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Research Paper

Permanent Deformation and Moisture Induced Damage Potential of Stone Matrix Asphalt (SMA) Containing Barite Powder

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Abstract

The aggregate particles in asphalt mixtures get connected by (bitumen + mineral filler) mastic. The goal of this paper is to study the feasibility of partial and total substitution of Limestone (LS) filler by Barite powder (BP) in Stone matrix asphalt (SMA) mixtures. To evaluate barite powder performance, resilient modulus, indirect tensile strength, freeze-thaw cycles, dynamic creep at two different temperatures, and bitumen draindown tests were used. The obtained values revealed that an increase in barite powder content from 50% to 100% improved the Stone matrix asphalt mixture moisture performance by 4.5% after going through 5 freeze-thaw cycles while on the other hand, it had an 18.5% reverse effect on the permanent deformation in higher temperatures. Also, despite barite powder's positive effect on bitumen draindown compared to the control samples; it could not yet thoroughly control SMA bitumen draindown.

Keywords: Filler, Stone matrix asphalt (SMA), Barite powder, Moisture Damage, Permanent Deformation

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1. Introduction

Stone Matrix Asphalt (SMA) has become a popular mixture for the wearing course of flexible pavements with medium and heavy traffic loads. SMA is characterized by its strong skeleton structure with a high content of coarse aggregates (70% - 80%), because of its special gradation, the SMA also consists of a large amount of mineral filler and bitumen to produce a strong durable structure (Mogawer and Stuart, 1996, Xie and Watson, 2004).The mineral fillers contain small particles and fill voids between coarse aggregates. Filler plays an important role in holding the aggregates together by affecting the properties of bituminous mastic. The mineral filler helps to create a dense and stiff asphalt mixture composition by reducing water-soluble constituents and other mechanical distresses of the asphalt mixture. Therefore, several studies have been conducted choosing a proper type of filler to improve pavement performance.

Ameli et al. in 2020 studied the effect of coal waste ash (CWA) and rice husk ash (RHA) on the asphalt mastic and SMA performance. By performing various moisture and dynamic tests on samples containing 0, 25, 50, 75, and 100% CWA and RHA instead of the control filler samples, it was found that RHA has a positive effect on the rutting failure and fatigue life of the, while CWA had the opposite effect (Ameli et al., 2020). Muniandy et al. evaluated four types of industrial and by-product waste powders, namely limestone dust (LSD), ceramic waste dust (CWD), coal fly ash (CFA), and steel slag dust (SSD) as filler material in SMA mixtures. They realized that the aforementioned industrial by-products used as filler increased the stiffness of the mixtures and enhanced some engineering properties of stone mastic asphalt mixtures (Muniandy,Aburkaba and Taha, 2013). Al-Khateeb et al. compared SUPERPAVE asphalt mixture designed samples containing two types of conventional limestone and basalt aggregates with the help of dynamic creep and rutting performance tests. Rutting in four different temperatures 40, 50, 60, and 65 °C at a loading frequency of 8 Hz revealed that samples containing basalt showed much better performance against increasing temperature. In order to prevent the occurrence of striping damage in asphalt samples containing basalt, equal to 1% of the total weight of aggregate materials, hydrated lime was used in the asphalt filler. Rutting rate in samples containing basalt had a linear relationship with temperature increase, while this relationship for asphalt samples was an exponential function (Al-Khateeb et al., 2013). Arbabpour Bidgoli et al. in 2019, studied the effect of four types of fillers, including limestone filler, portland cement, recycled concrete aggregates, and siliceous stone powder, on the moisture resistance of asphalt mixtures by analyzing mechanical and thermodynamic properties. The resilient modulus and indirect tensile strength of different samples were evaluated in comparison with the control sample (containing siliceous stone powder) after 1 to 10 freeze-thaw cycles. In addition, the amount of surface free-energy components of the mastic part and the degree of cohesion and adhesion of the mixtures were determined. The results of both set of tests showed the superior performance of samples containing cement powder filler in comparison with other fillers after all freeze-thaw cycles, which indicates the usefulness of cement powder in moisture resistance improvement (Arbabpour Bidgoli,Naderi and Moghadas Nejad, 2019).

