Research Article

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Assessment of potential resistance to moisture damage and fatigue cracks of asphalt mixture modified with ground granulated blast furnace slag

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Abstract: Fatigue and moisture damage have been recognized as the most prevalent problems on asphalt roads, necessitating large annual expenditures for road maintenance. Much industrial waste is added to bitumen paving to enhance its conventional quality while decreasing the negative impacts on the natural environment and increasing resistance to pavement distress. This research uses ground granulated blast furnace slag (GGBFS) to substitute conventional filler (Portland cement [PC]) in hot mix asphalt (HMA). To determine how the GGBFS affects the HMA's susceptibility to moisture and fatigue cracks, Marshall characteristics, tensile strength ratio (TSR), and index of retained strength (IRS) of the asphalt concrete were evaluated. HMA was prepared with different rates of GGBFS (0, 25, 50, 75, and 100%) instead of PC. The data support the usage of 50% GGBFS in asphalt pavements as a partial replacement of PC, which enhanced Marshal stability by 34.4%, reduced flow value by about 12.9%, and increased TSR and IRS by 11.1 and 14.54%, respectively. The fatigue resistance of the modified asphalt mix at the optimum rate was evaluated with the four-point bending beam test; the fatigue life (Nf) increased by 33.8% relative to the reference mixture. The results obtained from this research hold scientific value for researchers and method designers aiming to enhance the resistance of hot asphalt mixtures to moisture and cracking. Using waste materials as an alternative to PC contributes to cost reduction while mitigating the environmental damages associated with cement manufacturing. To summarize, this research highlights the significance of exploring sustainable options in the construction industry, emphasizing the importance of reducing costs, and minimizing environmental impacts.

Keywords: Marshall test, fatigue cracks, moisture damage, ground granulated blast furnace slag, index of retained strength, tensile strength ratio

1 Introduction

After the nineteenth century, the use of asphalt paving mixture spreads quickly around the world [1]. As a result, the total length of bituminous roads now exceeds three times the circumference of the Sun [2]. Significant investment is required for the development of the highways. The global interstate pavement construction industry has experienced substantial growth in recent decades as a result of a substantial increase in traffic volumes and permissible axial loads [3]. To mitigate the damages caused by these factors, there is a need for continuous improvement in road paving materials. This improvement is crucial to accommodate the predicted loads [4] and ensure the provision of affordable, safe, and long-lasting pavements [5]. Asphalt concrete (AC) consists of coarse and fine aggregate fillers and sometimes uses additives to enhance the AC performance.

Mineral filler is an inert substance that passes through a No. 200 sieve and can serve various functions in asphalt mixtures. First, filling the spaces left by the coarser particles and acting as a mineral aggregate component strengthens the mixture (increasing the mix's stiffness). Second, when combined with a binder, filler forms mastic, the high-consistency cement or binder that holds together larger binder particles; a significant portion of the filler may remain suspended binder, and a lesser component forms the load-bearing structure [6,7].

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"Durability, stability, flexibility, and skid resistance (in surface layers)" are the primary attributes that bitumen paving mixtures may possess [8]. The ability of hot mix asphalt (HMA) to resist the water action without suffering considerable decay is a crucial durability issue. The most common distress in HMA pavements is moisture damage, fatigue, and permanent deformation [9]. The main processes with moisture damage in bituminous pavement include the loss of the bitumen film cohesiveness and stiffness and the failure of the adhesive link between bitumen and aggregate [10] or the weakening of the bond among pavement layers [11]. The asphaltic pavement's susceptibility to moisture might be viewed as a severe flaw that led to stripping and other issues like fatigue cracking [12].

