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Evaluation of Using Slag Powder as a Filler for Asphalt Concrete

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Abstract

Filler materials have a significant effect on the performance of asphalt concrete by filling the voids and modifying the binder viscosity. Many types of filler have been used; the Ordinary Portland Cement (OPC) is the most used due to its properties, which align with the required properties. The cost, production emissions, and drain for natural resources formed negative points of its usage. Accordingly, this study is dedicated to evaluating the asphalt concrete properties using byproduct material as a mineral filler. The Electric Arc Furnace Slag Powder (EAFSP) has been selected to replace the OPC with ratios from zero to 100% with an increment of 25%. Marshall and Indirect Tensile Strength (ITS) results in different testing conditions were employed to evaluate the use of EAFSP. The results revealed that using EAFSP as a filler material improved asphalt concrete strength and resistance to moisture effects, especially at high temperatures. More binder content was needed, about 0.6%, the voids in the total mix were reduced by about 1%, and the stiffness increased by about 0.5 kn/mm when replacing the OPC with EAFSP. Based on that, it's recommended that the replacement ratio should be proposed according to the weather condition, materials availability, and cost-benefit analysis.

Keywords: Asphalt Concrete; Electric Arc Furnace Slag; Sustainable Pavement Materials; Marshall Test; Indirect Tensile Strength.

1. Introduction

Highway infrastructures are essential in local and international studies of developing urban cities because of their direct and indirect effects on urban area growth, environmental issues, and socioeconomic problems. Since highway pavement is the most expensive component of the highway infrastructure, experts and researchers have carefully considered it. Assessing and enhancing the properties of pavement materials are the primary factors considered when analyzing and improving pavement performance.

To create high-performance pavement structures, the material mixtures used to build the pavement surfaces should be of a higher caliber than those used in the underlying courses. As a result, highway construction projects become more expensive. Researchers have been concentrating on identifying alternative materials for the various pavement structure courses to overcome the financial difficulties of building highways and maintain a higher level of structural performance. However, a lot of natural resources are used in the road construction process. One promising strategy to preserve natural resources and eliminate the pollution caused by waste is to recycle some solid waste into road construction. Rubber [1, 2], plastic [3, 4], construction waste [5-8], steel slags [9, 10], and so on are examples of typical wastes.

The most popular method considered in pavement material research is altering the mixture design of pavement surfaces, particularly asphalt surfaces. Certain attributes of the used aggregate, such as its quality, quantity, and grading, influence how hot mix asphalt (HMA) behaves in terms of strength and stability. Fillers are materials smaller than 75 µm [11], significantly impacting asphalt pavement mixtures' performance. Particle size distribution, shape, surface area, surface texture, void material, and mineral composition of aggregate and fillers significantly impact asphalt mix

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performance [12]. The bitumen absorbs a portion of the filler while the remainder minimizes air voids [13]. Fillers act as micro-rollers, allowing greater aggregate packing and extra contact points between aggregate particles, improving stress distribution. When filler particles encircle aggregates, a rolling surface of contact is produced, increasing compaction, density, and pressure [14]. Although a higher filler content improves an asphalt mixture's hardness, an excessive amount of filler deteriorates the mixture because more bitumen is needed to bind the aggregate and filler [12, 15]. As finer particles fill the gaps in the asphalt mix matrix and improve resistance to movement, coarse and fine aggregates bind together more firmly [12].

Pell [16] found that adding more filler increases fatigue efficiency by extending the bitumen and decreasing air voids. According to Behiry [17], filler increases a pavement's resistance to long-term deformation at the expense of stability and fatigue resistance. A suitable filler must be added to obtain the required strength and density properties in asphalt mixtures used for paving applications—typically 5–10% of the total weight. The filler particles' main function in the asphalt mixture is to fill in the gaps between the coarse and fine aggregate particles, increasing the mixture's overall density and mechanical strength [18-21].

Recently, waste materials and less energy-intensive materials with cementitious qualities have been used as fillers worldwide, and HMA researchers are paying close attention to these issues. One example of this kind of content is Pozzolanas. It comes in various forms, including fly ash and limestone dust. This substitute is considered one of the most economical fillers [18, 19]. A common component of Hot Asphalt Mix (HAM), Portland cement, is not considered environmentally sustainable because of the high greenhouse gas emissions and excessive use of natural resources during production. About one ton of carbon dioxide (CO_2) is released, while one ton of cement is produced. Therefore, alternative materials need to be investigated to lessen the environmental impact of Portland cement [22]. The concrete industry must use additional cementitious materials as substitutes in response to the global call for sustainable development.

Electric Arc Furnace Slag Powder is a waste product obtained by separating molten steel from impurities in steel-making furnaces during metallurgical manufacturing. Although slags are widely utilized, iron waste dates back to the origin of the first metallurgical materials and melting production processes. The amount of steel slag by-products derived from steel-making increased significantly with the rapid development of the steel industry in the last century, resulting in a growing need for effective recycling, as in civil engineering and road construction [23, 24]. Recycling is urgently needed due to the massive volume of steel by-products, and it may also be a promising strategy to conserve natural resources. Reusing and converting waste can effectively address environmental consciousness [25]. Using byproduct materials in the pavement industry is essential, especially with the growing amount of waste generated by the population and industrial growth. As a result, recycling waste is becoming increasingly important. Landfilling, abiotic degradation, and resource extraction can all be reduced by reusing waste or recycled materials [26]. Most prior research has focused on using slag as an aggregate material in asphalt pavements [27, 28].

The studies that used slag as a filler material focused on using the Basic Oxygen Furnace Slag Powder (BOFSP), which has a negative environmental effect [29, 30]. Instead, this study utilizes the Electric Arc Furnace Slag Powder (EAFSP), a relatively low environmental effect, as a recycled industrial byproduct in asphalt pavement. The current study aimed to advance this field of study. The study's findings will help discover the suitability of using the EAFSP as a substitute for traditional mineral fillers, particularly OPC, used in HAM mixes, and determine the optimum filler combination to satisfy the sustainability requirements.

Al-Tameemi et al. [31] studied to critically assess the use of steel slag in place of mineral filler to create a sustainable mixture. Three different contents—0%, 50%, and 100%—were used in the replacement, which was combined with a modified asphalt binder that contained 4% styrene-butadiene-styrene polymer. They underwent tests for Marshall stability and volumetric characteristics; all of the mixtures with the ideal binder content had their moisture susceptibility assessed using an indirect tensile test. Additionally, the crystal structure, microscopic characteristics, and chemical makeup of the limestone dust and steel slag particles were analyzed using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) to compare their differences. The conclusion found that adding steel slag as a mineral filler can greatly improve asphalt mixtures' moisture susceptibility and Marshall qualities. The beneficial effect was amplified when combined with the SBS-modified binder. Steel slag has a rough, angular surface texture with a high porosity and specific surface area, according to SEM analysis. Steel slag's pozzolanic composition was validated by EDX analysis.