Barite is a mineral composed of Barium sulfate, $BaSO_4$. Barite is chemically inert and insoluble. In nature, it exists in the mineral form of barite and usually comes colorless (Yu et al., 2016). Barite gets its name from “barys” meaning heavy in Greek. This is due to the high atomic weight of Barium (Ba). Because of the abundance of barite reserves in most parts of the world also its special features, it has found a lot of use in various industries.

The global consumption of barite is mainly in the oil and gas industry, this amount includes 85% of the global demand for barite, which is often converted into powder. Other applications concern heavyweight concrete production, the chemical industry, and radiological protection (Saidani,Ajam and Ouezdou, 2015). Therefore there have not been many studies on asphalt mixtures barite powder modification.

Middendorf et al. evaluated the mixing quality of bitumen modified with two types of barite sand and powder using CT imaging methods beside the shear rheometer test in the temperature range of 30-90°C. Three sets of bitumen samples with 10 wt%, 15 wt%, and 20 wt% barite powder were prepared, where barite was added to bitumen in the wet method. Based on the obtained results despite the appropriate mixing of both types of barites in bitumen, the samples containing barite sand did not cause any change in the phase angle values and just the barite powder sample with 20 wt% was able to increase the Resilient Modulus value (Middendorf et al., 2021). Hamedi et al. in 2019 investigated the physical and rheological properties of modified asphalt binders with 1%, 2%, 3%, and 4%, barium sulfate ($BaSO4$) nanoparticles. The penetration grade test and the softening point test on the controlled and modified asphalt binders showed improvement. Dynamic shear rheometer (DSR) test results also revealed asphalt binders containing 2% of nanoparticles in each of the unaged and short-term aged modes had the maximum value of rutting parameter ($G^*/\mathrm{Sin}(\delta)$) at all temperatures. The friction between nanoparticles and asphalt binder chains, in addition to the friction between asphalt binder chains with themselves, seemed to increase the resistance of asphalt binder chains against external forces as well as deformation and rupture (Hamedi,Sahraei and Halimi, 2019).

So far the studies carried out on barite powder have only concentrated on asphalt binder's modification with barite powder as a filler modifier in the wet process. The present study is one of the very first studies that examines the performance effects of barite filler composition in the asphalt mixture aggregate gradation (dry process modification). To meet this goal, common limestone filler was replaced with barite powder for about 50% and 100% in SMA. The performance properties of SMA mixtures were investigated through, resilient modulus, indirect tensile strength (ITS), freeze-thaw cycles, dynamic creep, and bitumen draindown tests alongside scanning electron microscopy (SEM) analysis of studied fillers.

2. Materials and Methods

2.1. Materials

2.1.1. Asphalt Binder

The binder used in this study was PG 64-22 epoxy resin modified binder; the physical properties of the binder are presented in Table 1.

Table 1. Asphalt binder Properties

Test	Standard	value
Penetration Test (0.1mm)	ASTM D5-73	57
Ductility Test (cm)	ASTM D113-79	135
Softening point (°c)	ASTM D36-76	59
Flash point (°c)	ASTM D92-78	302

2.1.2. Fibers

Based on the suggestion in AASHTO M325 specification for stone matrix asphalt (SMA) design, it is needed to use 0.4% mineral fiber by the total weight of the mixture to avoid the draindown of binder. Ceramic fiber (provided by Sepid Ceramic Fibers Company in Iran) was used in this study. It's a lightweight fiber with high tensile strength and high chemical stability. The fiber has an approximate length of 20 mm and a diameter of 3-5 microns. After the addition of binder to dry aggregates, the fiber was added to the mixture.

2.1.3. Aggregates

Aggregates were from a local limestone quarry in the Yazd province. The physical properties of the aggregate materials were determined using a series of laboratory tests based on ASTM, as summarized in Table 2. Figure 1 shows the gap-graded SMA aggregate gradation curve with a 20mm nominal maximum aggregate size according to Iran Highway Asphalt Paving Code No.234 standard. The middle limit was chosen for mix design, where the content of the mineral filler is 9.5% by aggregates weight.

