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RESEARCH ARTICLE

Copper Slag as a Sustainable Alternative to Conventional Aggregates in Moisture - Resistant Asphalt Pavement for Hilly Terrain

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ABSTRACT: The accelerated development of infrastructure in hilly regions has necessitated a corresponding increase in road construction activities, leading to heightened consumption of conventional aggregate (CA) materials. This surge in demand has placed considerable pressure on natural resources, resulting in their progressive depletion. Additionally, the unique environmental challenges of hilly areas, particularly those related to moisture, exacerbate the degradation of asphalt pavements, complicating both the construction and maintenance of roads. In response to these challenges, this study explores the potential of substituting CA with copper slag (CS), a byproduct of the copper smelting process, in asphalt pavement mixes. The research aims to evaluate the moisture resistance of CS-modified asphalt mixes compared to traditional CA-based mixes. The findings reveal that incorporating CS not only alleviates the burden on natural resources by reducing CA usage but also significantly enhances the moisture resistance of asphalt pavements. This improvement is attributed to the superior physical and chemical properties of CS, including its angular shape, low water absorption, and higher alkalinity, which contribute to stronger asphalt-aggregate bonding. The study concludes that CS can be a viable alternative to CA in asphalt mixes, particularly in hilly areas where moisture-induced pavement failure is a critical concern. This approach supports sustainable road construction practices while addressing the material scarcity and environmental issues associated with conventional aggregates.

Keywords: Copper slag, Moisture resistance, Asphalt pavement, Hilly areas, Sustainable construction.

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1. INTRODUCTION

The rapid expansion of infrastructure in hilly areas has driven the need for extensive road construction. This increased pace of development has led to a significant rise in the consumption of conventional aggregates (CA), which are essential for building durable asphalt pavements. However, the accelerated use of CA has raised concerns about the depletion of natural resources, as the extraction of these materials is unsustainable over time. The scarcity of suitable construction materials, coupled with the challenges posed by the harsh environmental conditions typical of hilly regions, particularly moisture-related degradation, makes the construction and maintenance of roads in these areas particularly difficult [1].

Moisture-related damage is one of the primary factors contributing to the deterioration of asphalt pavements in hilly regions [2]. Moisture damage occurs when water from sources such as humid air, rainfall, or melting snow infiltrates the pavement layers through capillary action, leading to chemical reactions that weaken the adhesion and cohesion of the bitumen binder [3-4]. This moisture can degrade the binder-aggregate system through various processes, including hydraulic scour, emulsification, displacement,

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detachment, induced pore pressure, and other environmental effects [5-7]. The result is a range of pavement distresses such as fatigue cracking, rutting, ravelling, stripping, and other issues that compromise the durability and integrity of the road surface [8-11].

The challenge is rooted in the chemical nature of the materials used. While aggregates typically have polar surfaces, the asphalt binder consists of 5%–20% polar asphaltenes and 80%–95% nonpolar maltenes [12]. The polar components of the binder often form weak and unstable hydrogen bonds with the polar aggregate surfaces [13-14]. In contrast, the nonpolar maltene components, which form stronger covalent bonds, struggle to bond effectively with the hydrophilic aggregate surfaces. Therefore, modifying the aggregate surface to make it more hydrophobic is crucial for enhancing the moisture resistance of asphalt pavements.

One of the simplest strategies to reduce the reliance on CA is to incorporate alternative materials into asphalt mixes. Copper slag (CS) is a promising waste material that can serve this purpose. CS is a byproduct generated during the matte smelting, conversion, and refinement of copper, with approximately 2.2 tonnes of CS produced for every tonne of copper [15]. The use of CS in asphalt mixes aligns with the goals of sustainable construction, offering environmental benefits by reducing the burden on natural resources and addressing the disposal challenges associated with CS. According to previous studies, it is feasible to create asphalt mixes using waste materials like ceramic waste, steel slag, glass powder, CS, and recycled concrete aggregate.

