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Moisture Susceptibility of Asphalt Concrete Incorporating Pulverized Fine Aggregate as Filler

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ABSTRACT

Moisture damage is a leading cause of premature failure in asphalt pavements, often resulting from the stripping of the binder film and loss of aggregate–binder adhesion. The use of suitable filler materials can enhance the resistance of asphalt concrete to such damage. This study investigated the moisture susceptibility of asphalt concrete incorporating pulverized sand as a filler, with a focus on comparing the performance of white and brown sand powders. The main objective was to evaluate their influence on the tensile strength ratio (TSR) under both dry and saturated conditions. Asphalt concrete samples were produced with varying filler contents of 3%, 5%, 7%, and 9% by means of the Marshall mix design technique. Indirect tensile strength (ITS) was measured according to standard procedures, and the TSR was calculated following AASHTO T-283 (2003) guidelines, which established a minimum TSR of 80% for mixtures to be considered resistant to moisture damage. The results showed that ITS values under dry conditions were consistently higher than under saturated conditions, confirming the detrimental impact of moisture. Mixtures containing white sand powder demonstrated superior performance, with TSR values consistently above 99% and peaking at 134% for the 3% filler content. In contrast, mixtures with brown sand powder exhibited inconsistent behavior, with TSR values falling below the 80% threshold at 3% and 9% filler contents, indicating susceptibility to stripping. These differences were attributed to the mineralogical properties and surface characteristics of the sands. Based on these findings, it is recommended that white sand powder be used as a filler in asphalt concrete to enhance durability and improve resistance to moisture-induced damage.

Keywords: moisture damage, tensile strength ratio, asphalts, filler, pulverization

INTRODUCTION

Moisture damage (MD) is one of the most critical factors affecting the durability and long-term performance of asphalt pavements (Alsheyab et al., 2024; Luo et al., 2024). It occurs when water infiltrates the pavement structure, leading to a loss of adhesion amongst the asphalt binder and aggregates as well as a reduction in cohesion within the binder matrix (Omar et al., 2020; Gao et al., 2021; Cong et al., 2023). The resulting effects include stripping, ravelling, rutting, pothole formation, and ultimately the premature failure of pavements (Little et al., 2017; Albayati & Ismael, 2025).

The susceptibility of asphalt concrete to moisture is strongly influenced by the type and properties of mineral fillers used in the mixture (Kumlai et al., 2022; Chen et al., 2022; Liang et al., 2023). Although fillers represent only a small portion of the total aggregate volume, they significantly affect the binder aggregate interfacial bonding, mixture stiffness, and durability (Zeng et al., 2021; Wang et al., 2022; Chen et al., 2022). Common fillers such as hydrated lime and cement have been widely studied, with hydrated lime shown to improve resistance to moisture damage, while limestone filler often demonstrates lower performance (Wang et al., 2022; Adwar & Albayati, 2024).

Despite extensive research on traditional fillers, pulverized sand has not been thoroughly examined as a mineral filler in asphalt mixtures. Previous studies on dune and river sand fillers suggest that they may reduce compactness and increase susceptibility to moisture damage (Younsi et al., 2022; Khelil et al., 2023; Younsi et al., 2024). However, limited evidence exists regarding the performance of finely pulverized sand with controlled particle size distribution. This gap leaves uncertainty about its potential to either mitigate or exacerbate moisture-induced damage in asphalt mixtures.

The study seeks to address the lack of knowledge on how pulverized sand as filler affects the moisture susceptibility of asphalt concrete. The central problem is that conventional fillers are often expensive, regionally limited, or environmentally demanding to produce (Mohanty et al., 2018; Nassar et al., 2021), while abundant sand resources remain underutilized. Determining whether pulverized sand can improve or at least maintain the moisture resistance of asphalt mixtures would provide a sustainable and cost-effective alternative.

The novelty of this investigation lies in its systematic evaluation of pulverized sand, an unconventional filler for its effect on MD in asphalt mixtures. Unlike previous studies that focused on limestone, hydrated lime and cement fillers (Jiang et al., 2020; Segura et al., 2020; Alyousef et al., 2023), this work investigates how the fineness and surface characteristics of pulverized sand influence binder aggregate bonding under moisture conditioning. The findings could contribute to localized pavement design strategies, especially in regions where sand is abundant but other fillers are scarce or costly.

This research is designed to elucidate the factors that govern the resistance of asphalt mixtures to moisture damage. In particular, it emphasizes the application of the ITS test to assess the influence of aggregate gradation on moisture susceptibility, investigates the effect of binder grade on the TSR, and formulates a statistical model capable of predicting TSR values as a function of aggregate gradation and volumetric properties of the mixture. Through these objectives, the study seeks to provide both a pragmatic basis for pavement design and an analytical framework for the prediction and evaluation of moisture damage in asphalt mixtures.