The industry focuses on sustainability in construction to save energy and lower carbon dioxide emissions [13,14]. Employing wastes from diverse industrial processes conserves invaluable resources, lowers pollution, and recovers energy used through waste generation [14,15]. The substantial quantity of unprocessed pavement components used for road construction and repair, such as asphalt binder and gravel materials, represents a detriment to losing the earth's resources and the associated negative impacts on the surrounding environment [16]. Incorporating these wastes in the bituminous pavement is an environmentally friendly and cost-effective option that, if built, can significantly increase the pavement's resilience to the common distress experienced by flexible paving [17,18]. Blast furnace slag is a byproduct produced by iron manufacturers. Iron ore, coal, and limestone are delivered into the furnace, and the resulting molten slag floats above the melting iron at approximately 1,500–1,600°C. The chemistry of melted slag, about 30–40% SiO_2 and 40% CaO, is virtually identical to the chemical composition of Portland cement (PC) [19]. The massive store of ground granulated blast furnace slag (GGBFS) has a variety of consequences. It takes up much space, and its sewage leakage causes water contamination and soil devastation during wet seasons. Environmental reuse ground granulated blast slag (GGBS) will address these challenges [20]. Compared to the energy needed to produce PC, less power is required to produce GGBS. Carbon dioxide emissions will significantly reduce when GGBS is used instead of PC. As a result, GGBS is an eco-friendly building material. GGBFS is widely used as an alternative cementitious material to PC in concrete works [21,22]. The use of GGBFS as an alternative cementitious material to PC is commonly used in concrete works. Few studies have addressed its use in various types of asphalt mixtures (cold, warm, and hot). The goal of this study is to learn more about whether or not it is possible to use GGBFS as a cement material in asphalt mixtures industry. Different amounts of slag will be added to the mixtures to make them more resistant and improve their performance.

Al-Khafaji et al. created a new cold mix asphalt designed as a binder course from waste resources. As fillers in a polymer-modified emulsion, GGBS was used to replace the mineral filler (limestone dust), and cement kiln dust (CKD) was used as an activator. The mechanical properties were examined using the indirect tensile stiffness modulus, and water susceptibility was assessed using the stiffness modulus ratio. Scanning electron microscopy (SEM) was then used to analyze the samples' microstructure. The outcomes showed that adding GGBS and CKD significantly improved the mechanical characteristics and the water susceptibility. SEM verified these improvements and linked them to the early hydration product production in the sample [23].

Shahba et al. studied the possibility of partially substituting styrene–butadiene–styrene with GGBS to modify bitumen and porous asphalt mixtures. The following tests assessed modified bitumen and asphalt mixes: "penetration test, softening point, ductility, Marshall stability (MS), indirect tensile strength (ITS), moisture susceptibility, uniaxial compression test, porosity, and permeability." The finding suggests that the additives used reduced bitumen penetration and ductility by 6–22 and 6.5–21%, respectively, while increasing its softening point from 43 to 60°C, strengthening asphalt mixture parameters such as Marshall strength, ITS, and uniaxial compression strength [24].

Al-Hdabi et al. evaluated using GGBFS instead of conventional mineral filler to produce the HMA. Marshall test, ITS test, compressive strength test, and mean MS ratio evaluated the mixes. The finding supported using GGBFS as a mineral filler in HMA. The stability was increased by 40% compared with the traditional blend; the durability of the modified mix was also enhanced. On the other hand, both the tensile strength ratio (TSR) and index of retained strength (IRS) of the GGBFS mix exhibited significant improvement compared with the control mix [25].

Chegenizadeh et al. studied the impact of applying GGBFS as a portion of filler materials (hydrated lime [HL]) in HMA on pavement distress. The control mixes with 1.5% HL were compared with the modified mixes with 1.5, 3, and 5% instead of HL. The results promote the usage of GGBFS in asphaltic pavements. The mixes with 3% GGBFS gave the best results after tasting with fatigue, rutting, and AMPT tests [26].

Previous research has mainly focused on enhancing the efficiency of asphalt pavements or using alternate filler materials. This research aims to examine the possibility of utilizing GGBFS as a filler in HMA and demonstrate its influence on MS, moisture susceptibility (TSR and IRS), and fatigue resistance. The mixes designed with various proportions of GGBFS were used to assess the effect on moisture damage compliance with Iraqi requirements SCRB/R9, 2003 [27] and evaluate the performance of the modified asphalt mix using a four-bending beam test. The findings add significant scientific value to the study by extending the life-span of the pavement and increasing its strength. Additionally, the environmental impact of this approach is noteworthy as GGBFS is considered an industrial waste material, contributing to reducing the use of conventional cement materials and mitigating environmental waste.

2 Materials and test methods

The starting point of the laboratory work was to identify the optimal bitumen content (OBC) for the reference mixture (without the addition of the GGBFS). The OBC determined by this test will be used to create mixes for the Marshall test, indirect tensile, and compressive strength tests calculating TSR and IRS, respectively.

2.1 Asphalt cement

This study used one grade of asphalt cement (AC 40–50) from the al-Dora refinery. It was tested to ensure it complied with SCRB/R9, 2003. The physical characteristics of AC are represented in Table 1. The tests were done at the labs of the civil engineering department at the university of technology, Baghdad, Iraq.