The disposal of CS poses several environmental challenges, including groundwater contamination, air pollution due to dust dispersion, terrain alterations, and restrictions on land use, as it is often stored near copper mining and smelting sites. However, the granular nature of CS, characterized by its angular and irregular shape, high abrasion resistance, soundness, and low water absorption, makes it particularly suitable for use as an aggregate in asphalt mixes [16]. These properties suggest that CS could enhance the mechanical performance of asphalt pavements, especially in terms of resistance to moisture-induced damage.

This study aims to compare the characteristics of CS with CA in asphalt mixes, focusing on the effectiveness of CS in constructing roads in hilly areas. The research also investigates the moisture resistance behavior of CS-modified asphalt mixes to assess the potential for reducing moisture-related pavement failures in these regions.

2. EXPERIMENTAL DETAILS

2.1 Aggregates

The conventional aggregate (CA) and copper slag (CS) used in this study were procured from a local contractor. The CS is a fine, black-colored material. The gradation curve of CS is presented in Figure 1, illustrating its particle size distribution. Table 1 summarizes the physical and mechanical properties of both CA and CS. The CS exhibited distinct characteristics that are relevant to its potential use in asphalt mixes, including its angular shape and high density. The gradation of CS was analyzed to ensure it meets the required specifications for asphalt mixtures. These results highlight the potential advantages of CS in terms of its mechanical properties, which could contribute to the durability and performance of asphalt pavements, particularly in hilly areas where moisture resistance is crucial.

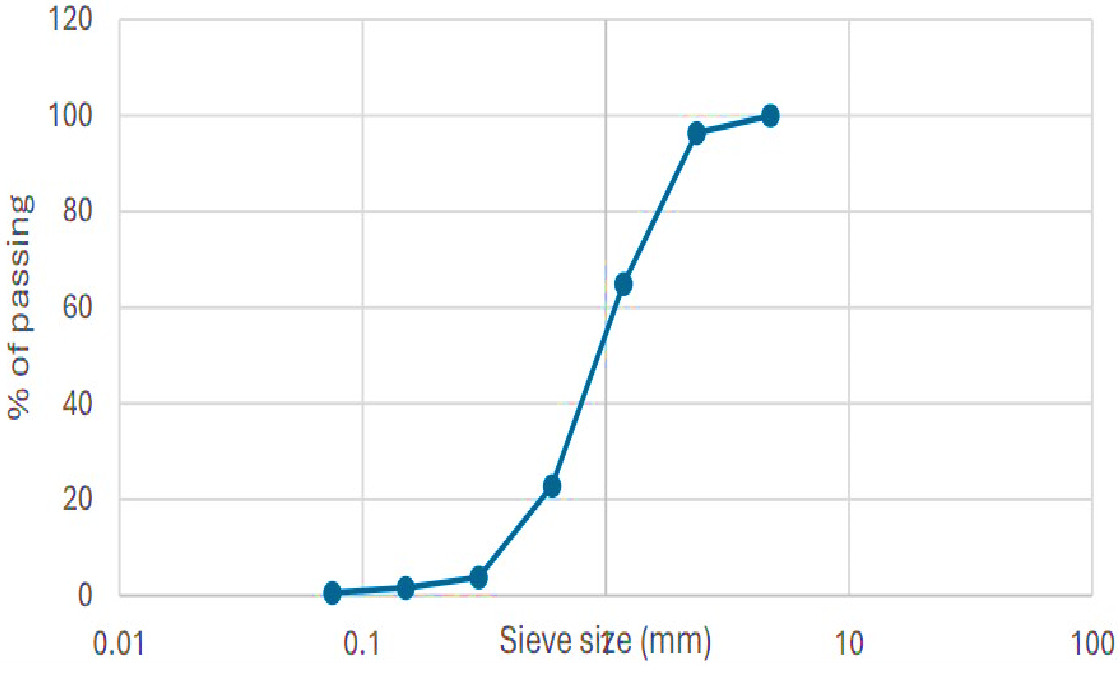

Fig. 1. Gradation curve of CS.

Table 1. Physical and Mechanical Properties of CA and CS.

