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Feasibility of using electric induction furnace steel slag and copper slag in the production of hot mix asphalt

Chaubey, N. K.[1] and Mishra, A. K.[2*]

[1]Research Scholar, Department of Civil Engineering, Madan Mohan Malaviya University of Technology Gorakhpur, Uttar Pradesh, India. e-mail: njchaubey@gmail.com
[2]Professor, Department of Civil Engineering, Madan Mohan Malaviya University of Technology Gorakhpur, Uttar Pradesh, India. e-mail: akmce@mmmut.ac.in

[*]**Corresponding Author e-mail**: akmce@mmmut.ac.in

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Abstract

Industries produce large amounts of electric induction furnace steel slag (EIF) and copper slag (CuS) as waste, and their disposal poses serious economic and environmental issues. The use of these slags in pavement could ease environmental concerns and promote the conservation of non-renewable resources. This paper is based on an experimental investigation into the potential for employing EIF and CuS at 0, 5, 10, 15, 20, and 25% as a partial replacement of fine natural granite aggregate (NGA), whose size ranges from 4.75 mm to 0.075 mm, in producing dense hot mix asphalt (HMA) mixes. The physical, chemical, morphological, and expansive properties of EIF and CuS were investigated. The Marshall method of mix design was adopted to produce HMA mixes. The results showed that for EIF-based HMA mixes, stability, indirect tensile strength (ITS), and rutting resistance increased, whereas for CuS-based HMA mixes, these properties decreased but satisfied their required permissible criteria. The tensile strength ratio (TSR) of EIF and CuS-based HMA mixes was found to be increased. The findings of this study indicated a high possibility for using EIF and CuS as aggregates, and a replacement level of 20% of these slags in HMA mixes was suggested as optimal.

Keywords: Recycled materials, Marshall stability, ITS, TSR, Rutting

1. Introduction

Rapid growth is taking place in the transportation sector in India due to an increased emphasis on infrastructure development. This is generating a huge demand for pavement materials, which is putting pressure on natural resources. On the other hand, industrial waste products such as steel slag, copper slag, blast furnace slag, fly ash, and other waste are found abundantly in India, which is resulting in a shortage of disposal areas and creating a tremendous threat to public health and ecology. India has the world's second-largest road network, with around 6.2 million kilometers, and it is growing at a rate of 37 kilometers per day to keep up with economic growth. Asphalt is used in the construction of nearly all major Indian highways, and this trend is projected to continue. The most extensively used method for building asphalt pavement is the hot mix asphalt (HMA) process. Natural aggregates make up about 90% of the total weight of the asphalt mixture. According to Chaubey and Mishra (2020), one kilometer of pavement requires approximately 30000 metric tons of aggregate. The environment and ecosystem are rapidly deteriorating because of excessive quarrying of natural aggregate resources. Therefore, new alternate materials as a substitute for natural aggregate must be discovered and developed to protect natural resources.

Substituting industrial by-products and wastes for natural aggregates is one of the easiest tactics for achieving sustainable pavements since it provides two benefits: One, the rate of depletion of natural resources can be reduced, and another, the deposition of waste in landfills can be avoided, resulting in environmental benefits. In addition to having a favorable impact on the environment, using these discarded materials in asphalt mixes can help achieve the goals of sustainable construction as per Ipekyol et al. (2022). Some studies have suggested that it is feasible to produce asphalt mixtures with recycled concrete aggregate (Xu et al., 2022), reclaimed asphalt pavement (Naser et al., 2022), steel slag (Zhao et al., 2022), waste ceramic (Rochlani et al., 2021), and glass powder (Ming et al., 2022). India's copper, iron, and steel industries, on the other hand, have grown fast in line with the country's rapid economic boom. The slag coming out of these industries is considered a strong construction material, and Patel and Shahu (2018) have suggested that it is possible to use it profitably in the construction of base and subbase courses instead of natural aggregates. Steel slag and copper slag are common waste materials that have been utilized in the road construction sector as aggregate.

India is estimated to produce 12 million tons of steel slag each year. Steel production in India is mainly done through oxygen and electric routes. The oxygen route comprises a basic oxygen furnace (BOF), while the electric route includes an electric arc furnace (EAF) and an electric induction furnace (EIF). According to Ghanbari and Bayat (2022), steel slag is a solid waste that is generated during the steelmaking process, and its utilization could be advantageous for environmentally friendly construction practices. For every ton of steel produced, a steel plant generates 2–4 tons of waste, which includes solids, liquids, and gases. It was stated by Xu et al. (2020) that the steel slag produced by proper crushing and processing resembles natural aggregate in shape and has shown improved mechanical properties, moisture susceptibility, skid resistance performances, and crack resistance behavior. Asi et al. (2007) investigated several samples of asphalt mixes produced by substituting 0%, 25%, 75%, and 100% coarse limestone aggregate with steel slag. They observed better indirect tensile strength, rutting resistance, resilient modulus, fatigue, stripping resistance, and creep modulus. Except for creep performance, improved mechanical properties of asphalt concrete mixes were discovered when 100% of the coarse limestone particles were replaced with steel slag. Steel slag replacement of coarse limestone aggregates was adequate at 75%, while 25% replacement was optimal. Ahmedzade and Sengoz (2009) examined the effects of using 100% steel slag in HMA. They discovered that steel slag mixed with asphalt mixtures demonstrated higher fatigue resistance, indirect tensile strength, and modulus values. To test the skid resistance of a thin asphalt surface, Kehagia (2009) carried out a site investigation on four different sections of a high-traffic PATHE motorway in Greece. It was observed that after one year of service, the EAF mixed asphalt mix outperformed the natural aggregate mixed asphalt. The mixture with the highest EAF content provided the most significant skid resistance. Steel slag was found to improve the roadway conditions in the study. Kandhal and Hoffman (1997) investigated the performance of asphalt mixes incorporating fine steel slag as aggregate in Pennsylvania. The steel slags in the asphalt mix, both cured and uncured, were discovered to be non-expanding. It was discovered that the expansion of untreated steel slag mixes was constrained by the presence of a bitumen layer on the steel slag. The Pennsylvania Department of Transportation permits the incorporation of fine and coarse steel slag aggregates with natural aggregates in producing asphalt mixes. Though steel slag mixtures with a higher asphalt content may minimize expansion, they also reduce skid resistance.

Despite having numerous advantages, there is literature available that explains the disadvantages of employing these slags in the production of asphalt mixes. It was reported by

Rohde et al. (2003) that the steel slag expands when it meets moisture due to the existence of free lime. Because when free lime reacts with water, it produces $Ca(OH)_2$, which causes an increase in volume. Consequently, volumetric instability can affect the performance of asphalt mixes. The use of steel slag in asphalt mixes must be restricted to replacing fine or coarse fractions of aggregates, but not both the sizes at the same time. Because of the angular shape of the steel slag, 100% steel slag mixed HMA mixes are more likely to develop a high percentage of air voids and expansion issues. Asi et al. (2007) reported that a high proportion of air voids consumes more asphalt content and will be prone to flushing because of traffic load. Moreover, it was also suggested that slags in asphalt mixes should be kept limited to avoid excessive density increases, which could result in higher mixing and transportation costs.

Copper slag (CuS) is a waste material that has shown high potential for its application in the asphalt mix. CuS is a waste obtained from the copper industry during the matte smelting, converting, and refining of copper. According to Chaubey and Mishra (2020), approximately 2.2 tons of CuS are generated for every ton of copper produced. As per Modarres and Bengar (2019), slag that has a copper content of less than 0.8 percent is often dumped as waste in slag dump yards. Deposition of copper slag causes various environmental issues, including pollutant seepage into groundwater, air pollution from dust dispersal, landscape effects, and land use restrictions. It is generally stored near copper mining and smelting premises. According to Ziari et al. (2017), granular CuS has many properties suitable for its use as aggregates, such as its angular and irregular morphology, better abrasion resistance, soundness, and low water absorption characteristics.