2.2 Aggregate

Crushed stone from the Al-Nebaie quarry near Al-Taji, north of Baghdad, was used in this investigation. By conducting standard laboratory tests on coarse and fine aggregates, it was verified that they conform to the state Corporation of Roads and Bridges SCRB R/9 for aggregates used in the asphalt surface layer regarding gradation and physical properties. The wearing course aggregate's maximum size must adhere to the SCRB R/9, 2003. Table 2 and Figure 1 illustrate the used aggregate's physical properties and their gradient curves. The test were conducted by the National Center for Constructions Labs, Baghdad.

2.3 Filler

Cement, HL, and stone dust are the three fillers used most frequently in asphalt mixtures. It is feasible to use some materials as a whole or as a partial replacement for the filler to enhance the qualities of the asphalt mixture. In this study, PC and GGBFS were both used.

2.3.1 PC

The conventional asphalt mix was made using local ordinary PC as a mineral filler. The physical characteristics of PC are illustrated in Table 3.

2.3.2 GGBFS

GGBFS, in contrast, can be produced by the iron-making industry through organized processes based on temperature and duration, or it can be obtained from iron sections. Table 4 represents GGBFS's physical properties.

3 Experimental work

3.1 Marshal mix design method

The technique entails producing and complying with cylindrical asphalt paving mixture specimens measuring 4 in.

Table 1: Asphalt binder's physical characteristic

The conditions of laboratory tests	Standards	Tests values		Iraqi limitation CSRB/R9, 2003
Penetration, 25°C, (0.1 mm)	ASTM D5	44.5		40–50
Ductility, 25°C, 5 cm/min	ASTM D113	+120		>100
softening point (°C)	AD36	51.6		—
Specific gravity 25°C	ASTM D70	1.046		—
Flash and fire point	ASTM D92	Flash	295°C	>232°
		Fire	302°C	—
Rotational viscosity Pa s	ASTM-D4402	0.543@135°C		
		0.157@165°C		

Table 2: Coarse and fine aggregate's physical characteristics

Laboratory test	ASTM designations	Coarse aggregate	Fine aggregate	Iraqi limitation CSRB/R9, 2003
The Bulk specific gravity	ASTM C127, C 128	2.615	2.626	—
% Water absorption	ASTM-C 127, C 128	0.362	0.481	—
Toughness, by Los Angeles abrasion test	ASTM-C131	20.5%	—	Max. 30%

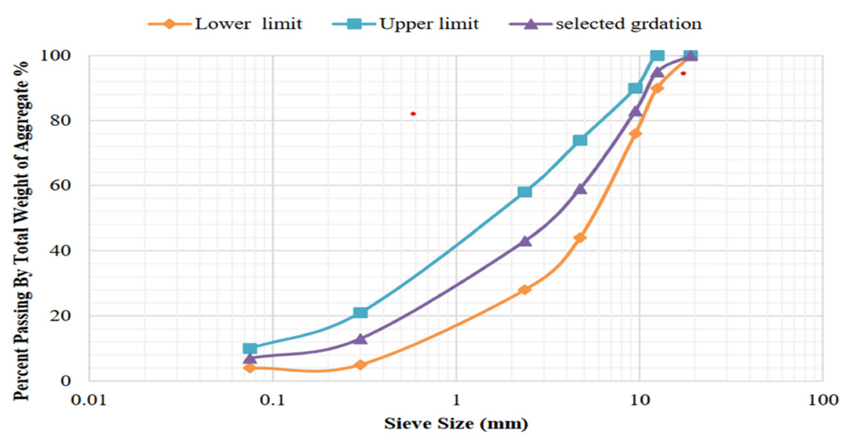

Figure 1: Aggregate's gradation curve.

Table 3: Physical characteristics of PC (tests were done by the NCCL, Bagdad, Iraq)

Properties	Tests results
Specific gravity	3.15
Passing sieve no. 200 (0.075 mm)	96%
Fineness (cm^2/g)	3,200

Table 4: Physical characteristics of GGBFS (the material processor processed these data)

Property	Test results
Slag	Hot
Type	Powder
Color	Light grey
Fineness	4,900–5,100 cm^2/g
Specific gravity	2.8
Passing sieve No.200 (0.075 mm)	97.5%

(101.6 mm) in diameter and nominally 2.5 in. (63.5 mm) in height, according to ASTM D6926-16 [28].

Determining the optimum binder content (OBC) was the first step. The asphaltic mixes were made and evaluated according to ASTM 6927-15 [29] for stability (MS), flow, density, air voids (VA), voids in mineral aggregate, and voids filled with asphalt. There were 15 prepared specimens in total (three for every%). The asphalt content of the mixtures was 4, 4.5, 5, 5.5, and 6%, respectively, by weight of the total mix. Consequently, the OBC was determined to be 4.9% of the total weight of the mix.