Property	CS	CA
Los Angeles Abrasion (%)	25	-
Impact (%)	9.40	-
Combined Flakiness and Elongation (%)	30.2	-
Specific Gravity (Coarse Aggregate)	-	-
Specific Gravity (Fine Aggregate)	2.73	3.5 g/cm³
Stripping (%)	2.64	-
Water Absorption (Coarse Aggregate, %)	5	-
Water Absorption (Fine Aggregate, %)	>95	1.87

Table 2. Properties of Asphalt.

Test Name	Result	Requirement
Stripping Value (%)	>95	≥95
Penetration Test at 25°C	98.66	≥ 80
Ductility at 25°C (cm)	91.25	≥ 75
Softening Point (°C)	42	≥ 40
Flash Point (°C)	235	≥ 220
Specific Gravity	1.04	-

2.2 Asphalt

The asphalt used in this study was Viscosity Grade 10 (VG-10), selected for its suitability in road construction under varying environmental conditions. Several tests were conducted to assess the engineering properties of the asphalt, adhering to Indian standard testing protocols. The results, shown in Table 2, confirm that all measured properties of the VG-10 asphalt meet the requirements outlined in IS 73 (2013), making it an appropriate binder for this investigation. The tests confirm that the VG-10 asphalt exhibits the necessary properties, such as high penetration and softening points, which are critical for ensuring the durability and resilience of the asphalt mix, especially under the moisture-prone conditions of hilly terrains.

2.3.1 Hydrophilic Coefficient

Hydrophilic materials, which prefer water over asphalt, tend to absorb less asphalt on their surface when dry, leading to weaker bonding with the binder. The hydrophilic coefficient, which measures the preference of the material for water versus kerosene, is a critical parameter in determining the suitability of materials for asphalt mixes. Materials with a lower hydrophilic coefficient bond better with asphalt, resulting in mixes that are more resistant to water, temperature fluctuations, and pressure.

2.3.2 Volumetric Expansion

The potential for volumetric expansion of CS when exposed to moisture is a crucial factor, particularly given its high CaO and MgO content. Volumetric expansions of CS were measured according to ASTM D4792 (2013) standards. This test is essential to ensure that the inclusion of CS in asphalt mixes does not lead to excessive expansion, which could compromise the structural integrity of the pavement.

2.3.3 Texas Boiling Water Test

The Texas Boiling Water Test, conducted according to ASTM D3625 (ASTM 2005), assesses the stripping potential of asphalt mixes when exposed to boiling water. In this test, 250 g of loosely formed asphalt mix at a temperature above 85°C was submerged in distilled boiling water for 10 minutes. After cooling to room temperature, the bitumen coating was visually inspected for separation from the aggregate. This test is particularly important for evaluating the moisture resistance of mixes containing siliceous aggregates, which are more prone to stripping.

2.3.4. pH Test

The pH test was performed to determine the alkalinity of the aggregates, which is indicative of their ability to bind with asphalt. Aggregates with higher pH levels are expected to form stronger bonds with asphalt due to its slightly acidic nature, thereby enhancing the resistance of the asphalt mix to moisture-induced damage. The results of this test will provide insights into the potential durability of the asphalt pavement in moisture-prone environments.

3. RESULTS AND DISCUSSION

3.1. Hydrophilic Coefficient

The hydrophilic coefficient is a critical parameter that indicates the affinity of a material for water compared to kerosene. In the context of asphalt mixtures, a material with a high hydrophilic coefficient is considered hydrophilic, meaning it absorbs more water, which could lead to poor bonding with the asphalt binder and increased susceptibility to moisture damage. Conversely, a low hydrophilic coefficient indicates hydrophobicity, where the material has a higher affinity for kerosene, suggesting better bonding with asphalt and improved resistance to moisture. In this study, the hydrophilic coefficients of both CA and CS were determined, as shown in Figure 2. The results revealed that CS has a hydrophilic coefficient within the optimal range for asphalt applications, between 0.7 and 0.85, indicating that it possesses a balanced hydrophilic-hydrophobic nature. This characteristic is crucial because materials that are too hydrophilic (coefficient > 1) can lead to weak bonding with the asphalt, while materials that are too hydrophobic (coefficient < 0.7) may not wet sufficiently during mixing, leading to incomplete coating and potential failure of the asphalt pavement.