MATERIAL AND METHOD

Material

Bitumen of 60/70, procured from a local supplier, was employed as the binding medium. Crushed stone characterized by angular shape and rough textures functioned as the coarse aggregate, whereas natural sand with particle dimensions between 0.09 and 2.0 mm served as the fine aggregate. The gradation of aggregates was executed in accordance with ASTM C136, while both white and brown sands were pulverized and sieved through a 75 µm mesh following ASTM D242 (2000) to ensure uniform fineness. The processed material, compliant with ASTM C595 (2017), was subsequently incorporated as a mineral filler in hot mix asphalt at proportions of 3%, 5%, 7%, and 9% by total weight of the mixture. To determine the optimum bitumen content (OBC) for the designated gradations, the Marshall mix design methodology, as prescribed in ASTM D6926 (2015), was adopted. The evaluation encompassed both volumetric and mechanical parameters, including air voids (AV), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and OBC, alongside performance indicators such as Marshall stability and compacted density. A synthesis of the volumetric properties together with the final OBC is provided in Table 1.

Method

HMA Specimens production

The specimens were produced following the guidelines of the *Marshall method as presented in Figure 1(a)*. The bitumen was mix with aggregates (pulverized sand filler, fine and coarse) at a mixing temperature of 175-190 °C. Cylindrical Marshall samples were then compacted using the standard Marshall hammer with 35, 50, and 75 blows applied to each face at a bitumen content of 4.8%. The corresponding average air voids (%Vair) recorded for these levels of compaction were 5%, 3%, and 1.4%, respectively.

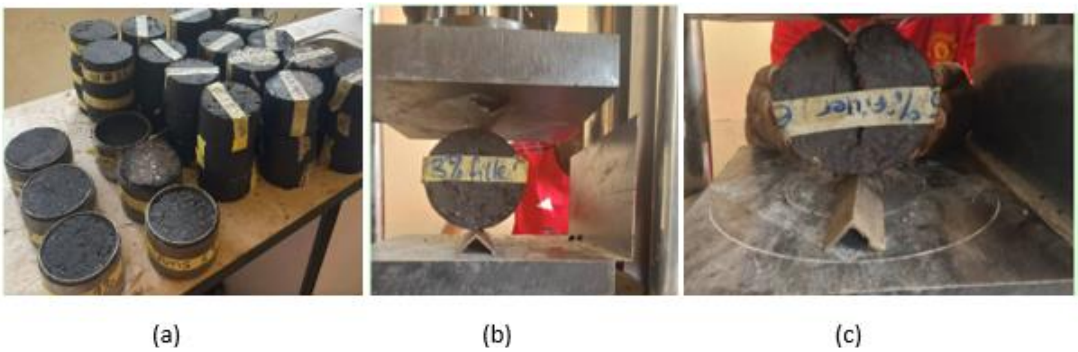

Figure 1: (a) AC Samples; (b) ITS Test and (c) Split Sample

Indirect Tensile Strength Testing

The ITS of the asphalt concrete (AC) samples was determined following ASTM D6931 (2012) in the Civil Engineering laboratory, as presented in Figure 1 (b) and (c). Each specimen was positioned in a universal testing machine, as illustrated in Plate 3.4, and subjected to a constant loading rate of 50 ± 0.5 mm/min. The temperature of the test chamber was maintained at 25 °C throughout the procedure. For every mix type, at least three specimens were tested, and the maximum load at failure was recorded. The ITS values were then calculated using the equation specified in ASTM D6931 (Eq. 1.0).

$$ITS_t = \frac{2P}{\pi TD} \quad (1)$$

where ITS_t is the indirect tensile strength in kPa, P is equal to maximum load resist (N), T is the sample height in mm, and D is the sample diameter in mm.

Moisture conditioning of the asphalt concrete specimens was executed in strict conformity with ASTM D4867 (2012). For each mixture, eight specimens were prepared: three were subjected to evaluation in an anhydrous state, whereas the remainder underwent aqueous conditioning (hereinafter designated as "saturated"). The protocol consisted of immersing the specimens in a hydrothermal bath maintained at 60 ± 10 °C for a duration of 24 hours, thereafter transferring them into distilled water stabilized at 25 ± 1 °C for one hour to permit thermal equilibration. The resistance of the mixtures to hydric degradation was subsequently quantified through the Tensile Strength Ratio (TSR), formally defined as the quotient of the indirect tensile strength (ITS) of conditioned specimens to that of unconditioned counterparts, calculated in accordance with Eq. (2).