In a study conducted by Modarres and Bengar (2019), they investigated the usage of CuS powder as a filler in HMA mixtures. It was discovered that adding more CuS powder improved the mechanical characteristics of HMA. The average values of the ITS, indirect tensile toughness index, fatigue life, and resilient modulus of HMA containing the same proportion of CuS powder were 10.2, 8.5, 7.5, and 21.6% greater than those of the control mix, which contains 6% limestone filler. The parameters of the fatigue life indirect tensile toughness index and fatigue life resilient modulus were found to be significantly correlated. For all strain levels, the indirect tensile toughness index correlation coefficients were more important than the resilient modulus. All the samples were determined to meet the necessary requirements, and the presence of toxic components in the leachates obtained from the CuS powder and, in particular, the CuS powder based HMA was found to be less than the maximum allowable levels. Pundhir et al. (2005) investigated the mechanical properties of various types of bituminous mixtures, which contained up to 30% of fine CuS particles. Based on the results of stability and ITS, they concluded that CuS improves interlocking, which enhances the mechanical and volumetric properties of bituminous macadam, dense bituminous macadam, bituminous concrete, and semi-dense bituminous concrete. Hassan and Al-Jabri (2011) explored the feasibility of using granulated CuS as a fine portion of aggregate in HMA mixtures. Various aggregate mixtures containing up to 40 percent CuS were subjected to the Marshall mix design process. Master curves were established for the control and CuS-containing mixtures after executing the dynamic modulus testing at various frequencies ranging from 0.1 to 16 Hz and temperatures ranging from 25 to 60 °C. The modulus value was found to decrease with an increase in slag content as well as temperature. The obtained TSR was better than that of the control mix with limestone aggregates, even though the indirect tensile strength (ITS) findings for moisture resistance tests showed a loss. The findings suggest that using CuS as fine aggregate in HMA has enormous potential. To enhance performance and reduce industrial waste, Zalnezhad et al. (2022) carried out a laboratory investigation in order to explore the potential use of CuS at 0, 10, 20, 30, and 40% as a partial substitute for aggregate in producing microsurfacing mixtures. Their findings indicated that the use of CuS in microsurfacing treatment appeared to be quite promising. Due to its angularity and high fraction of Fe_2O_3 and SiO_2, CuS, especially at 30%, enhanced the performance of asphalt mixes with respect to abrasion resistance, curing time, and vertical and lateral displacement. The findings of the analysis of variance (ANOVA) also demonstrated that the cure time and deformations brought on by traffic loads were more significantly influenced by the CuS than by residual bitumen. Hu et al. (2022) conducted experimental work investigating the microwave absorption characteristics of HMA containing CuS. The specimen's interior temperature and heating rate were tested in the mixture cylinder at various heights using a fiber-optic thermometer. The infrared thermometer also captured the surface temperature. The effects of the mixture's age, heating capacity, and CuS content on its healing capacity were examined through semicircular three-point bending tests. According to reports, CuS has superior microwave absorption qualities compared to conventional aggregate. Compared to standard mixtures, the mixture with CuS has a more pronounced healing effect. The heating speed and healing effectiveness are significantly influenced by microwave heating power.

As per Indian Mineral Yearbook (2019), In India, there are approximately 18 BOF units, 50 EAF-based steel units, and 999 electric induction furnace units in operation. The standard integrated BOF approach produces about 44.6% of steel, and the electric route produces roughly 55.4% of steel, with the EIF and EAF routes accounting for 29.7% and 25.7% of production, respectively. To the best of the authors' knowledge, no research has been done on including EIF in the production of asphalt mixes, even though this approach produces far more steel than the EAF route. Moreover, limited research has been done on the inclusion of granulated CuS as a fine aggregate that passes 4.75 mm and is retained on a 0.075 mm sieve in producing HMA mixes.

Therefore, the research presented in this paper aims to study the feasibility of using EIF and CuS as fine aggregate in producing HMA mixtures and to minimize the consumption of mineral aggregates.

2. Materials and Methods

To ensure that the qualities of the materials to be used in the asphalt mixes are within the bounds specified in pertinent standards and guidelines, they were first examined using standard testing methods. The chemical, morphological, and volumetric expansion behaviors of EIF and CuS aggregates were determined to assess their suitability and feasibility for producing HMA mixtures. After testing the materials, the laboratory investigation was done on the HMA mixture produced by substituting NGA with EIF and CuS in fractions of 0, 5, 10, 15, 20, and 25%. The usefulness of replacing the fine NGA with both slags was concluded by evaluating the Marshall parameters for mechanical performance, the ITS test for cracking behavior, and the TSR test for determining moisture susceptibility and rutting resistance for assessing the deformation behavior of the HMA mixes. The data are statistically examined using analysis of variance (ANOVA) at a level of significance of 0.05. The methodology of this research is illustrated in Figure 1. Each of these procedures is discussed in detail in the following subsections:

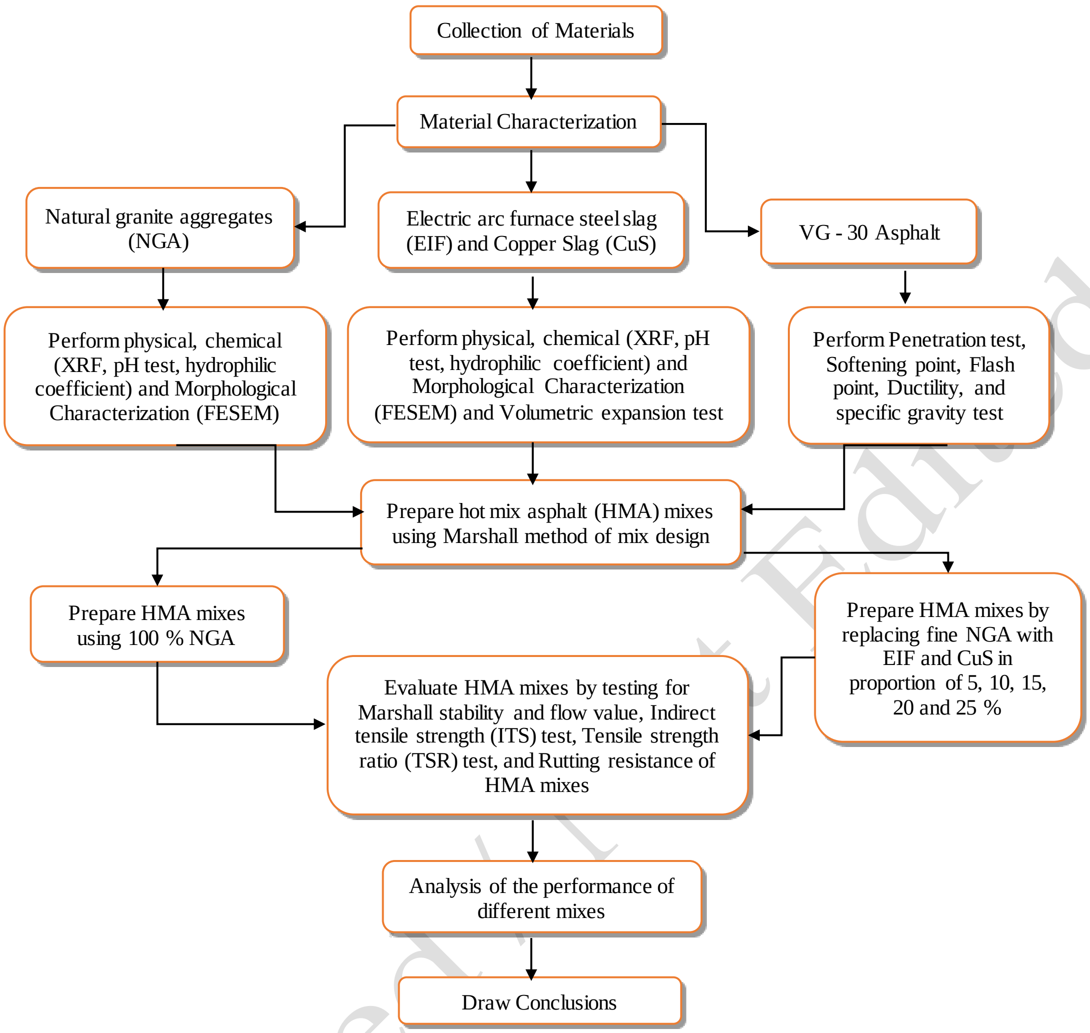

Fig. 1. Flowchart showing methodology

2.1 Aggregates

The NGA were obtained from the mines located in Kabrai city, Uttar Pradesh, India (25.42°N, 80.02°E), while the crushed EIF was procured from Gallant Ispat Limited, Sahjanwa, located in the district of Gorakhpur, Uttar Pradesh, India (26°45′N, 83°13′E), and the CuS was procured from the Indian Copper Complex, located in the district of East Singhbhum, Jharkhand, India (22.5950° N, 86.4515° E). Table 1 presents their physical characteristics. The general appearance of NGA, EIF, and CuS is shown in Figure 2. The middle gradation limit of dense bituminous macadam

(DBM) grade-II was chosen as per MoRTH (2013). Figure 3 shows the gradation curve used in this study.