After reviewing the main studies on this field, the importance and purpose of this study the introduced. The next paragraphs are devoted to demonstrating the adopted methodology, material properties, mix design, and evaluation of the asphalt concrete that contains different percentages of EAFSP based on the results of Marshall and ITS tests at different testing conditions. The results were discussed to show the effect of using EAFSP as a filler material. The use of percentages of EAFSP has proposed to form a filler combination to satisfy the required properties based on weathering condition, materials availability, and cost priority, then the main outcomes of this work have been illustrated in the conclusions.

2. Research Methodology

This study aims to enhance asphalt concrete by using byproducts as filler material. To achieve this, the effect of using the proposed alternative (EAFSP) as a mineral filler on the properties of asphalt concrete was evaluated by adopting the steps listed below. In addition, the flow chart that describes the main phases of the adopted methodology in this study is shown in Figure 1.

- Problem identification,
- Providing materials for asphalt concrete,
- Checking the materials' suitability according to the required properties,
- Mixes' Preparation, with different filler combinations,
- Mixes' design, determining the Optimum Binder Content (%OBC) for different filler combinations,
- Checking the mix properties at the %OBC that were found previously,
- Preparation and testing of samples with %OBC and different filler combinations,
- Determine the volumetric and strength properties to evaluate the effect of using EAFSP.
- Finding the optimum ratio of replacement of the OPC with (EAFSP),
- Proposing a combination of filler materials that satisfies the requirement with economic and environmental enhancement.

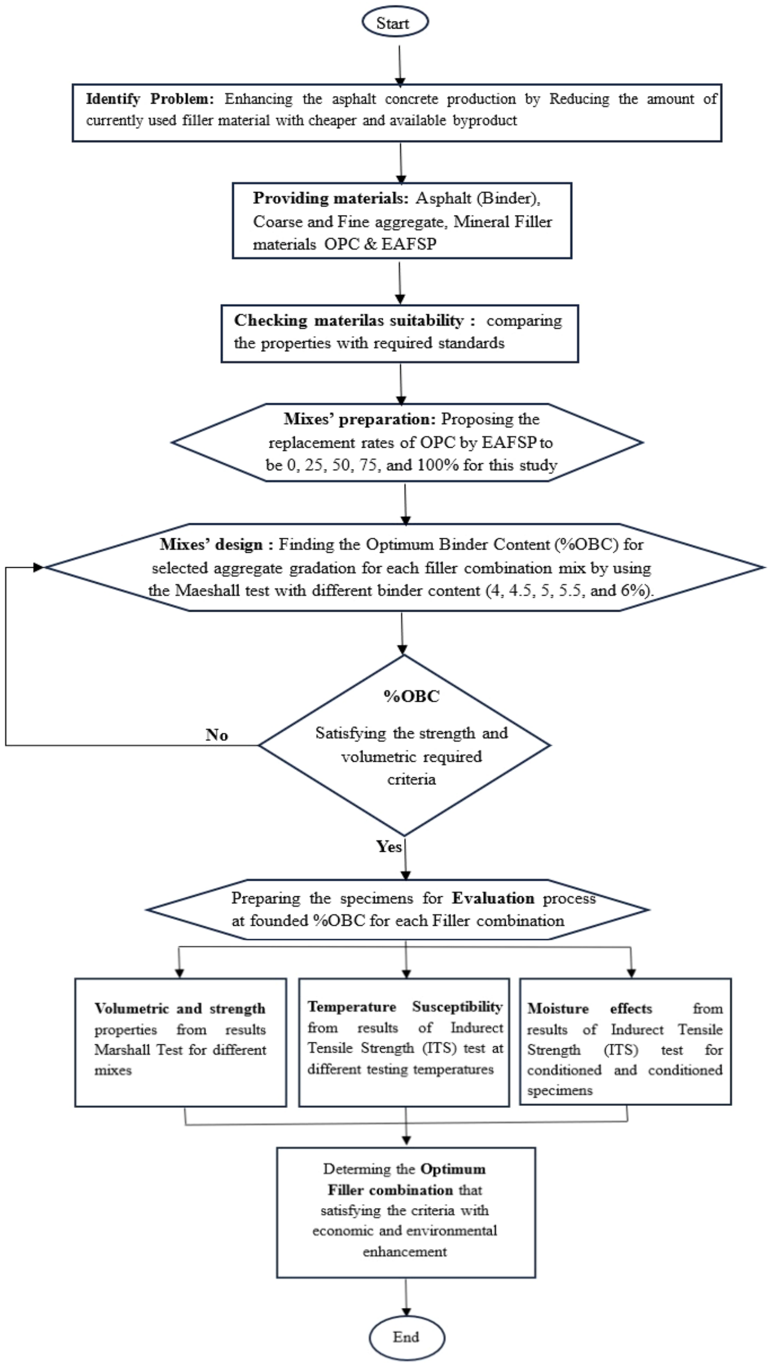

Figure 1. The flow chart of the adopted methodology for this study

3. Materials Selection

Asphalt concrete is one of the most used construction materials for paving and maintaining roads and parking. Providing the required raw and manufactured materials and the energy for producing asphalt concrete faces environmental, economic, and social challenges. So, to reduce the negative effect of producing asphalt concrete, recycled and industrial byproduct materials are recommended. The EAFSP resulting from steel production is one of these materials that can be used partially or instead of OPC as a mineral filler. The next paragraphs present the sources and properties of these materials, in addition to the Asphalt binder and aggregate used in forming asphalt concrete.

3.1. Mineral Filler

Mineral filler has a vital role in asphalt concrete due to its fineness (less than 0.075µm); it can affect the volumetric properties of the mix, besides its effect on the workability during mix preparation. So, its percentage and properties are critically important for achieving the required asphalt concrete criteria. Based on that, OPC is preferred to satisfy the requirements. The cost of OPC can be considered a negative point, besides the required energy and pollution associated with its production process. So, looking for cheaper alternatives is needed to enhance the sustainability of asphalt concrete. Many byproducts have been used as an alternative to the OPC; an example of these materials is those that result from metal production, such as fly ash and slag. Those byproducts are the most used in the construction sector. Slag is preferred over fly ash because it can resist chemical attacks, which satisfies the requirements of structures exposed to the environment, such as roads. Hence, the EAFSP was used as an alternative (partially and totally) to OPC as a mineral filler material for this study.