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \quad (2)$$

where TSR is expressed as a percentage, ITS_{wet} is the strength of the moisture-conditioned specimens, and ITS_{dry} is the strength of the dry specimens. According to AASHTO T283 (2003), a TSR value of at least 80% is recommended as the minimum acceptable threshold for asphalt mixtures. This criterion was adopted in the present study, and the computed TSR results are discussed below.

RESULTS AND DISCUSSION

Optimum Bitumen Content

From the results presented in Table 1, the mechanical and volumetric properties of the asphalt concrete mix vary with bitumen content, and the optimum bitumen content (OBC) is determined by considering stability, unit weight, and voids in total mix (VTM). The Marshall stability increases from 10.9 kN at 4.0% bitumen to a peak of 15.5 kN at 5.0% before decreasing, indicating maximum strength occurs around 5%. Similarly, the unit weight rises from 2.27 g/cc at 4.0% to 2.42 g/cc at 5.0% before declining, showing improved aggregate packing up to that point. On the other hand, VTM decreases from 5.96% at 4.0% to 2.44% at 5.0% before increasing again, with the desirable specification range lying between 3 to 5%. When the three plots of stability against bitumen, unit weight against bitumen, and VTM against bitumen are considered together, the optimum binder content is simply the point where all three meet the required standards at the same time. And that point was found to be at 4.8% of the total mix, meaning the asphalt performed best in terms of strength, density, and acceptable air voids at this binder content.

Table 1: Mechanical and Volumetric Properties of Designed Asphalt Concrete Mix

Sample Bitumen content (%)	Marshal stability (kN)	Marshal flow (mm)	Unit weight (gmb)	VMA (%)	VFB (%)	VTM (%)
4	10.9	2.2	2.27	11.4	76.1	5.96
4.5	14.5	2.8	2.25	25.4	77.5	6.6
5	15.5	2.68	2.42	22.7	76.6	2.44
5.5	13.3	2.8	2.36	23.5	76.2	4.72
6	12.3	2.3	2.31	23.3	75.0	5.56

Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR)

Table 2 presents the indirect tensile strength (ITS) values of asphalt concrete mixtures prepared with white and brown sand powders as filler materials under both dry and saturated conditions. The results show that the ITS in a dry condition is generally higher than in the saturated condition, reflecting the reduction in tensile capacity when exposed to moisture. For instance, at 3% filler, the ITS for white sand powder reached 340 kPa compared to 205 kPa for brown sand, showing the superior bonding and filler effect of white sand. Similarly, under saturated conditions, white sand mixtures exhibited higher resistance (455 kPa at 3% filler) compared to brown sand (56 kPa at 3% filler), indicating that white sand fillers provide better durability against moisture damage.

Table 2: ITS and Tensile Strength Ratio (%) for white sand powder as filler material

Filler Content (%)	Indirect Tensile Strength (ITS) in a Dry Condition		Indirect Tensile Strength (ITS) in a Saturated Condition		Tensile Strength Ratio (%)	
	Brown sand powder	White sand powder	Brown sand powder	White sand powder	Brown sand powder	White sand powder
3	205	340	56	455	27	134
5	205	383	246	465	120	121
7	303	336	253	361	83	107
9	309	469	137	460	44	99

The calculated TSR values further emphasize this difference: white sand consistently achieved ratios above 99%, with values as high as 134% at 3% filler, surpassing the minimum requirement of 80% specified by AASHTO T-283 (2003). This suggests that mixtures containing white sand are highly resistant to moisture-induced damage. In contrast, brown sand mixtures show greater variability; while the TSR values at 5% (120%) and 7% (83%) were acceptable, the mixture at 3% (27%) and 9% (44%) fell well below the AASHTO threshold, indicating a high susceptibility to stripping and loss of strength under moisture. The differences can be attributed to the mineralogical and physical properties of the fillers; white sand powder likely has better gradation and surface chemistry that enhances binder adhesion and reduces moisture intrusion, whereas brown sand powder may contain impurities or less compatible mineral compositions that weaken the aggregate–binder bond when exposed to water. Therefore, the results suggest that white sand powder is a more effective filler in improving the moisture resistance and overall durability of asphalt concrete mixes compared to brown sand powder.