Table 2. Physical properties of aggregates

Property	Standard	Value
Abrasion resistance (%)	ASTM C131	20.5
Flat and elongated ratio, (% at 5:1)	ASTM D4791	2
% crushed, single face	ASTM D5821	100
% crushed, two or more	ASTM D5821	99

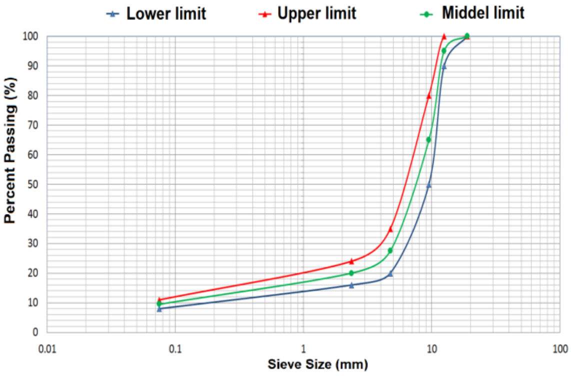

Figure 1. SMA aggregates gradation

2.1.4. Filler

As mentioned earlier, Limestone (calcium carbonate; $CaCO_3$) and Barite powder (Barium sulfate, $BaSO_4$) fillers were used in this study (see Figure 2). The limestone dust was obtained from a local asphalt factory, with a specific gravity of 2.73 g/cm^3. The barite powder with a PH value of 9, was earned from the mines in Salafchegan. It passes through sieve No. 200 and has a specific gravity of 4.4 g/cm^3. The mineralogical properties of the two fillers were measured through the XRD test; the chemical contents are presented in Table 3.

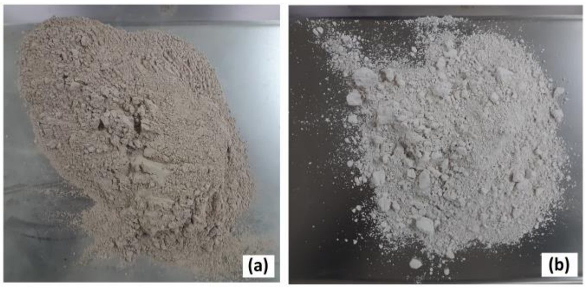

Figure 2. Photo of used mineral fillers: (a) Limestone; and (b) Barite powder

Table 3. Chemical Composition of limestone and Barite powder

Chemical Composition	Barite powder (%)	Limestone (%)
Al_2O_3	0.27	1.2
Fe_2O_3	0.04	0.3
SiO_2	1.225	1.3
K_2O	0.01	0.18
Na_2O	0.85	N.D
MnO	0.001	N.D
TiO_2	0.6	N.D
MgO	N.D	1.6
SO_3	36.29	N.D
P_2O_5	0.001	N.D
BaO	60.71	N.D
CaO	N.D	52.4
Loss on Ignition (L.O.I)	N.D	43.6

Note: LOI = Loss on ignition;
N.D = Not Detected

The scanning electron microscope (SEM) provides insight into the morphology of the fillers. The SEM image is very important to verify properties such as specific surface area, and particle distribution. As illustrated in Figure 3 the barite powder shape, size, and distribution is more likely fine and uniform. While the limestone filler consists of bigger particles, barite powder sample seems to have a higher specific surface area.