The second stage of the laboratory work included employing the optimum asphalt content that was calculated in preparing samples for the reference asphalt mixture (without adding GGBFS) and the improved mixtures where GGBFS was added in four different proportions, namely 25, 50, 75, and 100% by the weight of the mineral filler. These mixtures were then tested with the Marshal test to evaluate their MS, which represents the highest load resistance to the plastic flow, whereas the flow correlates with the strain's value at the highest load trace. Figure 2 shows the samples' preparation, mixing, and testing.

3.2 TSR specimen preparation and testing

To assess the moisture susceptibility of AC specimens ASTM D4867M-09 standards are followed [30]. The samples used in these tests had an VA of 7 ± 1% (the same as the number of voids in the field) obtained by trying different blows, as shown in Figure 3.

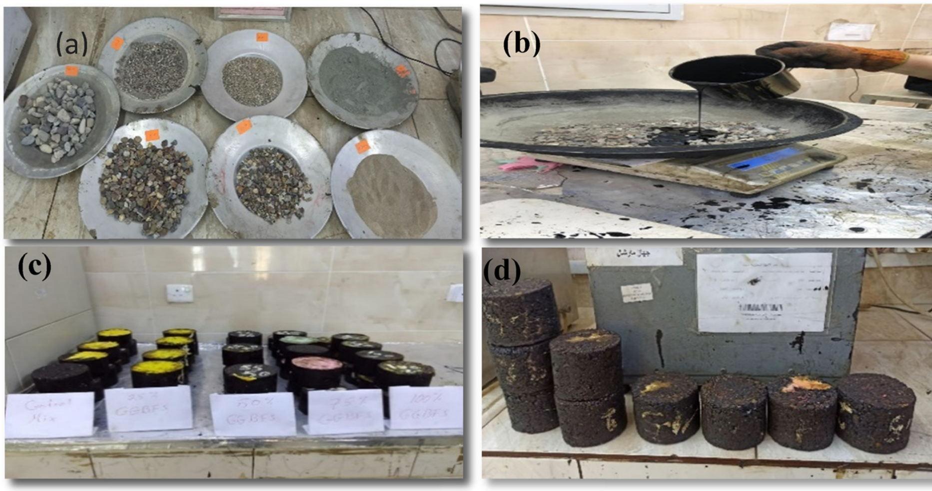

Figure 2: (a) Preparing the aggregate, (b) adding AC to the aggregate, (c) samples used in the tests, and (d) testing the samples.

After being removed from the mold, the prepared specimens were allowed to sit at room temperature for 24 h. They were then immersed in a water bath at 25°C for 30 min. The ITS [31] test procedure involves compressing a cylinder sample under two strips, creating a tensile stress in the vertical diametric plane and ultimately causing the sample to break. The ITS was run at a 50.8 mm/min rate until the sample broke. The maximum load value was captured at the instant the fracture appeared. The ITS was found using the following equation (Figures 4 and 5):

$$\mathrm{St} = 2 \times P/\pi \times D \quad \times t, \tag{1}$$

where St is the tensile strength (kPa), P is the maximum load (N), t is the height of the specimen (mm), D is the model diameter.

To determine the indirect strength ratio (TSR), two sets of molds are created for each additive percentage. Each set consists of three specimens. One of the groups tested dry, and the other wet. Wet specimens were placed in a vacuum container filled with distilled water to achieve a 55–80% saturation ratio. These partially saturated specimens are placed in a bath containing distilled water at 60 ± 1°C for 24 h. Finally, the temperature of the samples was adjusted to 25 ± 1°C by immersing them in another water bath before conducting the test. A constant load of 50 mm/min at 25°C was applied until failure, and the maximum load at failure was recorded and calculated for each group.

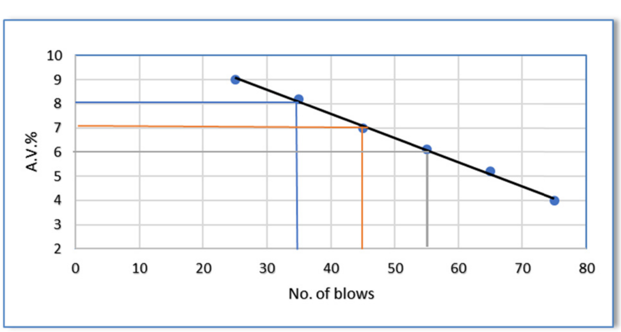

Figure 3: Relationship between number of blows and % A.V.