Table 1. Physical and Mechanical Properties of NGA, EIF and CuS

Properties	NGA	EIF	CuS	Requirements for DBM (MoRTH 2013)	Test Method
Los Angeles abrasion value, %	23.22	21.43	18.35	≤35	IS 2386-4
Aggregate impact value, %	12.35	11.88	-	≤27	IS 2386-4
Combined flakiness and elongation indices, %	31.34	29.54	-	≤35	IS 2386-1
Water absorption of coarse aggregate, %	0.20	0.50	-	≤2	IS 2386-3
Water absorption of fine aggregate, %	1.40	2.10	1.87	≤2	IS 2386-3
Specific gravity of coarse aggregate	2.723	2.786	-	2.5-3.0	IS 2386-3
Specific gravity of fine aggregate	2.647	2.928	3.807	2.5-3.0	IS 2386-3
Stripping, %	>95	>95	-	≥95	IS 6241

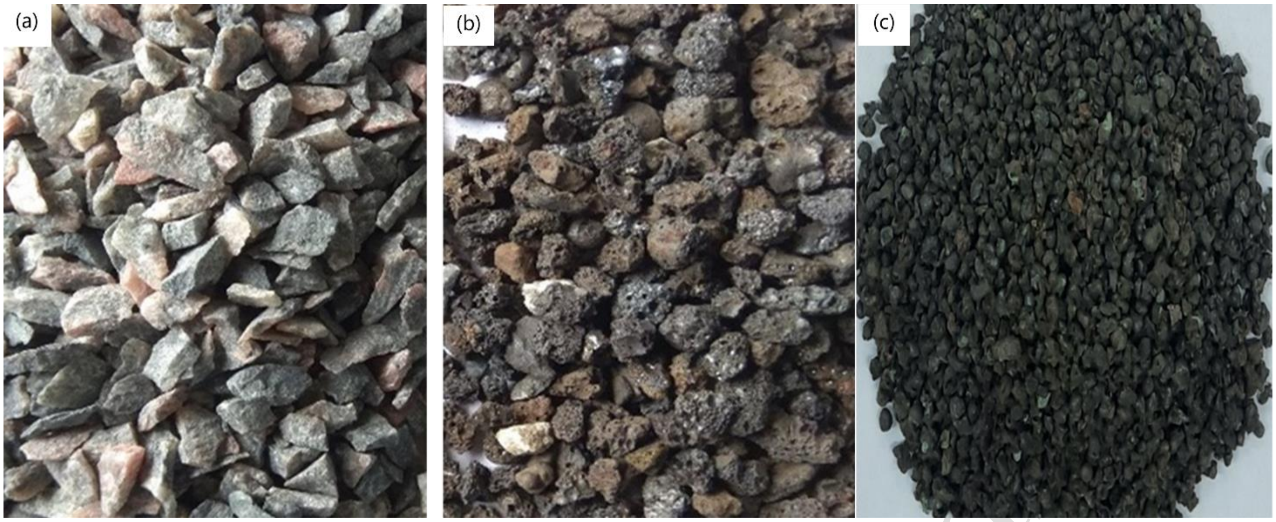

Fig.2. General appearance of (a) NGA, (b) EIFS and (c) CuS

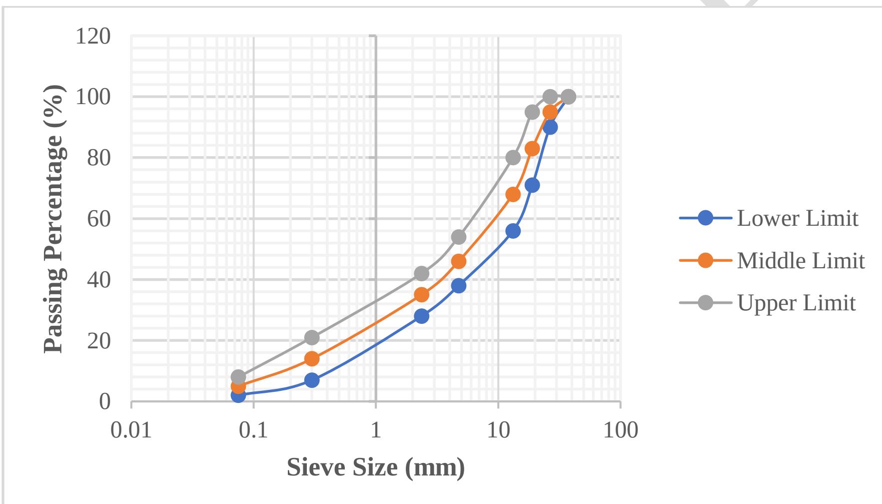

Fig. 3. DBM- II gradation curve

2.2 Asphalt

This study used asphalt with viscosity grade 30 (VG-30) produced by Hindustan Petroleum Corporation Limited. The results of the various tests conducted in accordance with Indian standard test procedures to assess the engineering features of the asphalt are shown in Table 2. All the properties of selected asphalt conform to the requirements as specified by IS 73 (2013) guidelines.

Table 2. Properties of asphalt

Characteristics	Result	Specifications	Test Method
Penetration at 25°C, 100 g, 5 s, 0.1 mm	66	≥ 45	IS 1203-1978
Softening point (R&B), °C	55	≥ 47	IS 1205-1978
Flash point	265	≥ 220	IS 1209-1978
Ductility at 25°C, cm	84.5	≥ 40	IS 1208-1978
Specific gravity	1.03	-	IS 1202-1978

2.3 Experimental program

The schematic representation of the experimental program conducted in this investigation is shown in Figure 1. The work was divided into two phases. The first phase included the characterization of NGA, EIF, and CuS, and in the second phase, the performance of slags incorporating HMA mixtures in terms of stability, cracking, moisture, and rutting was studied.

2.3.1. XRF analysis and pH Test

The XRF test was executed to obtain the chemical components of these aggregates. The experimental setup for XRF is depicted in Figure 4. The pressed pellets of NGA, EIF, and CuS were prepared to trace the chemical composition through an XRF test.

The alkalinity level of these aggregates was accessed by executing a pH test on them. A higher pH in aggregates is expected to increase their binding capacity with asphalt. Because of the acidic nature of asphalt, alkaline materials establish stronger bonds with it, providing higher resistance to stripping and thereby improving the resistance to moisture damage of asphalt mixes. Figure 5 shows the setup for the determination of pH. A specimen solution for each material was made by mixing it with distilled water in a 1:9 weight ratio and then setting it aside for two hours before testing.

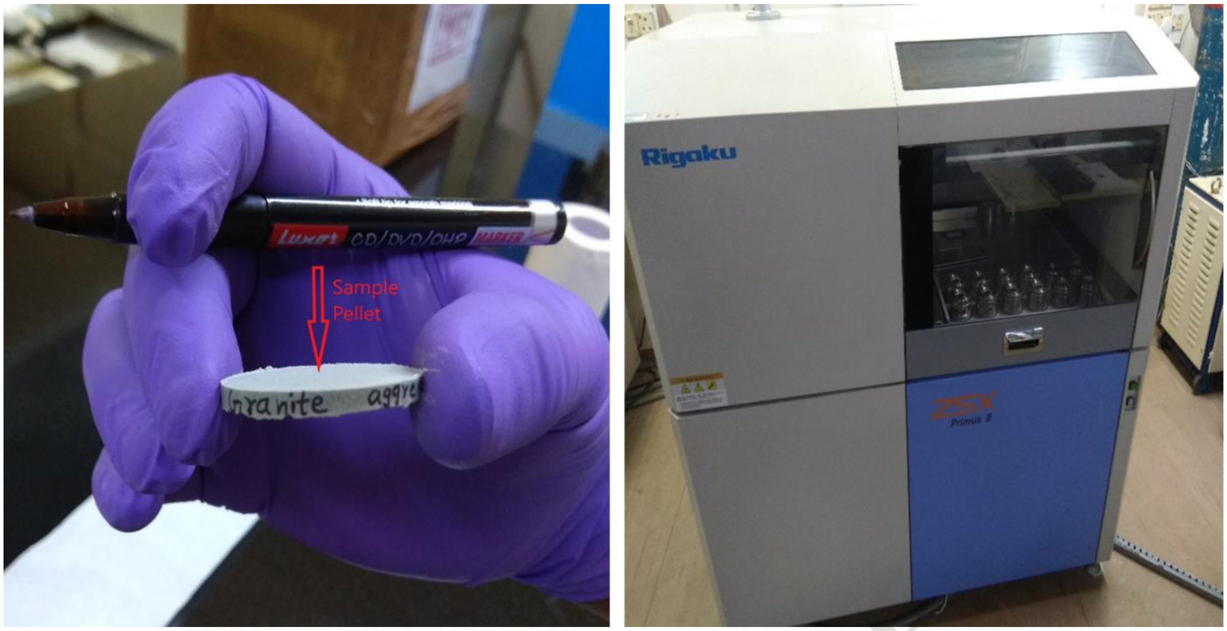

Fig. 4. XRF Test Setup

Fig. 5. Setup for the determination of pH value test

2.3.2. Hydrophilic coefficient

Some materials have a stronger affinity for water than asphalt. These materials are known as hydrophilic materials. Asphalt absorption on the surface of hydrophilic materials is substantially lower than that of hydrophobic materials when they are dry. Materials with hydrophobic characteristics stick to asphalt extremely well. Because hydrophilic elements do not have a reciprocal connection with asphalt, the quality of the asphalt mixes gets inferior, resulting in lower impermeability, strength, and temperature resistance. We must choose hydrophobic materials for making durable asphalt mixes. There is a procedure for choosing these materials. It is based on the hydrophilic coefficient of the materials being determined. During the research, the ability of the materials to absorb kerosene was compared with their ability to absorb water. The set-up for determining the hydrophilic coefficient is shown in Figure 6. Asphalt and kerosene are liquids that are covalently bonded. However, kerosene was utilized instead of asphalt during the test since kerosene has a lower density than asphalt, allowing for faster sedimentation. Because the sedimentation of materials was measured, quick sedimentation is extremely crucial. The hydrophilic coefficient is the ratio of volumes after 72 hours of material sedimentation in water to kerosene. The hydrophilic coefficient can be obtained from the following equation:

$$C = \frac{V_{water}}{V_{kerosene}}$$

Where C is the coefficient of hydrophilic, V_{water} is the volume of material in water after 72 hours of sedimentation, and $V_{kerosene}$ is the volume of material in kerosene after 72 hours of sedimentation.