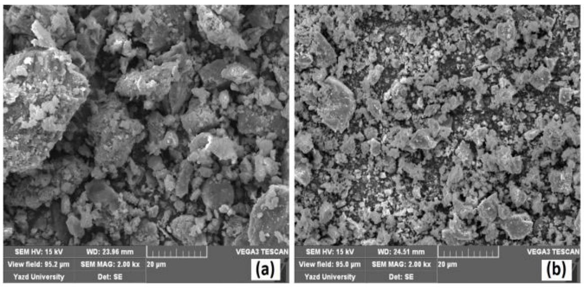

Figure 3. SEM images of fillers (2000× magnification, 20 µm scale): (a) limestone; and (b) Barite powder

3. Mix Design

Filler was added in the dry method and SMA samples were prepared by applying 50 blows on both sides at 160°C to make Marshall Specimens (d ¼ 101.6 mm; h ¼ 63.5 mm). The volumetric parameters are the direct controlling indicators in the design and preparation of the SMA mixtures. According to Brown and Haddock (1997), voids in coarse aggregates (VCA) for aggregates in dry-rodded condition (VCA$_{DRC}$) should be more than VCA in the entire mixture (VCA$_{MIX}$), to confirm the stone-to-stone contact Table 4 (Brown and Haddock, 1997). The optimal asphalt content (OBC) of different SMA asphalt mixtures was determined by AASHTO M325 standard limits for 4% air void, for samples SMA-LS (100% Limestone filler) as the control sample, SMA-LS/BP (50-50%), SMA-BP (100% Barite powder), were 6.2%, 6.3%, and 6.5% respectively.

Table 4. Volumetric properties of SMA mixtures at 6.5% bitumen content

Mixture	Bulk density of compacted mixtures (g/cm^3)	V_a	VCA$_{mix}$	VCA$_{Ratio}$
SMA-LS	2.306	3.4	30.92	0.73
SMA-LS/BP	2.454	4.07	26.48	0.62
SMA-BP	2.386	3.55	28.52	0.67

4. Test Methods

4.1. Draindown Test

This test was performed to measure the amount of draindown of each SMA mixture. So, based on the AASHTO T305 standard, 1200 gr of the loose mixtures were placed into standard wire basket in oven at the mixing temperature for 1 h. The acceptable amount of bitumen drain down is a maximum of 0.3% by weight of the asphalt mixture.

4.2. Resilient Modulus Test

The resilient modulus (Mr) test was run at 25°C by applying haversine load pulse with 100-ms loading and a total 3000-ms pulse repetition period, respectively. The Mr of mixtures was calculated based on Equation 1 ASTM D 4123.

$$Mr = \frac{P}{L \times H}(0.27 + v) \tag{1}$$

Where:

P refers to maximum load applied (N),
v = Poisson’s ratio;
L = sample length (mm);
H = horizontal recoverable deformation (mm).

4.3. Dynamic Creep Test

Dynamic creep test is thought to be one of the best methods for measuring the resistance of asphalt mixtures to permanent deformation (Majidi Shad et al., 2022). In this study, the EN 12697-25 standard was utilized to investigate the resistance of mixtures against permanent deformation through dynamic creep tests. The samples were tested with the Universal Testing Machine (UTM-14P) and got subjected to the stress level of 200 kPa with 1 s loading and 1 s unloading time at two different temperatures of 40°C and 60°C.

4.4. Freeze-thaw Splitting Test

In the field, asphalt mixtures may experience many F-T cycles during their service lives, which escalates moisture damage. Moisture damage is a factor in the deterioration of asphalt mixtures that causes a loss of adhesion between binder and aggregate and a loss of binder cohesion (Hamedi, 2018).

To evaluate the water susceptibility of the SMA mixtures in this study, the indirect tensile strength (ITS) method was used in accordance with AASHTO T283. The mixture specimens were prepared at 6% air-void content and were tested under wet and dry conditions. These samples were subjected to vacuum saturation until a 70%–80% level of saturation was reached, placed in a freezer at -18°C for 16 h, and then immersed in a 60°C water bath for 24 h. The ITS and tensile strength ratio (TSR) values of the samples were obtained using Equations 2 and 3, respectively.

$$ITS = \frac{2000P}{\pi t D} \tag{2}$$

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \tag{3}$$

Where:

P = peak load (N); t = specimen height (mm); D = specimen diameter (mm); ITS_{wet} = indirect tensile strength of wet conditioned specimen (kPa); and ITS_{dry} = indirect tensile strength of dry conditioned specimen (kPa).