The chemical composition of EAFSP, shown in Table 1, depends on the produced steel type, treatment method, and production process (furnace type), which are mostly Basic Oxygen Furnace (BOF) and Electrical Arc Furnace (EAF). The EAFSP that EAF produces was used for this study. It can be seen that the main components of EAFSP are the oxides of iron, silicon, and columbite. Table 1 shows the slag types' main chemical components, the OPC, and their Loss on Ignition (L.O.I.) properties.

Table 1. The chemical composition of EAFSP according to the production process and OPC [32, 33]

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	MnO	P_2O_5	SO_3	K_2O	Na_2O	L.O.I.
BOFSP	53	12	3	6	12	8	4	2	-	-	-	2.3
EAFSP	40	15	4	5	15	10	8	3	-	-	-	-
OPC	62	22	5	3	-	4	-	-	3	0.8	0.2	2.24

The Specific gravity, surface area, and other physical properties of EAFSP and OPC used for this study are shown in Table 2.

Table 2. Physical properties of EAFSP [34-36]

Property	Specific gravity <75 [µm]	Moisture Content [%]	Surface area [m^2/kg]	Finner 75 µm [%]	Water absorption [%]
EAFSP	3.40	0.02	442	100	0.64
OPC	3.15	-	390	94	-

3.2. Coarse and Fine Aggregate

The crushed quartzite aggregate (from the Al-Nibaee quarry) was used because it is mostly utilised to produce asphalt concrete in the middle zone of Iraq. The adopted grain size distribution is the mid-range of the Iraqi specification SCRB [37], which specifies upper and lower limits for aggregate gradation used to form asphalt concrete for wearing a layer of flexible pavement, as shown in Figure 2. The maximum nominal size of the used gradation is 12.5mm, the coarse aggregate is specified with that retained on sieve no.4 (4.75 mm), while the fine aggregate is quantified between that passing sieve no.4 and retained on sieve no. 200 (0.075 mm).

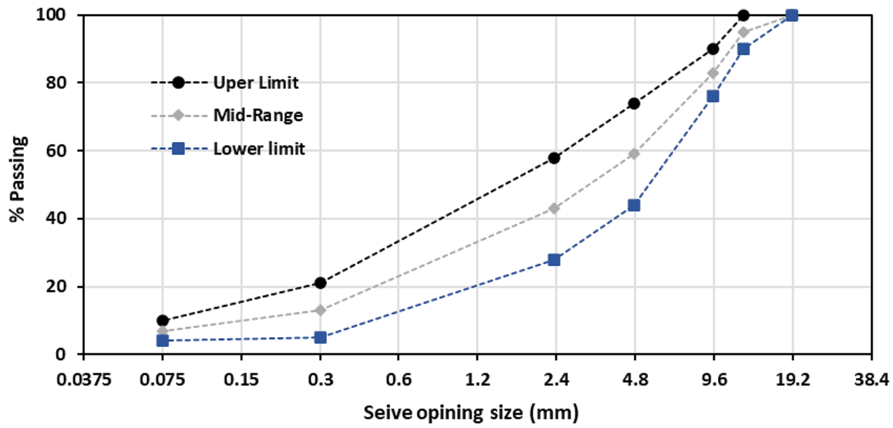

Figure 2. The aggregate gradation used in this study

The main physical and mechanical properties of used aggregate, with standards and required specifications, are shown in Tables 3 and 4.

Table 3. The physical and mechanical properties of the used coarse aggregate

Property	Bulk density [gm/cm^3]	Apparent density [gm/cm^3]	Water absorption [%]	L A* abrasion [%]	Soundness by Na_2SO_4 [%]	Flatness & elongation [%]	Fractured particles [%]
Designation	ASTM C127 [38]	ASTM C127 [38]	ASTM C127 [38]	ASTM C131 [39]	ASTM C88 [40]	ASTM D4791 [41]	-
SCRB [37]	-	-	-	30 Max	10 Max	10 Max	95 Min
Result	2.602	2.645	0.5	20.5	3.5	2.2	97

* L A: Los Angeles

Table 4. The physical and mechanical properties of the used fine aggregate

Property	Sand equivalent [%]	Bulk density [gm/cm^3]	Apparent density [gm/cm^3]	Water absorption [%]
Designation	ASTM D2419 [42]	ASTM C128 [43]	ASTM C128 [43]	ASTM C128 [43]
SCRB [37]	45 Min	---	---	---
Result	56	2.642	2.691	0.675

3.3. Asphalt Binder

The asphalt binder with grade penetration of 40-50, produced by Al-Dourah refinery located in Baghdad-Iraq, has been used to prepare the asphalt concrete specimens for this study. The properties of the utilised asphalt binder are listed in Table 5, while Table 6 shows the properties after short-term ageing.

Table 5. Asphalt binder properties

Property	Penetration ^{A} 0.1 [mm]	KV^B@135°C [cSt]	Softening Point R&B [°C]	Ductility @25°C 5cm/min [cm]	Specific gravity	Flashpoint [°C]
Designation	ASTM D5 [44]	ASTM_D2171 [45]	ASTM D36 [46]	ASTM D113 [47]	ASTM D70 [48]	ASTM D92 [49]
SCRB	40-50	-	-	100 Min	-	232 Min
Result	44	395	51	132	1.05	290

A: penetration of needle loaded with 100 g @ 25 °C;

B: Kinematic Viscosity.

Table 6. Properties of short-term aged asphalt residue from Thin-Film Oven test

Property	Retained Penetration [%]	Ductility @25°C 5 cm/min [cm]	Loss on heating [%]
Designation	ASTM D5 [44]	ASTM D113 [47]	ASTM D 1754 [50]
SCRB [37]	Min 55	Min 25	Max 1.0
Result	60	51	0.1

4. Asphalt Concrete Mix Design

Five percentages of replacement (0, 25, 50, 75, and 100) to the OPC have been adopted to study the effect of EAFSP as filler material on the volumetric and strength properties of asphalt concrete. Since EAFSP properties differ from OPC, finding the Optimum Binder Content (%OBC) for each replacement percentage is required, and the Marshall mix design criteria depend on it. These criteria require the determination of the ideal binder content that satisfies maximum stability (maximum load resistance) that allows for deformation (flow) of the asphalt concrete cylindrical sample laterally (in the direction of diameter) between 2-4mm, and maximum bulk density that provides 3-5% air voids. For the next testing phase of this study, the specimens were prepared using the same aggregate gradation and binder grade with different filler combinations at a specified %OBC for each mix.