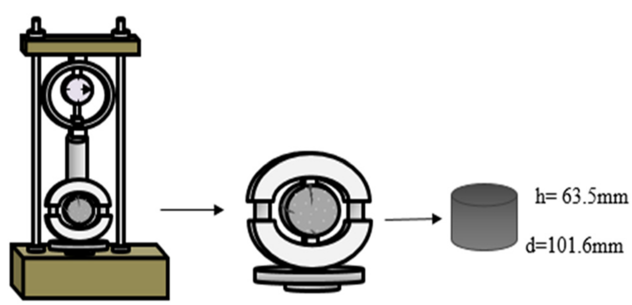

Figure 4: Testing sample with tensile strength apparatus.

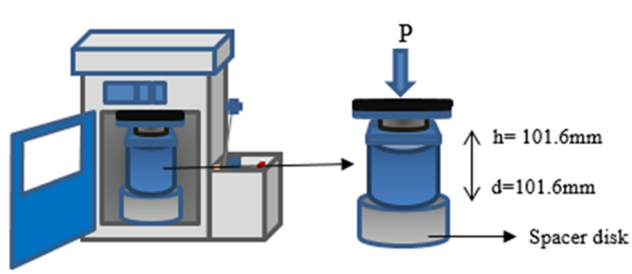

Figure 5: Specimens tested by compressive strength device.

The indirect tensile ratio (TSR) is computed following equation (2), and the minimum value of ITR should be 80% to meet Iraqi standards SCRB/R9, 2003.

$$\mathrm{TSR} = \left(\frac{S_1}{S_2}\right) \times 100, \qquad (2)$$

where TSR is the tensile strength ratio (%), S_1 is the soaked subset's relative tensile strength (kPa), and S_2 is the dry subset's relative tensile strength (kPa).

3.3 IRS: Specimen's preparation and testing

ASTM D1075-11 [32] covers the measurement of the loss of compressive strength resulting from the action of water on compacted bituminous mixtures containing asphalt cement.

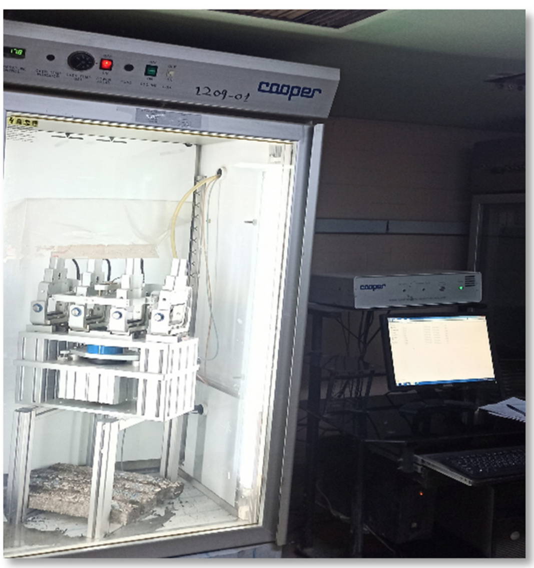

Figure 6: Flexural beam fatigue device.

Six samples, with 101.6 mm in diameter and 101.6 mm in height, were created for each percentage of the additive that has been used, and the samples were separated into two sets. The first set was composed of three samples left in the air path over 4 h at 25°C, after which the compressive test was conducted, and the mean value for the tested samples was documented (S_1). The other set similarly included another three samples. They were treated by storing them in a water bath to stay 24 h at 60 ± 1°C, then removing them and placing them in the water bath for 2 h at 25 ± 1°C. The test was then carried out on all these samples, and the mean value was documented (S_2). The experiment used a compressive force at a constant rate of 0.2 in./min (5.08 mm/min) to determine the maximal resistance load before failure. The IRS was determined following ASTM D 1075-07 equation (3), and the SCRB/R9, 2003, identified that the minimum value of IRS should be 70% to meet Iraqi standards.

$$\mathrm{IRS} = (S_2/S_1) \times 100\%, \qquad (3)$$

where S_2 is the specimen's wet compressive strength (kPa), S_1 is the specimen's dry compressive strength (kPa).

3.4 Four-point bending beam test

This test was performed using the flexural beam fatigue device, Figure 6, on the conventional mix with PC and modified asphalt mix using GGBFS. The test was done at the National Center for Construction Laboratories and Research laboratories. The test procedure was adopted according to AASHTO T321-14 [33] for the flexural beam test.