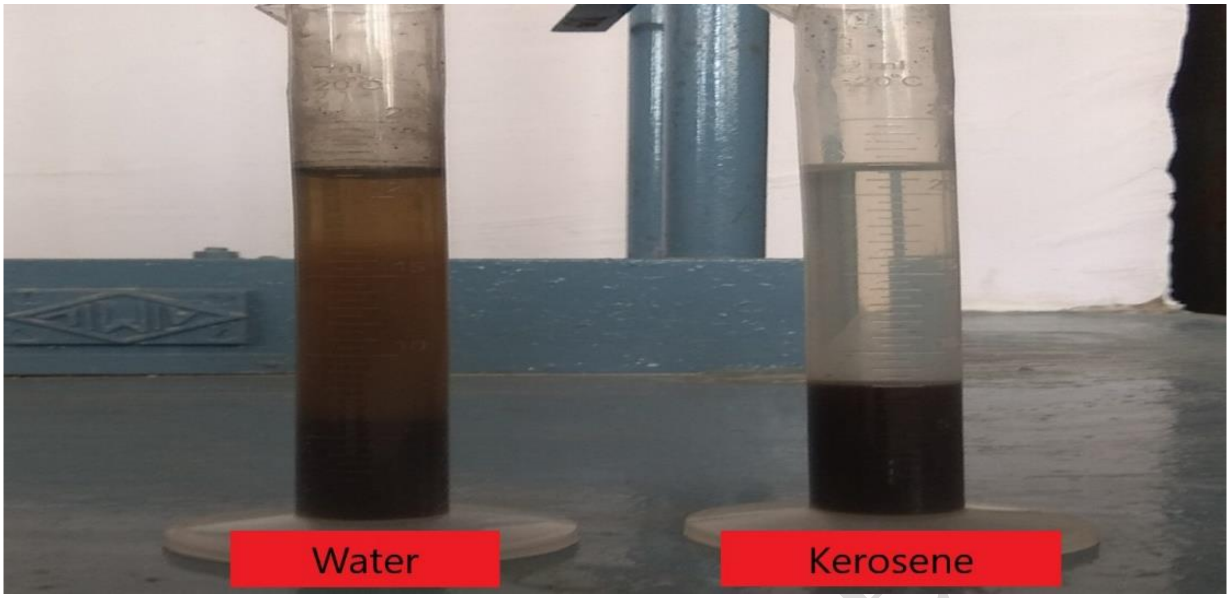

Fig. 6. Setup for the determination of hydrophilic coefficient value test

2.3.3. Morphological Characteristics

The field emission scanning electron microscope (FESEM) was used to obtain microscopic images of NGA, EIF, and CuS to study the morphological behaviors of aggregate surfaces.

2.3.4. Volumetric expansion

Because of the high CaO and MgO content, the slags may expand and disintegrate when exposed to moisture. The volumetric expansions of EIF and CuS were determined as per ASTM D4792 (2013).

2.3.5. Marshall test

Three types of HMA mixtures were produced with six different asphalt concentrations of 4.2, 4.5, 4.8, 5.1, 5.4, and 5.7% by weight of the total aggregates, in accordance with AASTHO T245 (2022). First, a control mix (CM) with 100% NGA was produced. Further, EIF and CuS-incorporated HMA mixes were prepared, respectively, by replacing 5, 10, 15, 20, and 25% of the fine fraction of NGA that passes through a sieve size of 4.75 mm and is retained at 0.075 mm. The specifications of each HMA mixture are represented in Table 3. The OAC of each asphalt mixture was calculated to correspond to a 4% air void as per MS-2 (2014).

Table 3. Types of HMA mixtures

Mixture Name	HMA Combinations
CM	Control mix having 100% NGA
EIF-5	5% EIF and 95% NGA
EIF -10	10% EIF and 90% NGA
EIF -15	15% EIF and 85% NGA
EIF -20	20% EIF and 80% NGA
EIF -25	25% EIF and 75% NGA
CuS-5	5% CuS and 95% NGA
CuS-10	10% CuS and 90% NGA
CuS-15	15% CuS and 85% NGA
CuS-20	20% CuS and 80% NGA
CuS-25	25 % CuS and 75 % NGA

2.3.6. ITS

The cracking performance of pavements is directly affected by their tensile strength. Cracking usually leads to more serious damage, such as potholes. The adhesion efficiency of the aggregate and asphalt mixture, which is a key aspect of its cracking behavior, determines the tensile strength of the asphalt mixture. Therefore, precisely measuring the tensile strength of asphalt mixtures is very important to the design and analysis of asphalt pavement. Ziaee and Behnia (2020) stated that it is challenging to measure the tensile strength of asphalt mixtures directly, the ITS test is commonly performed for this purpose. The ITS test was performed following ASTM D6931 (2012) guidelines. According to Gautam et al. (2018), the greater the value of ITS, the better the crack resistance.

2.3.7. TSR

The presence of moisture in asphalt mixes can weaken the bond between the asphalt and aggregates, causing the asphalt mixture to deteriorate and consequently reducing the load-bearing capacity of the asphalt pavement. Therefore, the damage caused by moisture in the asphalt mix was investigated. The tensile strength ratio (TSR) was determined in line with AASTHO T283 (2014) to measure the moisture sensitivity of asphalt mixes. TSR values were obtained as a percentage by dividing the indirect tensile strength of the conditioned samples (ITS wet) by the indirect tensile strength of the unconditioned samples (ITS dry). A TSR value below 80% is undesirable. Benavides et al. (2023) suggested that the greater the TSR ratio, the more resistant the mixture will be to moisture-induced damage.

2.3.8. Rutting

The rutting resistance of all HMA mixes was evaluated by measuring their MQ and performing wheel tracking tests on them. The MQ measures the stiffness and rutting resistance of the asphalt mixtures (Chaudhary et al., 2018). It was calculated by dividing the Marshall stability results by the flow value of the HMA mixes. A higher MQ provides better stiffness and improved capacity to distribute the imposed load while resisting creep deformation (Muniandy et al., 2018).

The rutting resistance was also measured by conducting wheel track tests on all the HMA mixes. This test was conducted following the EN 12697-22 test procedure, in which the apparatus moves a steel wheel with a 203.2 mm diameter and a 47 mm width across the surface of the test sample. The wheel traverses the sample 52 times per minute. This test was conducted on all the

HMA samples having a size of 300×300×50 mm at a temperature of 40°C with a loading of 705N over a course of 10,000 cycles. The Wheel tracking test assembly is shown in Figure 7.

Fig. 7. Wheel tracking test device

3. Results and discussion

3.1. XRF and pH test

The XRF investigation revealed the existence of calcium oxide (CaO), magnesium oxide (MgO), manganese oxide (MnO), aluminum oxide (Al_2O_3), silica oxide (SiO_2), iron oxide (Fe_2O_3), potassium oxide (K_2O), sodium oxide (Na_2O), phosphorus pentoxide (P_2O_5), titanium (TiO_2), and nickel oxide (NiO) as their fundamental chemical compositions. Due to their higher iron oxide content, EIF and CuS have a higher specific gravity than NGA. The XRF outcomes of these aggregates are presented in Table 4.

Table 4. XRF results of NGA, EIF, and CuS

Materials	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	P_2O_5	SiO_2	TiO_2	NiO	MnO
NGA	12.78	0.44	2.62	3.89	1.14	0.27	0.05	65.42	0.57	0	0.03
EIF	9.95	2.96	25.27	0.73	1.11	0.51	0.1	45.8	0.78	0	0
CuS	3.08	1.93	52.56	0.74	0.46	0.14	0.08	29.46	0.27	0.05	0.03

According to the results of the pH test, both the slag materials had pH values greater than 7, indicating that they were alkaline. Since aggregates with a higher alkalinity level have a greater ability to form bonds with acidic asphalt, a higher pH for EIF and CuS is anticipated to increase their ability to bind to asphalt compared to NGA, improving the resistance to moisture damage of asphalt mixes. EIF was discovered to have a higher pH value than NGA and CuS. The results of the pH value test are shown in Table 5.

Table 5. pH value of materials

Materials	pH value
NGA	8.83
EIF	9.63
CuS	9.52

3.2. Hydrophilic coefficient

Hydrophilic compounds absorb more water than kerosene. Therefore, they have a higher volume in water than in kerosene, resulting in a high hydrophilic coefficient, whereas hydrophobic compounds have a larger volume in kerosene than in water, hence their hydrophilic coefficient will be low. If the coefficient value is more than 1, the compound is hydrophilic, and it is hydrophobic if the value is less than 1. As per Chaudhary et al. (2018), the hydrophilic coefficient for asphalt-suitable materials should be between 0.7 and 0.85. According to the test results shown in Table 6, all of the materials exhibited hydrophobic properties, but EIF outperformed NGA and CuS. Therefore, its inclusion in asphalt may bestow durable asphalt mixes.