4.1. Marshall Test – Samples Preparation

The Marshall test has been used in this study due to its simplicity and wide range of use worldwide. According to the specifications of ASTM D6926 [51], this test requires preparing cylindrical samples of asphalt concrete of 4" (101.6mm) diameter and height of 2.5" (63.5mm). After mixing the components (asphalt, aggregate, and mineral filler) at about 155-160 °C, the mix is compacted at about 140-145 °C by using a hammer of 10 lb. (4.54 kg) weight and 18" (457mm) falling distance. Three levels of 35, 56, and 75 blows per face are specified for light, medium, and heavy traffic. For this study, 75 blows have been selected. Five percentages of binder content (4, 4.5, 5, 5.5, and 6) for each filler combination have been formulated to find the %OBC according to the test result. After finishing the compaction process, the samples were extruded from the mould and allowed to cool to room temperature for 24 hours before testing.

4.2. Marshall Test – Testing

The prepared Marshall samples were tested to evaluate the strength and volumetric properties and to select the %OBC. Before strength testing, the bulk density based on ASTM D2726 [52] for all samples was measured with corresponding percentages of air voids and correlated with percentages of asphalt content, as shown in Figure 3(A&B). The %OBC that meets the maximum bulk density for each filler combination group was found using the best-fit trend line (second-degree polynomial). The %OBC corresponding to the 4% of air voids was also determined for each filler combination group.

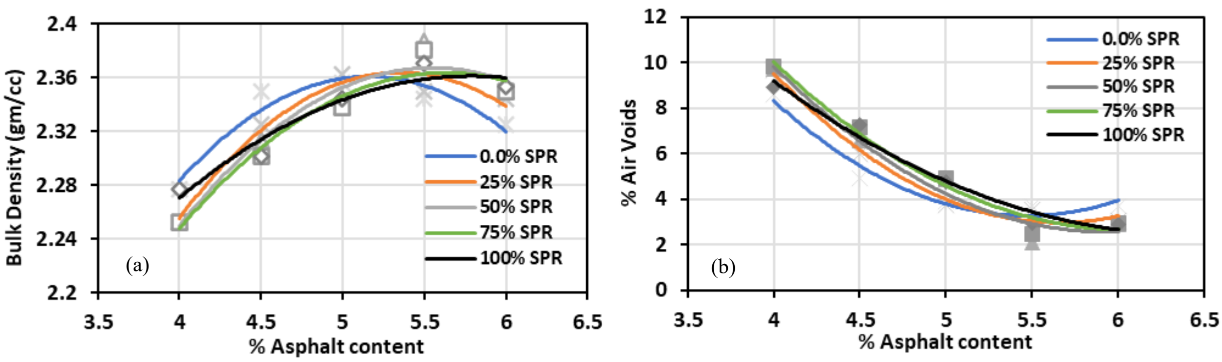

Figure 3. Relations of (a) bulk density and (b) % air-voids with % asphalt content for specimens with different filler combinations groups

For the strength part, the samples were submerged in the water bath of 60 °C for 30 minutes, as specified by ASTM D6927 [53], then compressed by a compression machine with a constant loading rate of 2" or 50.8 mm per minute, applying on the horizontal plane in the direction of diameter, by attaching the rounded side of the sample by using upper and lower semi-circle jaws as shown on Figure 4. The relations between Stability (maximum load resistance) and flow (corresponding deformation to maximum load resistance) have been plotted with asphalt content for each filler group combination using the best-fit trend lines of second-degree polynomial and linear, as shown in Figures 5-a and 5-b. The %OBC associated with the maximum stability was determined using these relations.

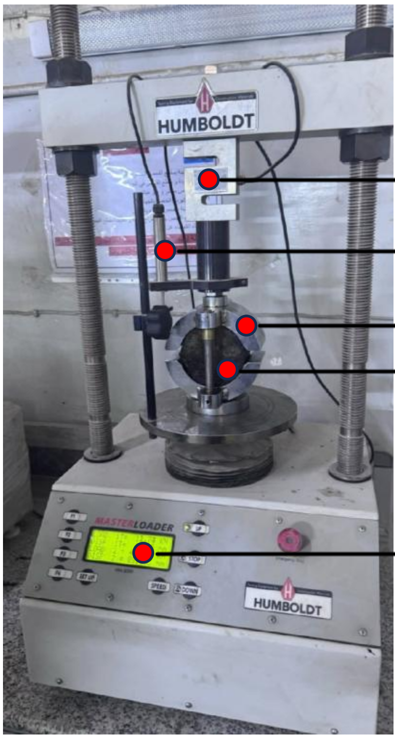

Figure 4. Marshall test

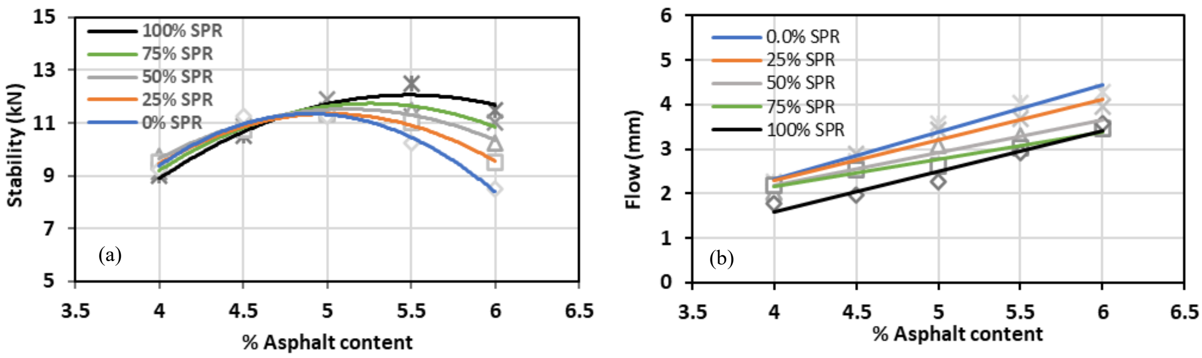

Figure 5. Relations of (a) Stability and (b) Flow with % AC for specimen groups with different filler combinations

4.3. Mix Design Results

As a result of the Marshall test, the %OBC associated with maximum bulk density, 4% air voids, maximum stability, and flow at 3mm has been determined for each mix of filler combinations. The average value of %OBC was calculated for each group and checked against the required criteria, as shown in Table 7.