A minimum TSR value of 0.8 is considered an acceptable and good resistance to moisture damage (Ziari et al., 2014).

5. Results and Discussions

5.1. Bitumen Drain down Results

As shown in Figure 4, adding barite powder in SMA mixtures with 6.5% bitumen content by weight of mixture helped reducing the amount of bitumen loss, but without the presence of fibers, it still was not able to control bitumen draindown under 0.3% (the 0.3% control limit is presented as the green line in Figure 4). Considering the fact that due to the higher specific gravity of barite filler, a smaller volume of barite filler is used in the mixture, it can be expected that the barite powder morphology has a more specific area compared to limestone filler which is also consistent with results illustrated previously in the analysis of both filler's SEM images. Although barite powder absorbs more bitumen than limestone filler the stabilizer agents need to be used in all samples.

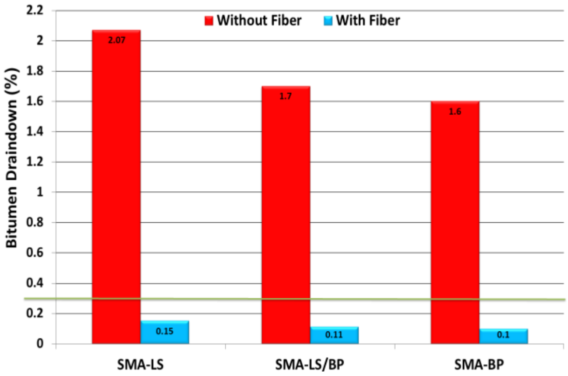

Figure 4. Draindown values of SMA mixtures

5.2. Resilient Modulus Results

The Resilient Modulus test results of SMA specimens at room temperature are shown in Table 5. The resilient modulus provides the basis for comparison of changes in material stiffness for different mixture types. Replacing conventional limestone filler led to a slight change in the stiffness of SMA mixture. Mr of the specimen with 100% barite powder was 9.3% higher than the control mixture, while the specimen with 50% barite powder had an approximately 1% higher Mr value.

Table 5. Resilient Modulus values of the SMA mixtures

Mixture	Young's modulus of elasticity (MPa)
SMA-LS	1697
SMA-LS/BP	1709
SMA-BP	1856

5.3. Dynamic Creep Results

A repetitive uniaxial compressive load on cylindrical asphalt mixtures specimens provides a reasonable prediction of asphalt pavement rutting which is the main load-related distress in flexible pavement. Figure 5 shows the SMA dynamic creep test results under 200 kPa axial pressure. As can be seen, the SMA-BP mixture had the highest deformation, followed by SMA-LS, and then SMA-LS/BP mixtures at both 40°C and 60°C. The results also indicated that at 60°C with the increasing number of cycles the accumulated permanent axial strain undergoes the typical three-stage permanent deformation behavior: primary, secondary, and tertiary stages. The primary stage represents the strain profile at initial loading. The secondary stage shows a relatively constant profile of strain after the initial period. The tertiary stage specifies the start of rutting until the mixture experiences failure as cracks appear (Arabani and Kamboozia, 2014). At 40°C all samples only showed the first two stages and had almost the same trend. However, SMA-BP mixtures reached a stable slope slightly faster compared with SMA-LS/BP and SMA-LS mixtures at 60°C. At the secondary stage, deformation is caused primarily by shear flow. This suggested that too much barite powder as filler may not modify the viscoelastic properties of the SMA mastic at higher temperatures and affect the mixture's stiffness. This might be attributed to barite powder's specific gravity and low volume in mastic which results in loss of friction and cohesiveness in the mixture under repetitive compressive loads.