Table 6. Coefficient of hydrophilic of materials

Materials	Coefficient of hydrophilic
NGA	0.94
EIF	0.75
CuS	0.91

3.3. FESEM Analysis

Yu et al. (2023) have suggested that the mechanical characteristics, rutting behavior, and moisture susceptibility of asphalt mixes are influenced by the surface morphology of the aggregates. Microscopic images of EIF, CuS, and NGA were acquired at different magnifications using FESEM and are shown in Figure 8. The EIF was found to have thicker, longer, and deeper surface pores and voids than those of the CuS and NGA, as seen in the obtained images. The surface characteristics of EIF were found to be similar to those found by Oluwasola et al. (2016). In their study, the EAF steel slag was discovered to be more porous and irregular than granite aggregate, which enhanced its bonding ability with asphalt. In addition, their mineralogical properties enhanced their alkalinity further, demonstrating their improved bond with asphalt. The rougher and more porous surfaces of EIF and CuS suggest that they will create a stronger bond with asphalt, but this may also require more asphalt in the mix. Therefore, this increase in asphalt will increase the cost of the project, but this can be compensated for as the waste is being utilized, which has environmental and technical benefits as per Noureldin et al. (1990).

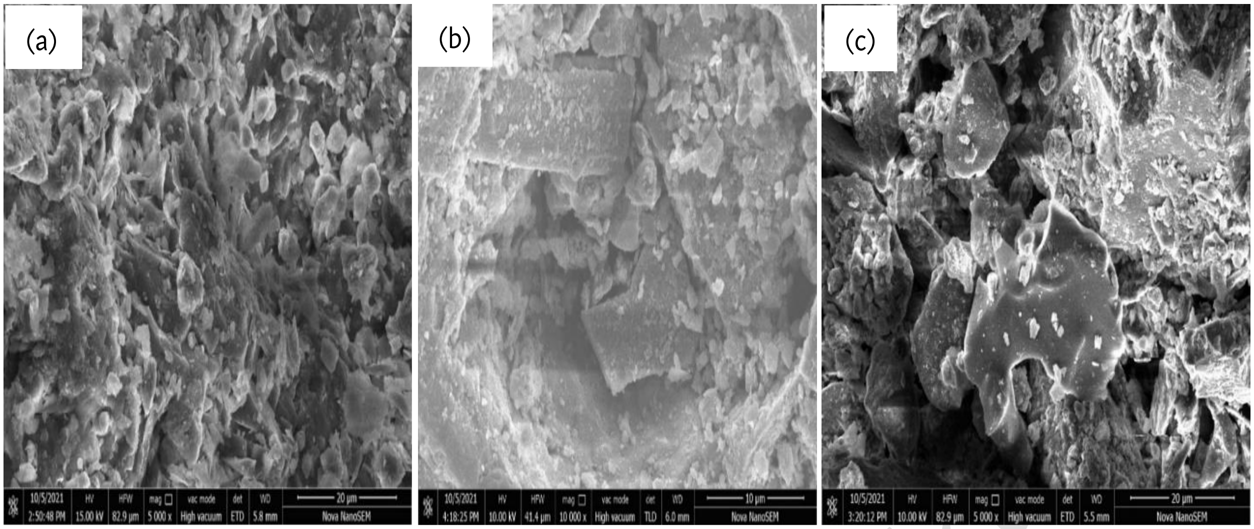

Fig. 8. FESEM image (a) NGA (b) CuS (c) EIF

3.4. Volumetric expansion

Because of the high CaO and MgO content, the slags may expand and disintegrate when exposed to moisture. To avoid volumetric expansion, Tozsin et al. (2023) have suggested that the slags can be weathered in the open air. It was found that the expansion rates of both slags for one week were much below the acceptable limits, which are 0.5% as per ASTM D4792 (2013) specification. The graph was plotted with respect to the obtained observation between duration in hours and expansion rate in percentage, as shown in Figure 9. Moreover, increased particle-to-asphalt adhesion can be aided by the high CaO component, which has a higher affinity for oil than for water as per Shen et al. (2009). Furthermore, due to the infiltration of adequate amounts of asphalt into the voids, the surfaces of EIF and CuS may get filled and well coated with asphalt, preventing moisture from contacting the CaO and MgO components of slag. As a result, moisture-induced slag volume expansion in HMA can be avoided.

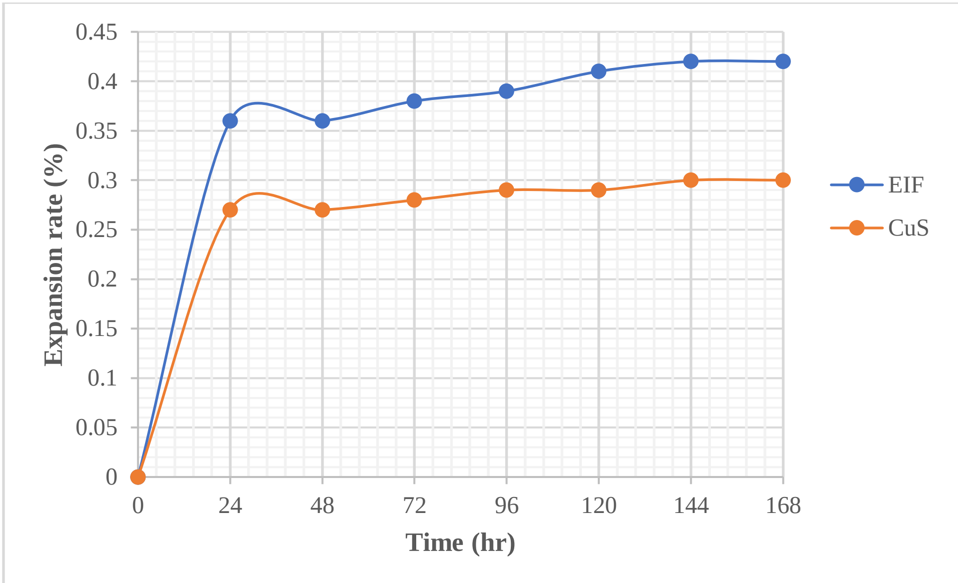

Fig. 9. Volumetric expansion curve of EIF and CuS

3.5. Marshall test result

The outcomes of Marshall parameters such as stability, flow, optimum asphalt content (OAC), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) are presented in Table 7. These results show that the optimum asphalt content (OAC) of EIF and CuS-incorporated HMA mixtures is higher than that of the control mix, and it increases as the replacement percentage increases. This increase was primarily brought on by the high surface porosity and irregularity of EIF and CuS, as determined through FESEM analysis, which cause increased voids in the HMA mixes. As a result, more asphalt is needed to meet the higher air-void requirement and completely coat the aggregate surface. Past research has also shown that the slag content enhances the OAC (Ziaee and Behnia, 2020) because of its high specific surface area (Ameri et al., 2013), surface porosity, and air voids (Asi et al., 2007).

The effect of increased air voids due to slag content can be seen in the results of the VMA and VFA values of these mixes. The asphalt mixes with EIF and CuS presented higher values than the control mix, and it was observed that these increased with an increase in slag fraction. The VMA significantly impacts the performance of asphalt mixtures because mixtures with a high and low VMA may have stability and durability issues, respectively. On the other hand, to avoid defects in the asphalt mixes, the limits of VFA must be maintained according to the required specification. MoRTH (2013) specifies the range of VFA between 65 and 75, and it was observed that by replacing 20–25% of fine NGA with both types of slag, one exceeded the permissible limits. Moreover, Hasita et al. (2020) suggested that less than 80% of VFA indicates high rutting resistance.

As for the results for stability, it was found that the Marshall stability for EIF-incorporated HMA mixes increased while it decreased for CuS incorporated HMA mixtures with their increasing proportions. As compared to the control mix, the stability of HMA mixes having 5, 10, 15, 20, and 25% of EIF and CuS increased by 4.46, 14.10, 17.10, 20.03, and 21.50% and was reduced by 1.21, 8.80, 15.82, 23.22, and 33.75%, respectively. The increased Marshall stability of the EIF-incorporated HMA mixture was attributed to the higher angularity, bulk specific gravity, and angle of internal friction of the EIF content, and the reason behind the significant decrease in Marshall stability of CuS-incorporated HMA mixes can be attributed to two reasons. One is due to the increased asphalt content, and the second is due to the higher specific gravity of CuS aggregate than NGA. The higher asphalt content was available to fill most of the voids, and therefore, the load is transmitted via hydrostatic pressure through the asphalt rather than the contact point of the aggregates, which weakens the mix and accounts for the decrease in stability with higher optimum asphalt content. As a result, when the amount of asphalt in the HMA mixes exceeds a particular level, their Marshall stability begins to decline. On the other hand, replacing the fine portion of NGA with CuS, which has a higher specific gravity, reduced the amount of fine particles in HMA mixes since gradation was based on weight batching. Fewer fine particles adversely impacted packing friction. As a result, stability declined. Abdelfattah et al. (2018) and Hassan and Al-Jabri (2011) obtained similar results for Marshall parameters for CuS-incorporated HMA mixes. However, the Marshall stability and flow value results of all mixes met the requirements specified as per MoRTH (2013).