The hydrophilic coefficient for CS being in the acceptable range suggests that CS is neither excessively hydrophilic nor hydrophobic, making it suitable for use in asphalt mixtures. This balance is essential for ensuring that the asphalt mix remains stable under varying environmental conditions, particularly in regions prone to moisture exposure, such as hilly areas. The inclusion of CS in the asphalt mix is expected to improve the mix's durability by reducing the likelihood of water-induced stripping, thereby enhancing the overall performance of the pavement.

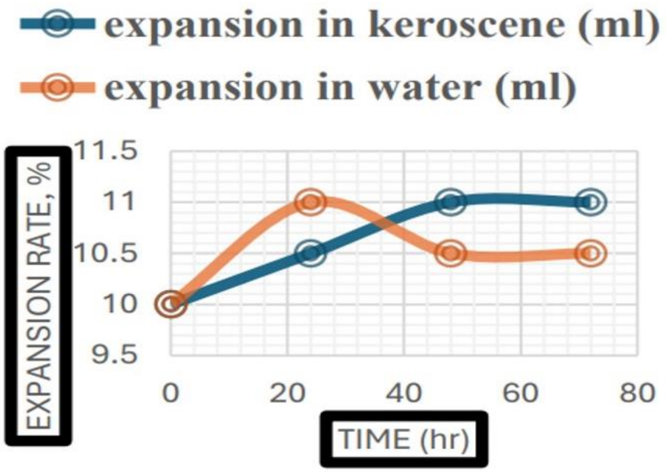

Fig. 2. Hydrophilic coefficient.

3.2. Volumetric Expansion

Volumetric expansion is a critical factor in evaluating the suitability of materials like CS for use in asphalt mixes, particularly in terms of their dimensional stability when exposed to moisture. The high content of CaO and MgO in CS can lead to expansion when the material is exposed to water, potentially causing cracking or other forms of pavement distress. Therefore, assessing the volumetric expansion of CS is essential to ensure that it remains within acceptable limits.

In this study, the volumetric expansion of CS was measured over a 7-day period, and the results are depicted in Figure 3. The expansion rate of CS was found to be 0.3%, which is significantly lower than the acceptable limit of 0.5% as per ASTM D4792 (2013). This low expansion rate indicates that CS is dimensionally stable and unlikely to cause significant swelling or cracking in the asphalt mix when exposed to moisture. The minimal volumetric expansion of CS is advantageous in asphalt applications, particularly in regions with high moisture levels. The inclusion of CS in the asphalt mix is not expected to compromise the structural integrity of the pavement, making it a suitable alternative to conventional aggregates. Moreover, the low expansion rate further supports the use of CS in environments where the pavement is subjected to frequent wetting and drying cycles, as it minimizes the risk of moisture-related damage.

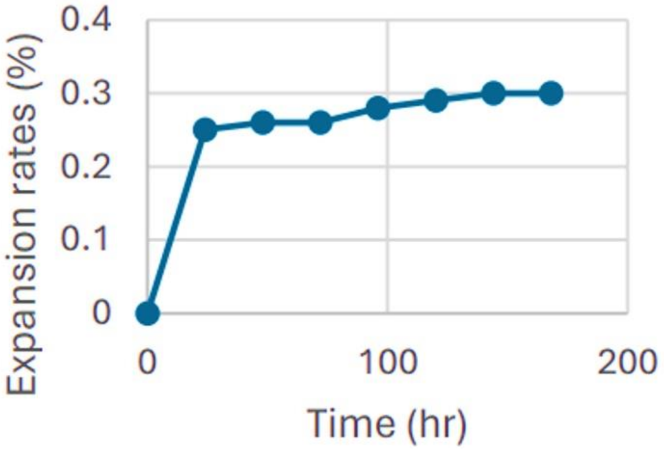

Fig. 3. Volume Expansion.

3.3. Texas Boiling Water Test

The Texas Boiling Water Test is a qualitative method used to assess the moisture susceptibility of asphalt mixtures. This test is particularly relevant for evaluating the potential of aggregates, like CS, to strip when exposed to water. Stripping refers to the loss of adhesion between the asphalt binder and the aggregate, which can lead to pavement failure. The test involves immersing an asphalt mix in boiling water and then observing the extent of bitumen separation from the aggregate.