Referring to Table 2, at 3% filler content, the TSR of 133.67% was significantly above the minimum requirement, indicating exceptional resistance to moisture damage, as the Indirect Tensile Strength (ITS) in the saturated condition exceeded that of the dry condition, suggesting that the pulverized white fine aggregate enhanced binder aggregate adhesion and produced a denser mixture with reduced permeability. Similarly, at 5% filler content, the TSR of 121.26% confirmed very good moisture resistance, which can be attributed to adequate filler binder interaction that effectively filled voids in the mineral aggregate (VMA) and limited pathways for water intrusion, thereby maintaining cohesion. At 7% filler content, the TSR decreased to 107.08%, and although still above the threshold, this reduction suggests that excessive filler disrupted the balance between the binder and aggregate skeleton, as higher filler proportions reduced the effective asphalt film thickness, making the mixture more brittle under moisture exposure. At 9% filler content, the TSR further dropped to 97.80%, which, while still acceptable, indicated the least resistant mixture among the specimens, implying that very high filler contents may stiffen the mix excessively, reduce binder film thickness, and increase susceptibility to stripping and microcrack propagation under moisture and traffic loads. Overall, mixtures with 3–7% filler contents demonstrated superior durability and resistance to moisture-induced damage, but at 9% filler content, although the TSR remained above the AASHTO minimum requirement, the long-term durability of the pavement could be compromised due to the critical balance between filler binder interaction, aggregate interlock, and effective asphalt film thickness that governs resistance to stripping.

Figure 2 illustrates the relationship between filler content and Tensile Strength Ratio (TSR) for asphalt mixtures containing brown and white sand powders as fillers. For brown sand powder, TSR rises sharply from about 25% at 3% filler to a peak of approximately 120% at around 5–5.5% filler, after which it declines steadily to about 40–45% at 9% filler content, indicating that moderate filler improves binder–aggregate adhesion by filling voids and enhancing cohesion, while excessive filler reduces binder film thickness, increases stiffness, and promotes moisture susceptibility. In contrast, mixtures with white sand powder display a consistently higher TSR across all filler levels, starting at about 135% at 3% filler and decreasing almost linearly to around 100% at 9% filler, suggesting that its finer texture and mineral composition provide more stable binder–filler interactions and better resistance to stripping, though increasing filler still reduces binder effectiveness. Overall, brown sand powder shows an optimum performance around 5% filler, whereas white sand powder maintains superior and more stable resistance to moisture damage across the entire filler range, albeit with a gradual decline as filler content increases.

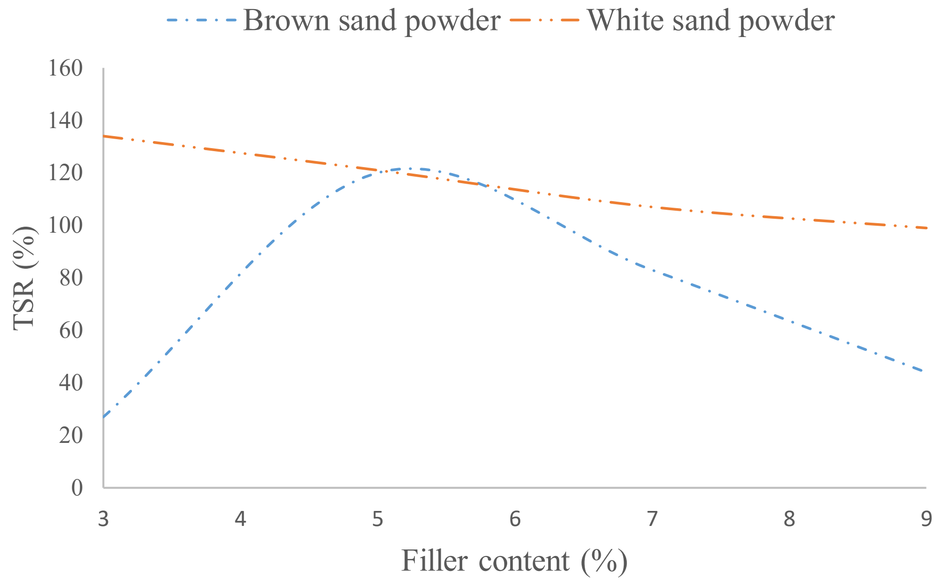

Figure 2: TSR variation as a results of filler material

CONCLUSION

The study concluded that white sand powder provided higher indirect tensile strength (ITS) under both dry and saturated conditions compared to brown sand powder, confirming its superior role in improving binder adhesion and resistance to moisture. The tensile strength ratio (TSR) results further showed that mixtures with white sand consistently met and exceeded the AASHTO T-283 minimum requirement of 80%, while brown sand mixtures failed at some filler contents, indicating greater vulnerability to stripping and moisture damage. In terms of practicability, incorporating white sand powder as a filler in asphalt mixtures is beneficial in regions prone to heavy rainfall or moisture infiltration, as it enhances durability and extends pavement service life without requiring significant changes in mix design practice. However, the study was limited to laboratory-scale testing under controlled conditions and considered only two types of pulverized sand fillers, therefore field validation, long-term performance monitoring, and assessment of economic implications are recommended to fully establish the practical applicability of the results.

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