Table 7. Marshall mix design results

Mixes	OAC	Marshall stability	Flow value	VMA	VFA	MQ
CM	4.74	15.67	3.87	14.60	72.64	4.04
EIF-5	4.91	16.37	3.84	14.94	73.24	4.26
EIF-10	5.02	17.88	3.78	15.21	73.71	4.73
EIF-15	5.21	18.46	3.74	15.56	74.31	4.93
EIF-20	5.56	18.81	3.71	16.28	75.46	5.07
EIF-25	5.67	19.04	3.68	16.47	75.71	5.17
CuS-5	4.91	15.48	3.76	14.98	73.29	4.11
CuS-10	5.07	14.29	3.52	15.38	74.00	4.05
CuS-15	5.35	13.19	3.62	15.99	75.00	3.64
CuS-20	5.58	12.03	3.34	16.51	75.85	3.60
CuS-25	5.69	10.38	3.28	16.80	76.20	3.16
MoRTH requirements	Min. 4.5	Min. 9-12	2-4	Min. 12	65-75	2-5

3.6. ITS

The cracking resistance of the produced mixes was assessed by conducting the ITS test. These results were found to be in line with the trend observed in the outcomes of Marshall stability studied earlier. The average value of three test samples was reported as the ITS value.

It was found that, compared with the control mixture, all the mixtures containing EIF had higher tensile strength values, which were found to increase with the incorporation percentage of EIF. Figure 10 depicts the ITS for EIF-based HMA mixes. The influence of surface roughness and angularity on EIF is greater than that of NGA. As a result, asphalt and EIF particles can develop a stronger interlock, leading to a higher ITS of the HMA mixes. This consequence can be seen in the fact that the ITS of the EIF-25 mix is 8.82% higher than that of the CM. The maximum increase in the ITS value was found for mix EIF-20, which is 9.48% higher than the CM. Following that, it was reduced to 0.60% from mix EIF-20 to mix EIF-25. This reduction was attributed to the higher stiffness of mix S-25, which was anticipated based on its higher MQ.

In contrast, the addition of the CuS fraction to HMA mixes lowers the ITS values, as shown in Figure 11. The ITS values for CuS-5, CuS-10, CuS-15, CuS-20, and CuS-25 mixes were found to be 2.24, 9.41, 10.08, 10.76, and 22.93% lower than the control mix, respectively. The maximum decrease in ITS was observed for mixes containing CuS-25 when the amount of CuS exceeded 20 percent in HMA mixes. This result is consistent with Hassan and Al-Jabri (2011) findings. They observed a reduction in the ITS as the slag content increased. Despite the decrease in ITS, all HMA mixes had ITS values higher than 0.44 MPa, which was the minimum required value that was suggested for pavement design by Hasita et al. (2020). However, a study carried out by Modarres and Bengar (2019) showed increased ITS value when copper slag is incorporated as filler in producing HMA concrete. This increase was due to the finer gradation of CuS than the limestone powder.

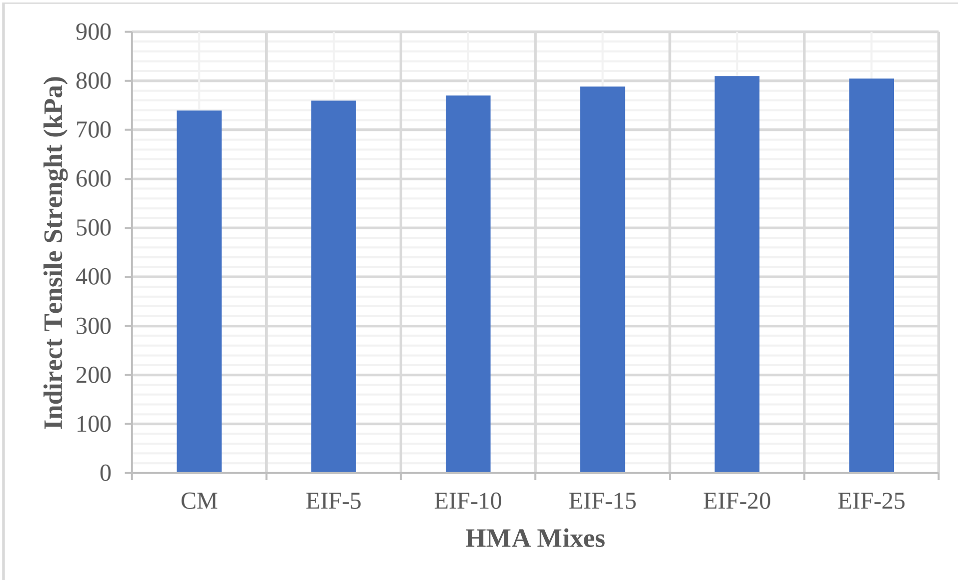

Fig. 10. Indirect Tensile Strength of EIF-based HMA Mixes

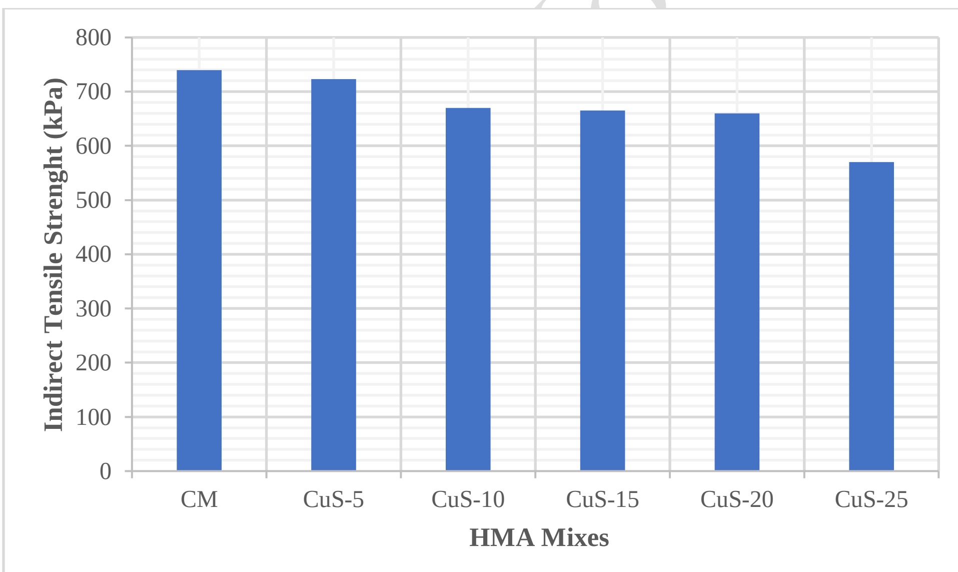

Fig. 11. Indirect Tensile Strength of CuS-based HMA Mixes

3.7. TSR

Moisture susceptibility was assessed by examining the TSR of the asphalt mixes, and their outcomes are shown in Figures 12 and 13, respectively. Deterioration of asphalt pavement due to moisture is one of the major concerns for the pavement industry because moisture affects adhesion properties, resulting in weak bonding between aggregate and asphalt, which leads to premature pavement failure. It was observed that the TSR for the EIF and CuS-incorporated HMA mixtures was increased as compared to the control mix. Ziari et al. (2017) discovered that the morphological, chemical, and physical properties of aggregate have a direct impact on moisture resistance. They also stated that the chemical composition and characteristics of the aggregates play a significant role in forming a bond with asphalt. Therefore, this result was attributed to two reasons. One was due to chemical characteristics, and the second was the surface morphology of EIF and CuS.

The chemical explanation for enhanced TSR was due to the higher alkaline nature of EIF and CuS. The CaO/SiO_2 ratio is an indicator used to evaluate the level of alkalinity of the aggregate. Compared to NGA, EIF and CuS exhibited higher alkalinity. A larger proportion of this ratio increases the adhesion between the aggregate and the asphalt, promoting moisture resistance. This phenomenon can be explained by the fact that when asphalt meets an alkaline aggregate, the carboxylic acid component of the asphalt is adsorbed on the surface and the hydrocarbon portion points outward. This changed the overall surface characteristics of the aggregate sufficiently for the asphalt to cling to it (Xie et al., 2013). Further, pH testing also confirms that the EIF and CuS were more alkaline than the NGA, which improves the adhesive bond. As a result, the TSR for the EIF and CuS-containing HMA mixes was improved. Additionally, EIF and CuS have more pores and cavities than NGA, as seen in Figure 8. The physical cling of asphalt to the cavities presents on the surface of this slag content resulted in improved adhesion between them. However, if an aggregate is entirely coated with asphalt, moisture cannot access its surface, and stripping potential can be considerably reduced. According to MoRTH (2013), all the HMA mixes produced met the minimum requirement of 80% TSR.