Table 7. %OBC for asphalt concrete mixes of different filler combinations

%EAFSP	% OBC				%OBC Av. 4-6	Checking mix properties at the average %OBC with the required criteria					
	Max Stab.	4% AV	Max BD	Flow 3 [mm]		Stab. [kN] Min. 8	Flow 2-4 [mm]	BD [gm/cc]	% VTM 3-5%	% VMA Min. 14	%VFB 70-85
0	4.897	4.914	5.160	4.644	4.90	11.340	3.271	2.351	4.28	15.80	72.93
25	5.013	5.000	5.350	4.783	5.00	11.343	3.200	2.358	3.94	15.73	74.973
50	5.116	5.070	5.550	5.119	5.20	11.510	3.060	2.361	3.61	15.90	77.273
75	5.257	5.180	5.630	5.336	5.35	11.720	2.982	2.359	3.56	16.18	78.00
100	5.489	5.270	5.791	5.555	5.53	12.060	2.977	2.358	3.43	16.47	79.18

The local criteria prepared by the Iraqi State Corporation for Roads and Bridges SCRB, 2003, Roads section R9, were used to check the values resulting from using the averaged value of %OBC [54]. These criteria were presented in Table 7, next to each property. All property values were within the accepted range. The local criteria required a minimum value of 14% for Voids in Mineral Aggregate (VMA) for the wearing layer mix. However, it did not mention the requirements for Voids Filled with Binder (VFB), although some local researchers noted that the acceptable range is between 70-85% [55]. For more information about the effect of volumetric properties on pavement performance, its recommended to see the study made by Wang et al. in 2019 [56]. As the determined %OBC satisfies the criteria shown in Table 7, the presented percentages of optimum binder content are adopted to prepare the rest of the samples dedicated to this study's next phases.

5. Evaluation of the Use of EAFSP on Properties of Asphalt Concrete

To complete the requirements of this study, the effect of using EAFSP as a filler material on the strength and volumetric properties of asphalt concrete must be investigated. Although the Marshall test gave a good impression about the effect of replacing the OPC with EAFSP as a filler material in different percentages, it is still required to understand other properties, such as tensile strength, one of the major properties responsible for causing different types of distress to flexible pavements subjected to wheel loads under various weather conditions. So, the Indirect Tensile Test (ITS) has been selected for this purpose because it is important in testing and evaluating asphalt concrete. Another thing that should be covered is the weathering conditions. Accordingly, the strength evaluation should be done using different testing temperatures. Also, the samples should be subjected to moisture attack to comprise the most conditions facing the paving material during its service life.

5.1. Tensile Strength

Asphalt concrete is a temperature-sensitive material. So, the properties of asphalt concrete are changing with temperature variation. That is because the asphalt tends to be soft at high temperatures and stiff at low temperatures. Therefore, the evaluation of asphalt concrete at different temperatures is required. The tensile strength should be checked to ensure the asphalt concrete performs satisfactorily. As the flexible pavement layers are subjected to wheel loads, tensile stresses develop at the bottom of these layers. These stresses are increased for layers close to the surface. As this study is dedicated to wearing layers, it is important to check its tensile resistance to the developed stresses. The filler materials play an important role in material stiffness due to their ability to fill the voids, directly affecting the material's elasticity level. Based on that, the ITS test is selected to complete the evaluation process of replacing the OPC with EAFSP as a filler material with different percentages.

5.2. The ITS Test

The ITS test evaluates the tensile resistance of asphalt concrete. This test requires preparing the specimens using the Marshall test procedure specified by ASTM D6931 [57]. In the middle of Iraq, the weather temperature ranges between intermediate to high for most of the year. Therefore, three testing temperatures, 25 °C, 40 °C, and 60 °C, have been selected to investigate the effect of temperature on tensile strength properties for asphalt concrete mixes of different filler combinations. The specimens were prepared at %OBC, which was determined previously, for each filler combination. The test was carried out using a loading machine with a 50.8 mm/min loading rate. The specimens were positioned vertically between two loading plates using lower and upper curved metal strips with a width of 12.7mm (0.5”) as shown in Figure 6.

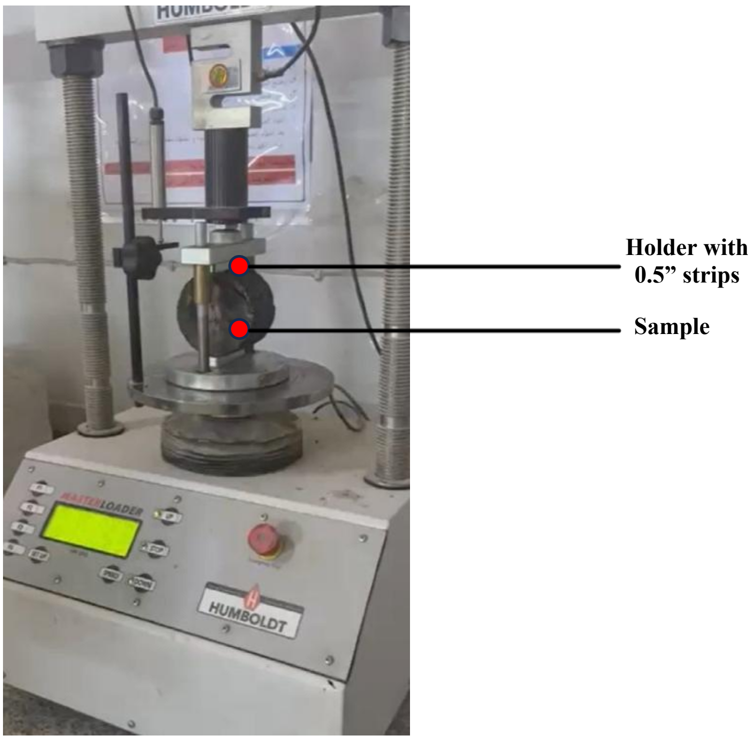

Figure 6. ITS test

The ultimate recorded load was used to calculate the indirect tensile strength using the following equation:

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot T} \quad (1)$$

where P: ultimate load, D: specimen diameter, and T: specimen thickness.

5.3. The Moisture Effects

As an external structure, the road's paving materials face many weather conditions, such as moisture. Exposure to water may lead to significant deterioration of the flexible pavement. So, as in this study, it is necessary to investigate the moisture susceptibility of asphalt concrete made with different filler materials. Accordingly, the ITS test assessed the tensile strength before and after the asphalt concrete specimens were subjected to moisture effects. ASTM D4867 [58] requires that the specimens be prepared using the Marshall test procedure with an air voids percentage of 7±1%. The relations between (compaction effort) number of blows per sample end and %AV have been correlated for each filler combination mix at %OBC. The 38-40 blows per end prepared the specimens with required air voids according to filler combination. Two specimen groups (unconditioned and conditioned) have been prepared, each containing specimens of different filler combinations. As needed, the vacuum device was used to get the saturation degree between 70-80%. Then, the partially saturated samples were sealed with Saran Wrap, put in a plastic bag with about 10 ml of water, and stored in a freezer at -18±3 °C for more than 16 hours. After the freezing phase, the samples were put in a water bath at 60 °C for 24 hours. Finally, the specimens were cooled to 25 °C using a water bath for about 2 hours to prepare for the ITS test. The testing results of two groups were used to determine the Tensile Strength Ratio (TSR) for each filler combination mix using formula number 2.

$$TSR = \frac{ITS_{Cond.}}{ITS_{Uncond.}} \quad (2)$$

where: $ITS_{Cond.}$: Indirect Tensile Strength for Conditioned sample, and $ITS_{Uncond.}$: Indirect Tensile Strength for Unconditioned sample.

