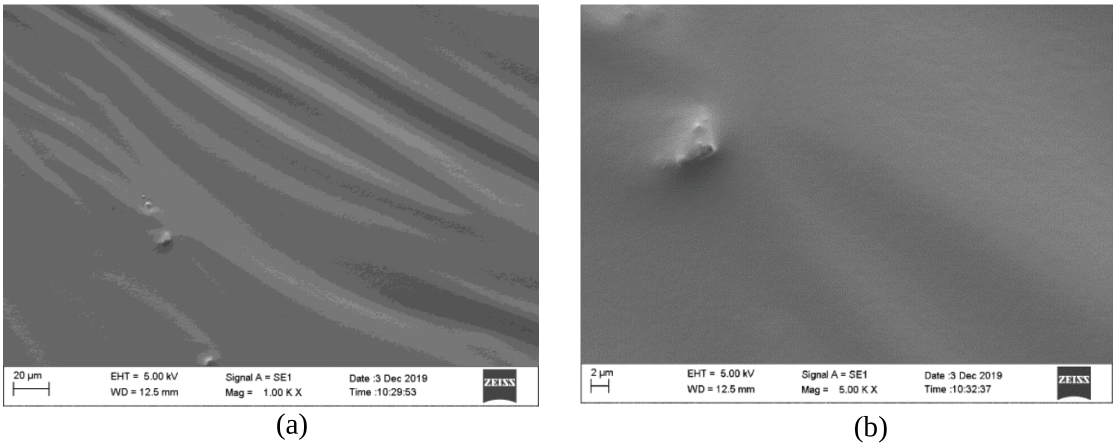


Figure 9 – Mastic with basalt powder sample SEM (filler/asphalt ratio = 1,2): (a) imagemagnified 1,000 times, (b) image magnified 5,000 times

CONCLUSION

In summary, higher filling material content yield the following effects: lower penetration, higher softening point temperature, lower ductility, less elastic recovery, and reduced mixtureworkability. The stiffness increase and the high amount of filler particles in the mastic preventing cracking growth are strong evidence that the addition of filler improves mixture performance regarding fatigue life. Besides, the insertion of filler in mastic can also improvethe mixture's permanent deformation performance since there was a decrease in temperaturesusceptibility and increase in strength and stiffness. However, the increase of filler amount in the mixture ductility and elastic recovery decrease, making the mixture more brittle and increasing the probability of non-reversible deformation. Therefore, further studies are required to determine asphalt mixture rheology and the proper filler dosage.

Comparing the two types of fillers, it is evident that, for the same proportions, the metakaolin acted more efficiently in altering the CAP's physical characteristics. Asphalt mixtures with metakaolin are more rigid, less elastic, and have worse workability than mixtures with basaltic filler. These differences provided by using these two different fillers may be due to the shape of the particles verified in the SEM analysis. The SEM's results showed metakaolin particles surface rougher and sharper, which contributes to better adhesion and bonding with the asphalt-binder in the mixture. The greater volume of metakaolin associated with the smaller size of its particles may favor the occurrence of agglomerations in the interaction with the asphalt binder, contributing to the mastic's workability reduction when compared to mastics made with basaltic filler. Thus, it is expected that the asphalt mixtures produced with metakaolin will inherit the behavior verified for the mastics in this study, showing greater rigidity and less elasticity than the mixtures made with the basaltic filler.

The more significant effect of the metakaolin on the asphalt characteristics can not be explained by the cementation reaction of the pozzolanic material because calcium hydroxide and moisture, which activates the pozzolanic characteristic's activating elements, were not present in the mixture. Besides, due to this more intense effect on the asphalt mastic, this work's recommendation is the use of a lower metakaolin/asphalt ratio for the formation of mastics to minimize the damage in workability and not result in a product that is too rigid.

It is noteworthy that the interaction between fillers and asphalt should continue to be investigated by tests that assess the behavior of mastics under dynamic stresses, in addition to assessing the effects on mechanical behavior and moisture-induced damage of hot mix asphalt.

DATA AVAIABILITY

All data, models, and code generated or used during the study appear in the submitted article.

Some or all data, models, or code generated or used during the study are available in a repository online in accordance with funder data retention policies.

ACKNOWLEDGMENTS

This work was supported by Federal University of Uberlândia.

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