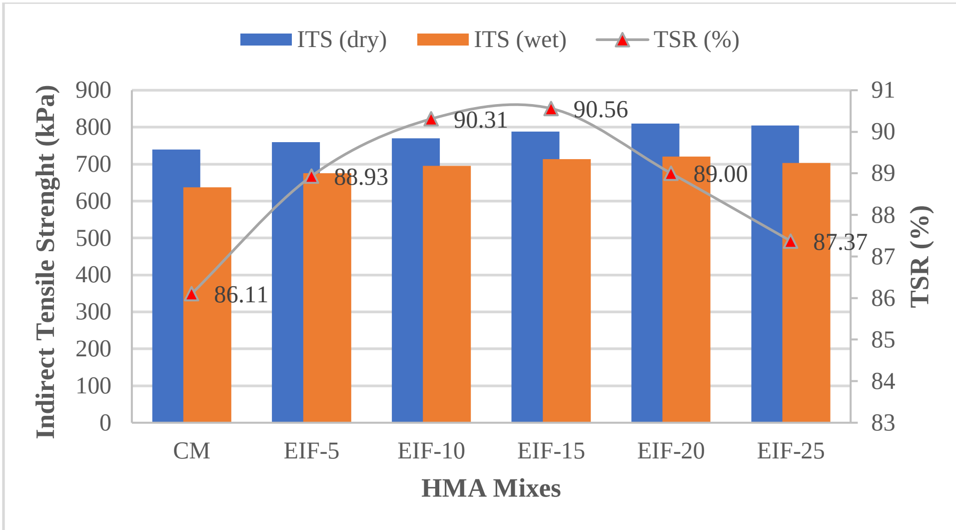

Fig. 12. Tensile Strength Ratio of EIF-based HMA Mixes

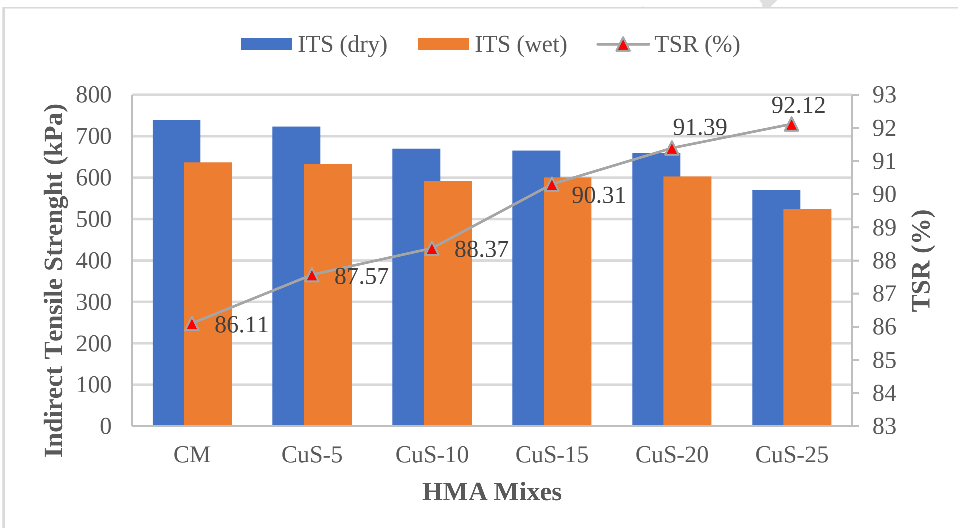

Fig. 13. Tensile Strength Ratio of CuS-based HMA Mixes

3.8. Rutting resistance

The MQ measures the resistance of the asphalt mixture to shear stress, rutting, and permanent deformation. As per Muniandy et al. (2018), the higher value of MQ suggests that the asphalt mixture will have a high degree of stiffness, increasing its ability to distribute loads and resist creep deformation. The MQ for EIF mixes was found to be higher than the CuS-incorporated HMA mixtures. It was found that the MQ increased for EIF mixes and declined for CuS mixes with their increasing proportions. Figures 14 and 15 illustrate the MQ results of EIF and CuS-incorporated HMA mixes, respectively. The MQ for the EIF-25 mix was found to be slightly higher than the maximum required criteria, and for the CuS-25 mix, it was slightly higher than the minimum requirement. Therefore, it can be stated that including more than 25 percent EIF and CuS content in the HMA mixes may significantly decrease the rutting resistance.

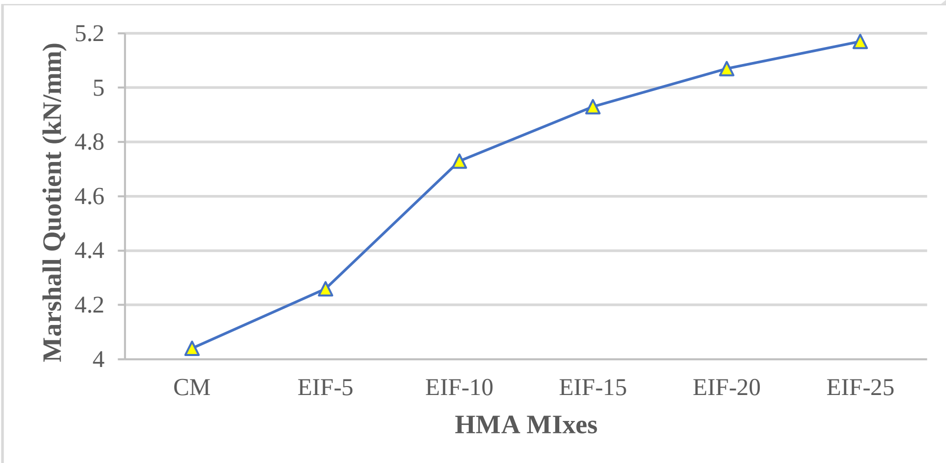

Fig. 14. Marshall Quotient of EIF-based HMA Mixes

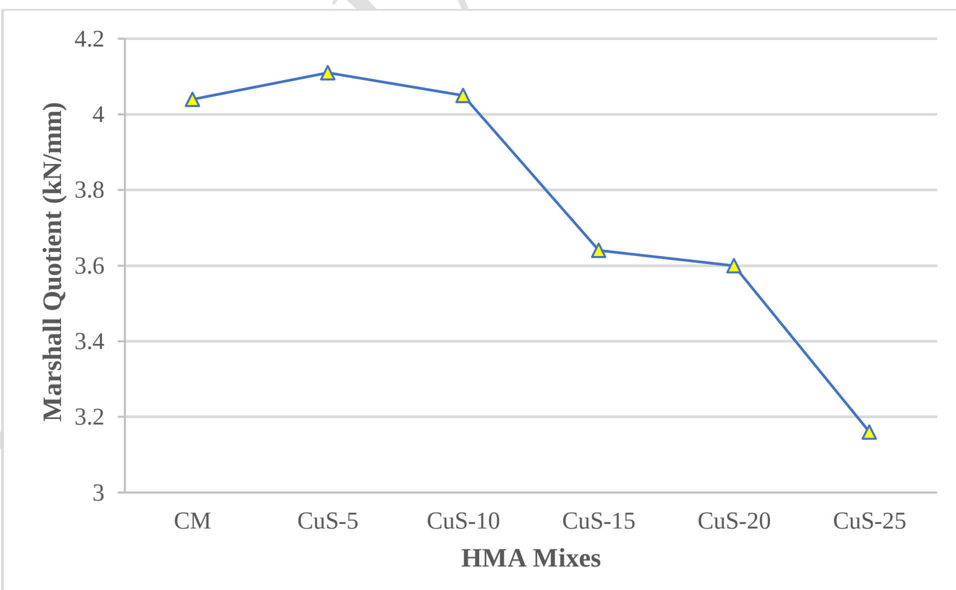

Fig. 15. Marshall Quotient of CuS-based HMA Mixes

Additionally, the rutting resistance was evaluated by conducting wheel track tests, and the outcomes for the HMA mixes with EIF and CuS incorporation are shown in Figures 16 and 17, respectively. Lower rut depth indicated higher rutting resistance. It was observed that the rutting resistance increases as EIF content increases, while the addition of CuS exhibited a lower rutting resistance as compared to the control mix.

The rutting resistance for the mix EIF-25 was increased by 36.01% as compared to the mix CM. This result was attributed to the high strength and rough surface texture of EIF that allowed for effective interlocking of the aggregates, which resulted in a reduction in rut depth for the EIF-incorporated HMA mixes. In contrast, the CuS-incorporated HMA mixes had an increase in rut depth due to the lack of fine CuS particles, which resulted in a reduction in rutting resistance. The rutting resistance of the CuS-25 mix was found to be reduced by 19.94%. The rut depth for the CuS-25 mix was found to be 4.63 mm and according to Fwa et al. (2012), several highway agencies classify rut depths under 12 mm as low-severe. Therefore, it can be concluded that adding up to 25% of CuS does not result in severe rutting problems on the asphalt pavement.