6. Results and Discussion

Based on the carried-out tests, the main outcomes of studying the effect of replacement of the OPC filler with EAFSP partially and totally on the properties of asphalt concrete can be divided into three categories: 1) Marshall test attributes, 2) Tensile strength, and 3) Tensile strength ratio.

6.1. Marshall Attributes

Besides its use in designing the asphalt concrete mix, the Marshall test can be used to evaluate asphalt concrete by using the strength, deformation, and volumetric properties that result from the test. So, the following results show the effect of partially replacing the cement filler with EAFSP.

6.1.1.1 Optimum Binder Content (%OBC)

As the percentage of replacing the OPC with EAFSP increased, the required %OBC increased, as shown in Figure 7. This increase might belong to the surface area of EAFSP, which is more than that of OPC, which needs more binder for covering and absorbing particles. It can also be seen that the increasing rate was about 2-3% for each replacement ratio compared with a zero per cent replacement condition. The total replacement of EAFSP instead of OPC needed about 13% more binder.

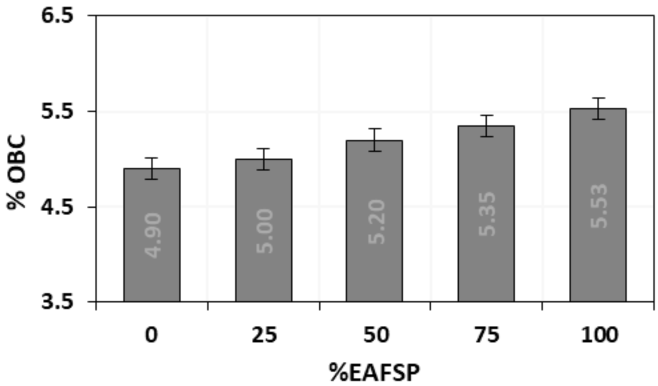

Figure 7. The change of %OBC with the ratio of EAFSP in the mix

6.1.2. Strength Properties

The stability (maximum strength) increased as the ratio of EAFSP increased. It can be seen from Figure 8 that the increase was nonlinear; it started slightly, and then the mixes with ratios of 75 and 100% EAFSP replacement showed a noticeable change. This change can be explained by increasing the stiffness of asphalt concrete by increasing the EAFSP ratio. This is clearer in Figures 9 and 10, which show the flow (deformation) and the stiffness (stability/flow) of asphalt concrete, which behaves stiffer in high ratios when using EAFSP as a filler material.

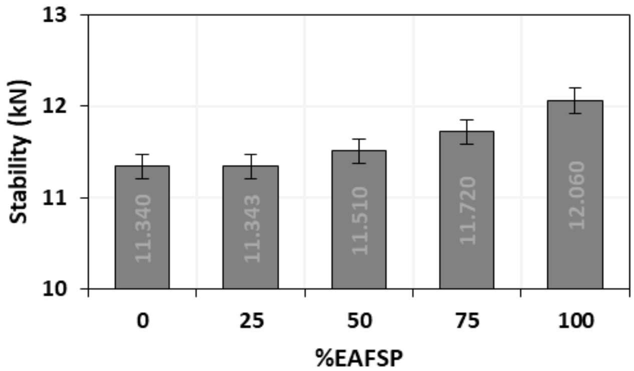

Figure 8. Effect of EAFSP replacement ratio on stability of asphalt concrete

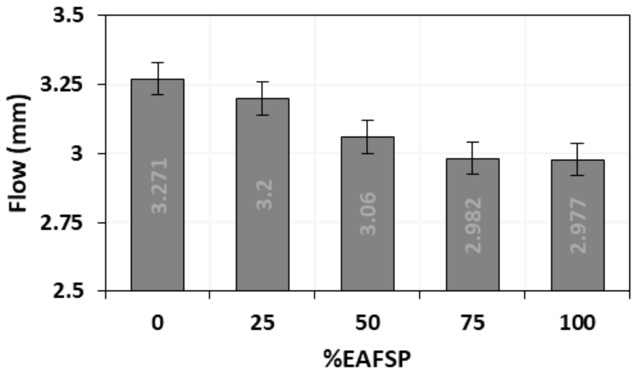

Figure 9. Effect of EAFSP replacement ratio on the flow of asphalt concrete

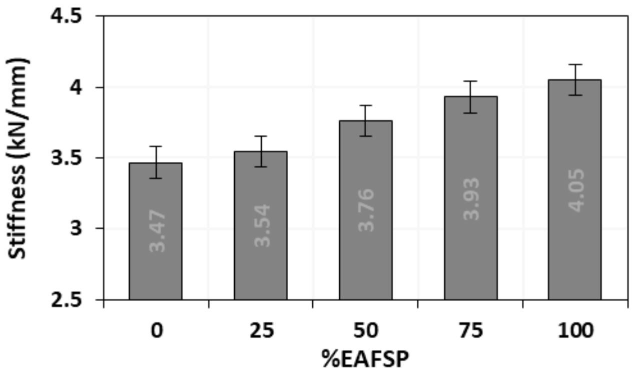

Figure 10. Effect of EAFSP replacement ratio on the stiffness of asphalt concrete

The result of strength properties shows a good agreement with the result of the study that was made by Al-Tameemi, et al. [31], who investigated the effect of using the slag powder as a filler material for asphalt concrete.

6.1.3. Volumetric Properties

Asphalt concrete contains granular materials represented by coarse and fine aggregate, besides mineral filler. These materials should form a dense product with a binder to give the required bonding to the mix. The criteria required a certain level of densification to help the mix perform at an acceptable level during its service life as a paving material. As presented earlier, these criteria require a blend with an air void of 3-5%, 14% voids in mineral aggregate, and 70-80% voids filled with asphalt. The effect of using EAFSP as a filler material on the volumetric properties' bulk density, voids in total mix, voids in mineral aggregate, and voids filled with asphalt is presented in Figures 11 to 14. It is apparent from this figure that the increase in the EAFSP ratio leads to a decrease in the total mix, which affects the increase in the voids in mineral aggregate and voids filled with asphalt. The increase in the percentage of voids filled with asphalt might belong to the fineness of EAFSP, which helps the asphalt mastic enter the voids unavailable with the asphalt mastic of OPC. That may also explain the increase in the stiffness of asphalt concrete with the rise in the ratio of EAFSP in the filler combination.