In this study, the Texas Boiling Water Test was conducted on asphalt mixes containing CS, and the results indicated no significant stripping occurred. The absence of bitumen stripping suggests that the incorporation of CS into the asphalt mix enhances the moisture resistance of the pavement. This finding is crucial for ensuring the long-term durability of the asphalt pavement, especially in moisture-prone areas.

The enhanced moisture resistance provided by CS can be attributed to its favorable physical and chemical properties, which promote strong bonding with the asphalt binder. The test results demonstrate that CS can effectively replace conventional aggregates in asphalt mixes, providing a resilient and durable pavement structure that can withstand the challenges posed by moisture exposure. The use of CS in asphalt mixes is therefore recommended for regions with high humidity or frequent rainfall, where moisture-induced damage is a significant concern.

3.4. pH Test

The pH level of aggregates plays a crucial role in determining their interaction with the acidic asphalt binder. Aggregates with higher pH values are more alkaline, which enhances their ability to bond with the slightly acidic asphalt, leading to improved resistance to moisture-induced stripping. The pH test conducted in this study aimed to evaluate the alkalinity of both CA and CS to assess their suitability for use in asphalt mixtures. The pH values of CA and CS are presented in Table 3. The results show that both materials are alkaline, with CS having a pH of 9.54, which is higher than the pH of CA (8.85). The higher pH of CS suggests that it has a greater potential to form strong bonds with the asphalt binder, thereby enhancing the durability and moisture resistance of the asphalt mix.

Table 3. pH Value of the materials.

Materials	pH Value
CS	9.54
CA	8.85

The alkaline nature of CS makes it particularly suitable for use in asphalt mixes, as it is likely to resist stripping and other forms of moisture-related damage. The higher pH value of CS compared to CA indicates that CS is more effective in preventing moisture-induced pavement failures. This characteristic is especially beneficial in regions with high rainfall or moisture levels, where the risk of stripping and other moisture-related issues is elevated.

The experimental results demonstrate that CS is a viable alternative to conventional aggregates in asphalt mixtures, particularly for use in moisture-prone environments. The hydrophilic coefficient, volumetric expansion, Texas Boiling Water Test, and pH test results all indicate that CS possesses the necessary properties to enhance the durability and performance of asphalt pavements. The use of CS in asphalt mixes is therefore recommended, as it offers improved resistance to moisture-induced damage, ensuring the longevity and reliability of the pavement structure.

4. CONCLUSION

The findings of this study lead to several important conclusions regarding the use of copper slag (CS) as an aggregate in asphalt mixtures. First, the hydrophilic coefficient test, which measures the adhesion potential of aggregates with asphalt, revealed that CS has a higher hydrophilic coefficient compared to conventional aggregates (CA). This suggests that asphalt mixtures incorporating CS are likely to experience less moisture-induced damage than those using CA, making CS a more suitable choice in environments prone to moisture exposure. Furthermore, the volumetric expansion of CS was found to be within permissible limits, indicating that the addition of CS to asphalt mixes does not pose a risk of excessive swelling or instability. This characteristic is crucial for maintaining the structural integrity of pavements, particularly in regions with significant moisture variations. The Texas Boiling Water Test, which assesses the moisture susceptibility of asphalt mixtures, showed no potential for stripping when CS was used. This result indicates that CS forms a stronger bond with the asphalt binder than CA, further enhancing the durability and longevity of the pavement. Additionally, the pH test demonstrated that CS has a higher alkalinity than CA, suggesting that it forms a more robust bond with the slightly acidic asphalt binder. This enhanced bonding capability translates to better resistance to moisture-induced stripping and overall improved performance of the asphalt mix. Based on these conclusions, it can be stated that using CS in asphalt mixtures not only reduces the consumption of conventional aggregates but also significantly enhances the moisture resistance of the pavement. Consequently, CS emerges as a viable and potentially superior option for constructing roads, especially in hilly areas where moisture-related issues are more prevalent. The incorporation of CS into asphalt mixtures promises to improve the durability and performance of pavements, making it a valuable material in road construction.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

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