3.4.1 Fatigue sample preparation

The samples were compacted using the rolling wheel compactor (RWC), Figure 7, according to the Asphalt Institute

Figure 7: The RWC.

(1982) recommendations, which pointed to this compaction method creating samples more simulated to the *in situ* conditions.

The molds have a standard dimension of 400 mm in length, 300 mm in width, and 120 mm in height; they were used to create test beams by cutting the samples in several beams of 380 ± 6 mm in length, 63 ± 6 mm in width, and 50 ± 6 mm in height (Figure 8). The sample weight was approximately 13,800 g compacted to achieve the desired void percentage, which was 3.96%.

4 Results and discussion

To establish the optimum asphalt concentration in AC mixtures, five percentages of asphalt contents (4.0, 4.5, 5.0, 5.5, and 6.0%) by weight of the mixture are used. It was found to be 4.9% by weight of the total mix.

4.1 Marshal stability and flow

Mixtures were prepared, and the Marshall test was performed to decide the controlled and the improved HMA's properties and their suitability for road construction. Figure 9 depicts the MS results. The minimum stability requirement of 8 kN was met. The stability of all samples with varying percentages of GGBFs surpasses the performance of the controlled mix. The maximum stability value was obtained with HMA containing 50% GGBF with a 34.4% improvement rate. The HMA with 100% yielded the lowest value, but it is still higher than the control mix with 5.4%, and these results agree with Hanson et al. [26]. This means it can withstand more

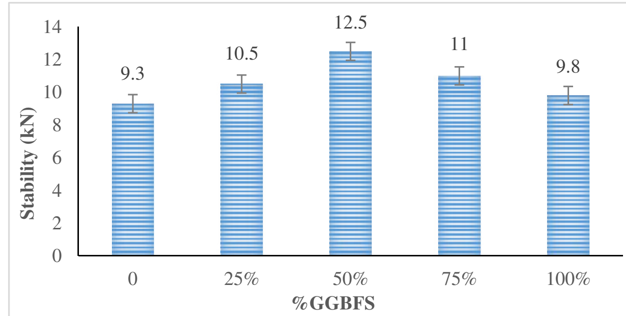

Figure 9: The effect of GGBFS content on MS.

horizontal deformation when subjected to heavy traffic loads. This improvement in MS values of GGBFS mixtures might be attributed to GGBFS particles strengthening the binder and enhancing the stiffness and cohesion of the new mastic [25].

The flow value is the overall deformation experienced by the Marshall test specimen at maximum load. Figure 10 represents the flow results for control and modified mixes. The flow value decreased gradually as GGBFS increased to 50% replacement. Because of the absorption of hydrocarbon elements from the asphalt, the stiffening of the mix makes it more stable and less deformed. As the percentages of the additive increase, so does the absorption rate. As a result, the binding between the mix's components weakens the flow value increases, and thus, its tendency to deform increases.

4.2 TSR

Including GGBFS significantly influences the amount of TSR in all the percentages employed in this article. As shown in Figure 11, values rose from 78.3 to 87% when

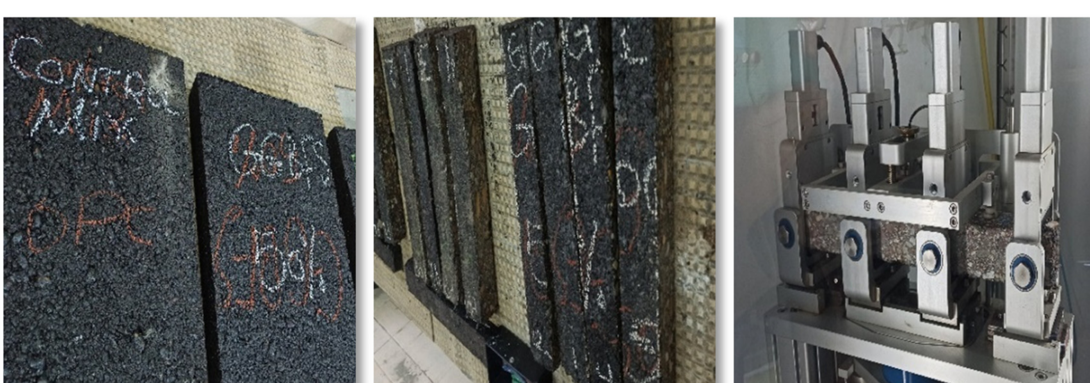

Figure 8: Fatigue test samples.