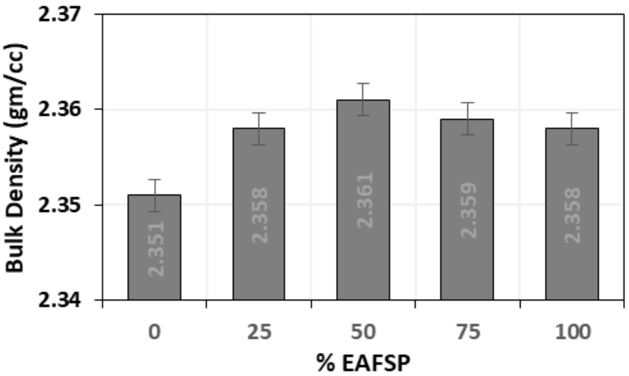

Figure 11. The effect of EAFSP ratio in filler combination on bulk density of asphalt concrete.

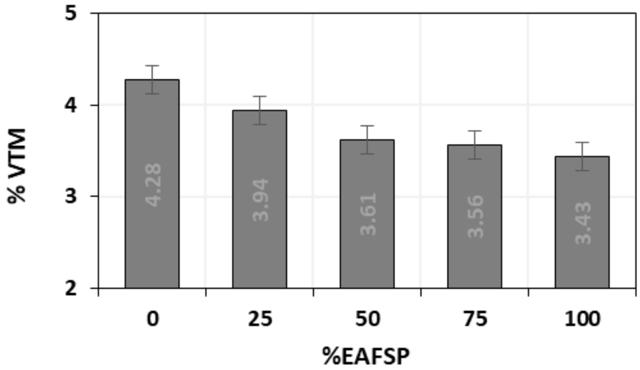

Figure 12. The effect of EAFSP ratio in filler combination on voids in total asphalt concrete mix.

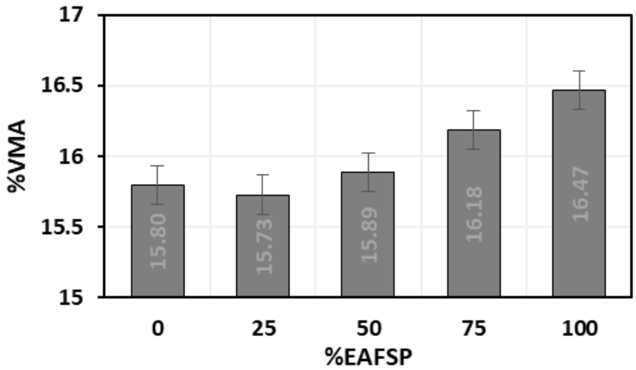

Figure 13. The effect of EAFSP ratio in filler combination on voids in mineral aggregate of asphalt concrete.

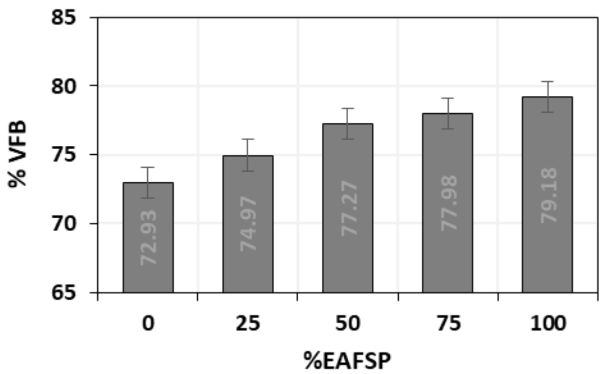

Figure 14. The effect of EAFSP ratio in filler combination on voids filled asphalt of asphalt concrete

6.2. Tensile Strength

To evaluate the effect of replacing OPC with EAFSP as a filler material, the tensile strength of asphalt concrete mixes made with different combinations of filler material was investigated. So, the ITS has been selected for this purpose. The test was conducted in various testing temperatures and sample conditions to study the susceptibility to temperature and moisture.

6.2.1. Temperatures Susceptibility

Figure 15 shows the ITS test result for three testing temperatures, 25, 40, and 60 °C, which were selected to study the effect of EABF as filler material on the tensile strength of asphalt concrete. The impact of replacing OPC with EAFSP was greater at high temperatures, reaching about 34% for 100% replacement. In comparison, it was about 11% at 25 °C and about 26% at 40 °C for the same replacement rate, relative to a 0% replacement ratio. These results indicate that using EAFSP as filler material will be useful at high temperatures.

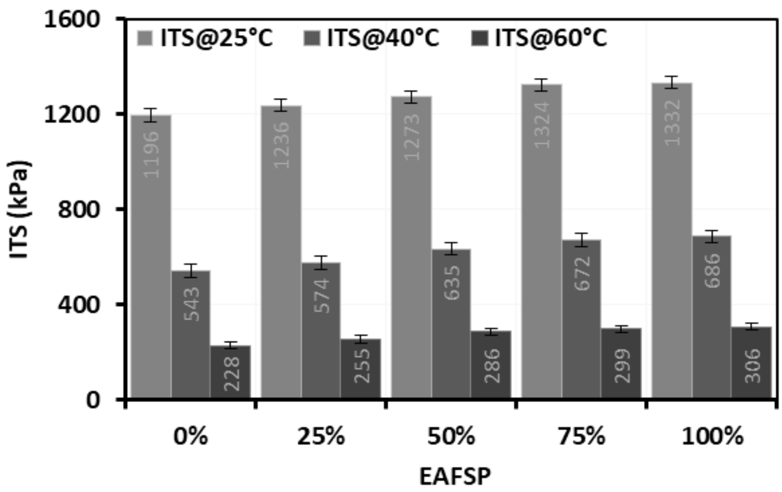

Figure 15. Tensile strength of asphalt concrete made with different filler combinations at various temperatures

6.2.2. Moisture Effect

The conditioned samples subjected to moisture, freezing, and thawing effects were tested using the ITS test. The results of these samples have been relatively compared with unconditioned tested samples to find the tensile strength ratio (TSR). Figures 16 and 17 show the results of this test. It can be seen that all mixes pass the required limit of 80% for accepted mixes. The results of TSR are close to each other, but the replacement ratio of 50% of EAFSP has the highest percentage of tensile strength. This result may be attributed to the mean binder content at this replacement ratio, which reduces conditioning effects compared with specimens with more or lower binder content.