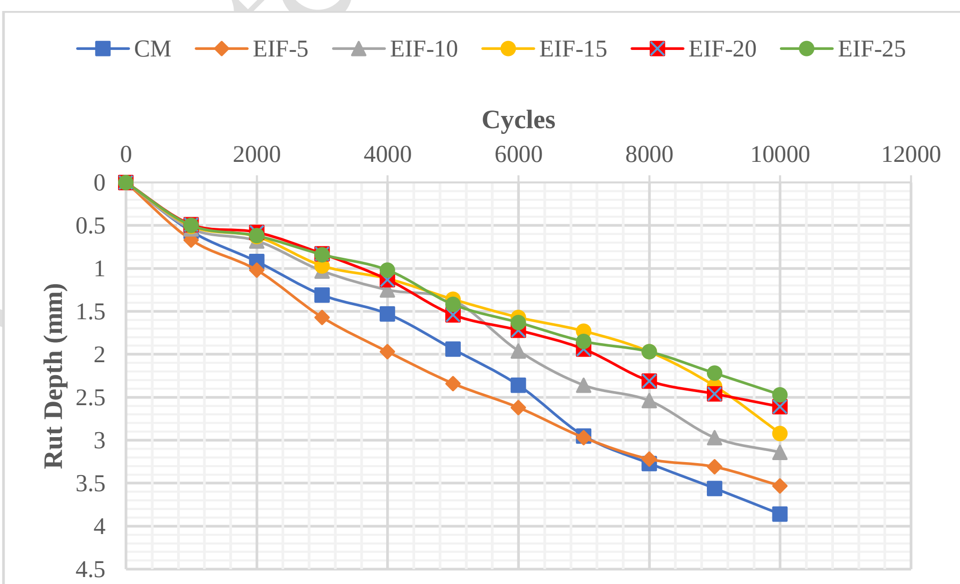

Fig. 16. Rut depth of EIF-based HMA Mixes

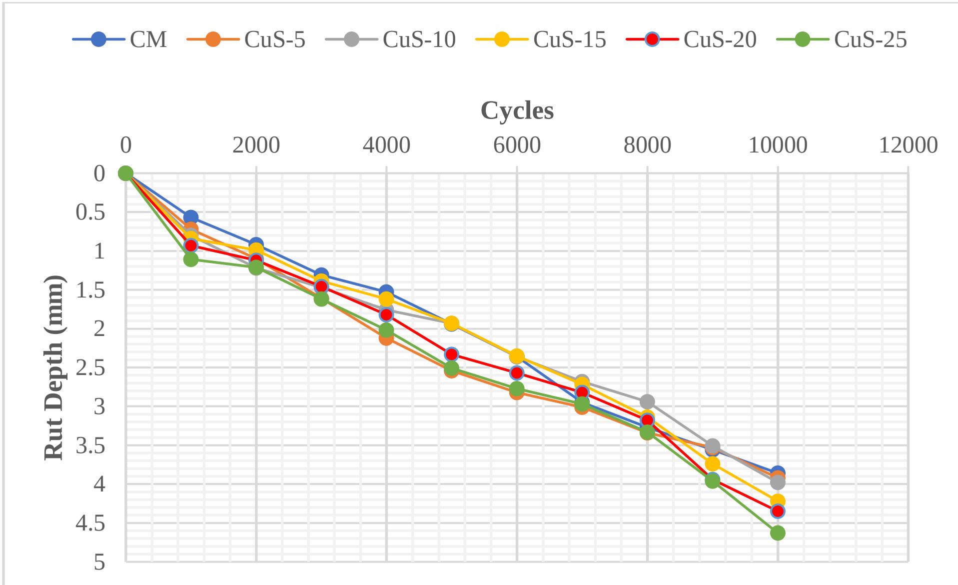

Fig. 17. Rut depth of CuS-based HMA Mixes

3.9 statistical Analysis

To ascertain whether the incorporation of slags in place of fine NGA significantly altered the properties of the HMA mixtures, the experimental findings were subjected to an analysis of variance (ANOVA) at a 95% confidence level. In this case, when the P value is lower than the specified significance level (SL), which is 5%, the results are statistically significant (Sig). Sig equal to Y and N indicates that the difference between the means is significant and not significant, respectively. Tables 8 and 9 show the one-way ANOVA outcomes for the EIF and CuS-incorporated HMA mixtures, respectively. The data confirmed that at 5% SL, the difference between the means of the Marshall parameters, ITS, TSR, and rut depth values was significant, indicating that the difference was caused by the addition of EIF and CuS content.

Table 8. Results of one-way ANOVA for EIF-incorporated HMA mixes

Properties	Source of variation	Sum of squares	Degree of freedom	Mean square	F value	P value	Sig
Marshall Parameters	Between group	22362.18	6	3727.03	285.63	<0.0001	Y
	Within group	456.69	35	13.04			
	Total	22818.87	41				
ITS	Between group	1761041.745	1	1761041.745	4246.66	<0.0001	Y
	Within group	4146.8857	10	414.6886			
	Total	1765188.6307	11				
TSR	Between group	2849193.9731	3	949731.32	2131.83	<0.0001	Y
	Within group	8909.99	20	445.4997			
	Total	2858103.96	23				
Rut depth	Between group	265.73	1	265.73	6.05	0.03365	Y
	Within group	438.93	10	43.89			
	Total	704.67	11				

Table 9. Results of one-way ANOVA for CuS-incorporated HMA mixes

Properties	Source of variation	Sum of squares	Degree of freedom	Mean square	F value	P value	Sig
Marshall Parameters	Between group	459.60	3	153.20	6.66	0.00267	Y
	Within group	459.61	20	22.98			
	Total	919.22	23				
ITS	Between group	1301927.151	1	1301927.151	715.04	<0.0001	Y
	Within group	18207.59	10	1820.759			
	Total	1320134.74	11				
TSR	Between group	2079693.2715	3	693231.0905	525.948	<0.0001	Y
	Within group	26361.1593	20	1318.058			
	Total	2106054.4309	23				
Rut depth	Between group	208.66	1	208.66	4.76	0.0539	Y
	Within group	437.94	10	43.79			

Total	646.60	11

4. Conclusion

In this study, the performance assessment of HMA mixtures containing fine EIF and CuS was examined. The strength, cracking resistance, moisture resistance, and rutting characteristics of the HMA mixtures were evaluated after natural granite aggregates were replaced by weight with 0, 5, 10, 15, 20, and 25% of fine EIF and CuS. From the test results, the following conclusions can be made:

1. EIF and CuS outperformed NGA in terms of physical and mechanical properties. XRF results revealed that the materials' major components were CaO, SiO_2, Al_2O_3, FeO, and MgO. The EIF and CuS were found to be more alkaline and hydrophobic in nature than the NGA. This signifies the better binding efficiency of materials with asphalt. Since no potential for volume expansion was found in either of the slags when tested for 7 days, their inclusion in asphalt mixtures can be recommended to minimize the damages related to volumetric expansion. The FESEM image analysis revealed the rough, porous, and irregular surface characteristics of EIF and CuS rather than those of NGA. The rough and porous surface enables the improved binding ability of aggregate with asphalt. Therefore, using EIF and CuS in HMA mixtures can be suggested to have better mechanical strength.
2. With the increase in EIF content in HMA mixtures, there was an increase in OAC, Marshall stability, and MQ values. At the same time, flow values were found to be decreasing. The volumetric parameters, such as VMA and VFA, were also increased but remained within the permissible limits. This outcome was attributed to the fact that the EIF content had higher angularity, surface porosity, bulk specific gravity, and angle of internal friction than

the NGA. On the other hand, the OAC, VMA, and VFA, also increased with the increasing percentage of CuS content in HMA mixes. Based on the Marshall stability results, replacing fine NGA with CuS decreased the strength of HMA mixes. The HMA mix containing 25% CuS experienced the most significant decline, measuring 33.75% as compared to the control mix.

3 The resistance to cracking of all mixtures was evaluated by conducting the ITS test. The asphalt mixture containing a higher percentage of EIF showed higher ITS values for the HMA mixtures, while the inclusion of CuS reduced the ITS. However, all the mixtures were found to be within the required range for ITS. Therefore, the use of an optimum amount of EIF and CuS in HMA mixes can be suggested as a solution to enhance the anti-cracking behavior.

4 The TSR of all HMA mixtures was studied to determine moisture sensitivity. It was found that the TSR increased as the replacement percentage of fine NGA with EIF and CuS increased. However, all the HMA mixtures met the value of 80%, which is the minimum requirement. The favorable chemical and morphological attributes of these slags were the reason behind this result.

5 The Marshall quotient of the HMA mix was found to be adequate up to 20% EIF content and 25% CuS concentration. The wheel tracking test results show that the rutting resistance of the HMA mixtures comprising EIF increased by 36.01%, while for CuS-based HMA mixtures, it declined by 19.94% for the 25% of their substitution.

6 When EIF increased from 15 to 20%, HMA mixtures showed the greatest improvements in Marshall parameters, resistance to cracking, and moisture damage. Thus, this quantity of EIF can be considered the optimum replacement content. The HMA mixes showed the

greatest decline in Marshall stability, ITS, and MQ values when the CuS content increased to 20–25%. However, it was discovered that the TSR for the 25% CuS mix was 6.99% greater than the control mix. Thus, the substitution of fine NGA with CuS up to 20% can be considered the optimum replacement content in HMA mixes.

In summary, it can be stated that the application of EIF and CuS as fine aggregates can reduce the consumption of conventional aggregates and offer a viable waste disposal option. These slags were procured for free from waste yards and didn't require any modification before their usage. They could therefore be used effectively where they are abundant. However, the selection of any suitable waste should be performed cautiously after a rigorous analysis of its physical and chemical compositions. For slag-based HMA mixtures, the optimum asphalt content and specific gravity of the HMA mix increased; as a result, it is critical to conduct a cost-benefit analysis to determine the requirements and appropriate amount of their use in each project.

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