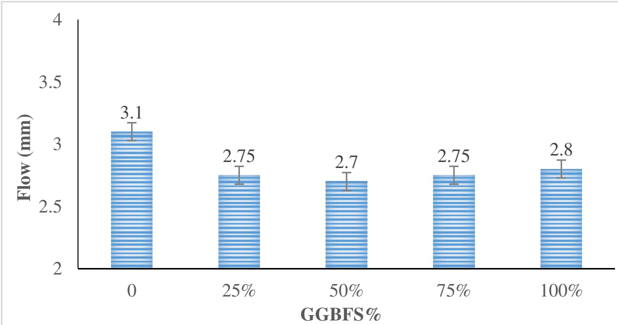

Figure 10: Effect of GGBFS content on Marshall flow.

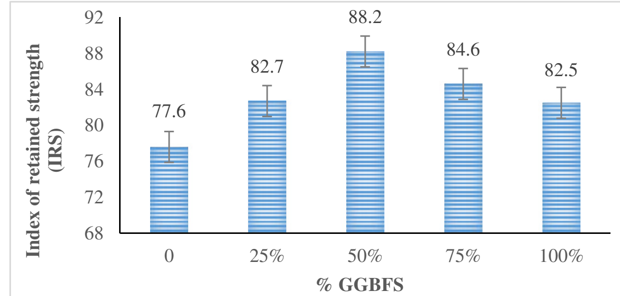

Figure 12: Impact of GGBFS on IRS.

the GGBFS content increased to 50% compared with the traditional mix, which will lead to lowering the potential hazard of moisture damage [25]. In contrast, increasing the GGBFS to more than 50% causes a reduction in the magnitude of tensile strength. Hence, the TSR of modified asphalt mixes is low due to the excessive hardness of the modified asphalt. This reduces the mix's workability and the amount of asphalt binder that coats the aggregate particles, rendering them susceptible to water infiltration and feeble. However, their resistance is still more significant than the reference mix [24].

4.3 IRS

The IRS was employed to assess the resistance of the mixtures to water damage for both conventional and mixes containing varying percentages of GGBFS. IRS calculated the average compressive strength of conditioned specimens (wet) to unconditioned models (dry) in each percent of GGBFS as a ratio. The results of the test are illustrated in Figure 12. The enhancement in IRS was clearly in the HMAs with GGBFS in all categories. The highest value was 88.2%, recorded at 50% GGBFS, while the control mixture with PC had a 77% IRS. Employing GGBS as a partial substitution for cement in HMA mixes has improved strength and durability. The increased strength can be attributed to the increased activity of GGBS with cement [21]. Continuously increasing the ratio of GGBFS decreases the compressive strength because of the rising hardness, making the asphalt mixture brittle and less resistant to applied loads.

4.4 Fatigue test result

A four-point bending test was conducted to evaluate the impact of adding GGBFS for enhancing HMA properties to resist fatigue cracking. The test was done according to the AASHTO T321 procedure. Constant strain mode at 400 με, 20°C, and 5 Hz were the test variables that were input to the device's software. The initial stiffness and the fatigue life for control and modified asphalt mixes are explained in Figures 13 and 14.

The initial stiffness of HMA is defined as the flexural stiffness at the 100th load cycle. Figure 13 shows the effect of the GGBFS on the initial stiffness value. There was an increase in stiffness by 19% compared with the control mix, which conformed to the previous test result.

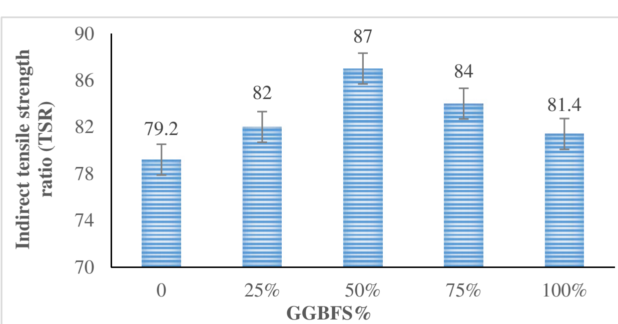

Figure 11: Effect of GGBFS content on TSR.

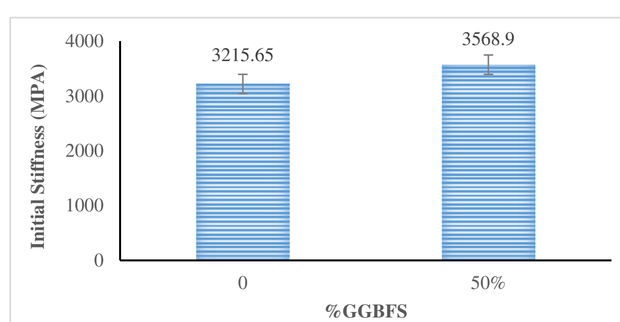

Figure 13: The initial stiffness of the HMAs before and after improvement.