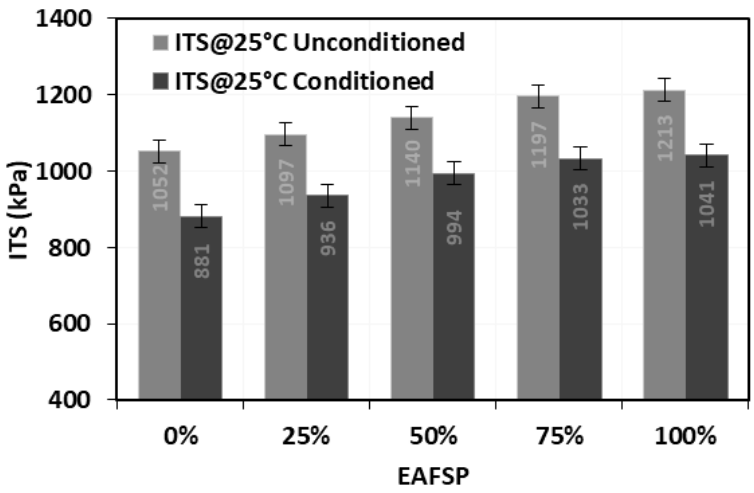

Figure 16. Tensile strength of asphalt concrete made with different filler combinations at various temperatures.

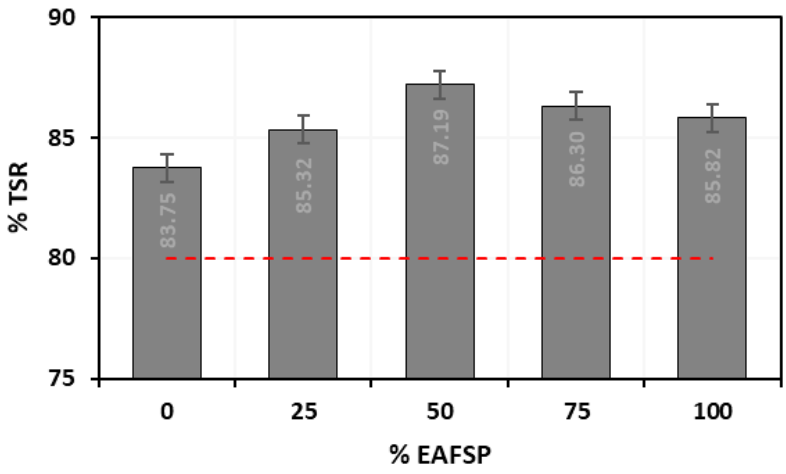

Figure 17. Tensile strength of asphalt concrete made with different filler combinations at various temperatures

7. Selecting the EAFSP Replacement Ratio

Based on the results of this study, it can be recognised that the use of EAFSP as a filler material for asphalt concrete has positive and negative points. Besides reducing the amount of OPC, it enhanced the strength of asphalt concrete and improved the temperature susceptibility and resistance to moisture damage. On the other hand, the increasing EAFSP replacement ratio instead of OPC required more binder content due to its surface area, which is more than OPC. The volumetric properties were also affected as the ratio of EAFSP increased the voids in the total mix, which led to an increase in the stiffness of asphalt concrete, which is not preferable in cold weather because of low resistance to cracking distresses. Consequently, the use of EAFSP as filler material should be determined according to the requirements, binder cost, availability, and weather conditions. The following table presents the proposed replacement ratio of EAFSP based on the weather conditions the pavement may face during its service life.

Table 8. The proposed replacement ratio of EAFSP is based on the weather conditions

Weather condition	Hot	Cold
Dry	75%	25%
Rainy	100%	50%

8. Conclusions

The main outcomes of evaluating the effect of using slag powder as a mineral filler material on asphalt concrete properties can be listed on the following points:

- The increase in the replacement ratio of EAFSP instead of OPC from 0 to 100% with steps of 25% changed the Marshall properties as follows:
  - The %OBC increased by about 13% for the total replacement, with an increment of 2-3% for each ratio.
  - The stability increased as the %EAFSP increased, gaining about 6% at a 100% replacement ratio.
  - The flow decreased as the EAFSP ratio increased, losing about 9% at the total replacement ratio.
  - The stiffness increased by about 2, 8, 13, and 16% with increasing the replacement ratio.
  - The bulk density increased, reaching a maximum value at 50% replacement ratio, and then decreased.
  - The voids in the total mix decrease as the ratio of EAFSP replacement increases in the mix.
  - The voids in mineral aggregate decreased slightly to a 25% ratio, then increased.
  - The voids filled with asphalt increased as the replacement ratio increased.
- The temperature susceptibility of asphalt concrete mixes with different filler combinations, evaluated using the indirect tensile test, revealed that increasing the EAFSP improves the loading resistance as the temperature increases.
- The assessment of the moisture effect on asphalt concrete with different contents of slag powder showed that:
  - The resistance to moisture effect improved when EAFSP was used as a filler material compared with OPC.
  - The tensile strength ratio test results showed that the maximum resistance was at a 50% EAFSP replacement ratio.

- Based on the results of this study, the limitations of using EAFSP were suggested according to cost analysis and materials availability, in addition to the requirements and weather conditions as follows:
    - Reducing the EAFSP for cold weather conditions is preferred to avoid low-temperature cracking.
    - When the rutting resistance is required in hot weather conditions, the EAFSP should be increased.
    - A mid to high ratio of EAFSP is required in rainy and cold to high-temperature weather, respectively.
    - It is worth mentioning that increasing EAFSP requires more asphalt content, so it is recommended to carry out a cost-benefit analysis and materials availability before deciding to use EAFSP as a mineral filler material in the asphalt concrete mix.
- It is highly recommended that this study be extended to assess the performance characteristics of flexible pavements subjected to different weather and loading conditions based on field measurements using EAFSP.

9. Declarations

9.1. Author Contributions

Conceptualization, Z.M.H. and M.Z.M.; methodology, M.Z.M.; software, M.A.M.; validation, Z.M.H. and M.Z.M.; formal analysis, Z.M.H.; investigation, M.Z.M.; resources, Z.M.H.; data curation, M.A.M.; writing—original draft preparation, M.Z.M.; writing—review and editing, M.A.M.; visualization, M.Z.M.; supervision, Z.M.H.; project administration, M.Z.M.; funding acquisition, Z.M.H. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in the article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Acknowledgements

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9.5. Conflicts of Interest

The authors declare no conflict of interest.

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