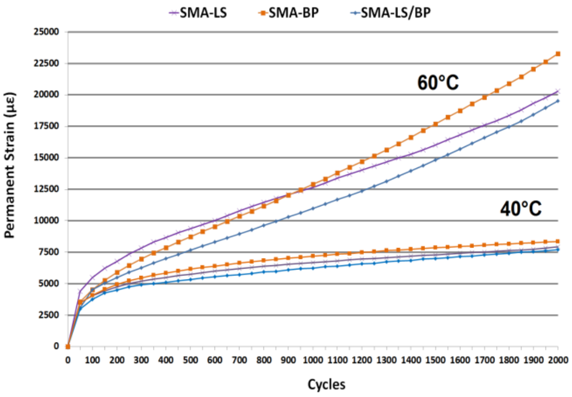

Figure 5. Accumulated deformation curves of SMA mixtures at 40°C and 60°C

5.4. Freeze-thaw Cycles Splitting Test Results

Moisture damage mechanisms are complex, and many attempts have been made to identify the multiple mechanisms involved in asphalt mixture performance against water (Bahmani et al., 2022, Omar et al., 2020). In this study, indirect tensile strength at 25°C was determined for unconditioned specimens (dry) as well as for conditioned specimens (wet) at 1, 3, and 5 freeze-thaw cycles.

The results (see Figure 6) show that the TSR values of SMA-LS/BP and SMA-BP in the first freeze-thaw cycle do not have any significant shift compared with SMA-LS mixture. But TSR values increased 7.83% and 11.62%, respectively, after experiencing 3 cycles of F-T, still meeting the specification requirement of a minimum 80%. After 5 cycles of F-W, SMA mixtures containing 50% and 100% of barite powder showed more improvement and the TSR values increased by 9.69% and 14.15%. One reason for this increase can be the alkaline chemical nature of barite powder (BaSO4) and its elemental compositions presented earlier, improving the adhesion of the polymer-modified binder to the limestone aggregates. Also, another reason is barite powder physical properties and the higher OBC in these specimens which provides more bitumen coverage for aggregate particles and better protection against moisture damage (Sengoz and Agar, 2007).

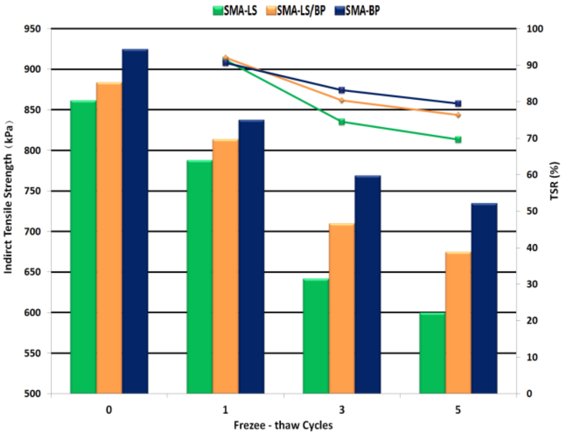

Figure 6. Indirect tensile strength and TSR results of SMA mixtures

6. Conclusions

This study evaluated the utilization of barite powder (BP) as a substitute for conventional limestone filler (LS) in SMA mixtures. The following conclusions are drawn based on the research objectives and the laboratory test results:

- The volumetric parameters value of the barite powder mixtures satisfies standard specifications. The OBC percentages in the

SMA-LS, SMA-LS/BP, and SMA-BP mixtures were 6.2%, 6.3%, and 6.5%, respectively.

- Barite powder mixtures decrease bitumen draindown, but yet SMA stabilizing additives are required.
- At room temperature the effect of 50% BP content is not significant (very close) on SMA mixture resilient modulus, while 100% BP shows to increase the difference nearly up to 9%.
- The presence of barite powder contributes to changes in the viscoelastic properties of the mastic in the SMA mixture at upper temperatures (60°C), where the addition of more barite powder caused a higher permanent deformation frailer rate.
- The barite powder SMA mixtures were able to withstand freeze–thaw cycles moisture damage better than mixtures with limestone filler.

Hence, considering all aspects of performance test results, using up to 50% barite powder (SMA-LS/BP) as a replacement for limestone filler is acceptable in asphalt pavements. However, more research about the long-term influence of incorporating barite powder as filler in the mastic is needed based on the acquired data.

Investigating the feasibility of reusing recycled barite from the oil and gas industry is recommended for future studies.

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