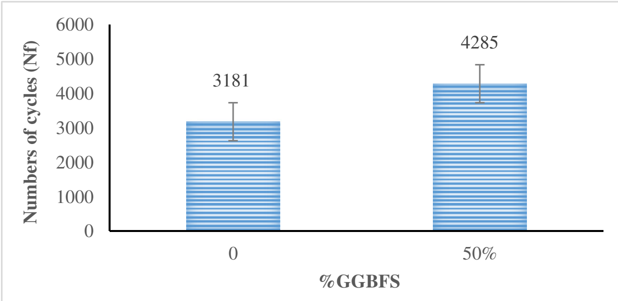

Figure 14: The relationship between HMA type and the number of cycles.

In this study, the bitumen mix beams' fatigue life (Nf) was defined as the total number of cycles that caused a 50% reduction in the initial flexural stiffness.

From the analysis of Figure 14, the number of cycles increased significantly by adding 50% GGBFS; the Nf increased by 33.8% relative to the reference mixture. The reason for this is that the use of GGBFS led to an increase in stiffness and an improvement in the mechanical properties of asphalt mixtures. The results are consistent with Chegenizadeh et al. [26]. Using GGBFS in HMA could be a promising solution for developing more durable and sustainable asphalt pavement.

5 Conclusion

This study has demonstrated the potential of using GGBFS as a substitute for cement in asphalt mixtures. The findings of this research highlight the following key points:

1. MS values significantly improve with the addition of GGBFS at different percentages (25, 50, 75, and 100%). Comparing the MS values to the conventional mix, which contained only ordinary PC as a filler, shows increases of 12.9, 34.4, 18.27, and 5.3%, respectively. These results could be due to enhancing the stiffness and cohesion of the new mastic.
2. The flow value of the mix was also impacted by using GGBFS in place of cement. For the compounds with 25, 50, 75, and 100% cement substitution, the flow value dropped by 11.29, 12.9, 12.25, and 9.67%, respectively. This shows that a greater GGBFS concentration causes a reduction in the mix's flow ability.
3. The indirect tensile ratio was improved by comparing each GGBFS combination to the standard mix. With rising GGBFS composition from 0 to 100%, the TSR reached its maximum value of 87% at 50% with a 9.84% increase rate. This shows that GGBFS improves the mix's tensile characteristics.
4. Including GGBFS also positively affected the mix's compressive strength. With 50% GGBFS content, the IRS reached 88.2%, demonstrating improved compressive strength recorded at 13.66% over the reference mixture. Increasing the activity of GGBS with cement improves the compressive strength.
5. In high concentrations, GGBFS hurts the performance of asphalt mixes by lowering their tensile and compressive strengths. This is because GGBFS is absorbed by the soft parts of asphalt (aromatic oils), which makes the bitumen stiff. As a result, bitumen becomes harder to deal with, and excellent workability is more challenging to achieve.
6. A relative improvement of around 33.8% was observed between the mix generated with 50% GGBFS and the reference mixture during the Nottingham fatigue test, indicating a considerable improvement in resistance to fatigue cracks. This improvement in crack resistance supports the results obtained during previous tests.
7. The experiments prove that GGBFS might partially replace the PC when utilized in an appropriate ratio.
8. In conclusion, the findings of this study highlight the added scientific value that GGBFS inclusion in asphalt mixtures brings. The improved stability, tensile and compressive strengths, and fatigue crack resistance demonstrate the applicability of these findings in the design and construction of asphalt pavements. However, caution should be exercised when using high concentrations of GGBFS since they might affect the performance of the mix in terms of workability and strength.
9. For future work, it is recommended to try other rates of GGBFS substitution to identify the optimal ratio that achieves the best results. In addition, it might conduct more performance tests to evaluate the GGBFS mix's behavior against rutting and low-temperature cracks.
10. Limitations: In scientific experimentation, the condition of laboratory equipment used for conducting tests and the difficulty in obtaining laboratory materials can indeed have an impact on the results. Additionally, the proportions of the additive used may also affect the outcomes. Therefore, it is recommended to explore alternative proportions. It is important to note that these factors should be considered within a scientific framework to ensure accurate and reliable results.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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