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A STRENGTH-NORMALISED FRAMEWORK FOR COMPARING COBBLESTONE AND ASPHALT CONCRETE WEARING COURSES IN LOW-SPEED URBAN ROADS

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Abstract: Low-speed urban road sections such as intersections, bus bays, parking areas, and braking zones are subjected to high contact stresses, frequent braking, and moisture exposure, conditions that often lead to rutting, deformation, and strength degradation in conventional asphalt wearing courses. Although cobblestone pavements have historically demonstrated durable performance in similar environments, their application remains largely based on empirical practice rather than systematic mechanical comparison with asphalt materials. This study proposes a strength-normalized performance framework to compare the mechanical suitability of cobblestone and dense-graded asphalt concrete wearing courses for low-speed urban applications. Cobblestone performance was characterized using aggregate crushing, impact, and abrasion tests representing compressive resistance, impact toughness, and abrasion durability. Asphalt mixture performance was evaluated using Marshall stability, indirect tensile strength, and unconfined compressive strength to represent shear, tensile, and compressive resistance. Test results were normalized into dimensionless indicators and integrated into composite strength indices reflecting dominant pavement stress modes. Results show that cobblestone achieved a strength index of 1.317, compared with 1.102 for asphalt under dry conditions, indicating approximately 20% higher resistance to compression- and wear-dominated loading. Under soaked conditions, the cobblestone index decreased to 1.152, approaching asphalt performance.

Keywords: cobblestone pavement, asphalt concrete, strength normalization, low-speed urban roads, mechanical performance

Abstrak: Ruas jalan perkotaan berkecepatan rendah seperti persimpangan, halte bus, area parkir, dan zona pengereman mengalami tegangan kontak tinggi, pengereman berulang, serta paparan kelembapan, kondisi yang sering menyebabkan lapisan aus aspal konvensional mengalami alur, deformasi, dan penurunan kekuatan. Meskipun perkerasan cobblestone secara historis menunjukkan ketahanan yang baik pada kondisi serupa, penerapannya masih banyak didasarkan pada praktik empiris dibandingkan dengan perbandingan mekanis yang sistematis dengan material aspal. Penelitian ini mengusulkan kerangka evaluasi berbasis normalisasi kekuatan untuk membandingkan kesesuaian mekanis antara cobblestone dan campuran beton aspal bergradasi rapat sebagai lapisan aus pada jalan perkotaan berkecepatan rendah. Kinerja cobblestone dikarakterisasi menggunakan uji nilai hancur agregat, uji impak agregat, dan uji abrasi Los Angeles yang merepresentasikan ketahanan terhadap beban tekan, benturan, dan keausan. Kinerja campuran aspal dievaluasi menggunakan stabilitas Marshall, kuat tarik tidak langsung, dan kuat tekan bebas yang merepresentasikan ketahanan geser, tarik, dan tekan. Hasil pengujian dinormalisasi menjadi indikator tak berdimensi dan diintegrasikan ke dalam indeks kekuatan komposit yang merepresentasikan mode tegangan dominan pada perkerasan. Hasil penelitian menunjukkan bahwa cobblestone memiliki indeks kekuatan sebesar 1,317, lebih tinggi dibandingkan aspal sebesar 1,102 pada kondisi kering, yang menunjukkan sekitar 20% ketahanan lebih tinggi terhadap beban dominan tekan dan keausan. Pada kondisi jenuh air, indeks cobblestone menurun menjadi 1,105 sehingga mendekati kinerja aspal.

Kata kunci: : perkerasan cobblestone, beton aspal, normalisasi kekuatan, jalan perkotaan berkecepatan rendah, kinerja mekanis

1. INTRODUCTION

The wearing course is the pavement layer directly exposed to traffic loading and environmental actions, and its mechanical performance plays a critical role in controlling surface durability, resistance to deformation, and long-term serviceability of road infrastructure. Advances in pavement materials research have established that the structural response of wearing courses is governed by material strength characteristics and loading conditions, which directly influence pavement distress development and service life (Zhang & Zhang, 2023). In modern urban road networks, asphalt concrete wearing courses are widely adopted due to their constructability, smooth riding quality, and the availability of well-established mix design and laboratory evaluation procedures (Luan et al., 2023).

However, the performance of asphalt wearing courses in urban environments is increasingly challenged by service conditions that differ from those assumed in conventional pavement design. Low-speed urban road sections, including intersections, bus bays, parking areas, and braking zones, are characterised by frequent stopping, acceleration, and turning movements that impose repeated traffic loading over relatively small contact areas. Under such conditions, wheel loads act for longer durations, generating high compressive and shear stresses at the pavement surface (Zhang & Zhang, 2023). These stress regimes have been shown to promote permanent deformation and shear-related rutting in asphalt pavements, particularly when combined with elevated temperature and moisture exposure (Deng & Shi, 2023). Experimental studies further indicate that asphalt mixture performance indicators developed for general traffic conditions may not fully capture deformation behaviour under slow-moving and channelized traffic loads (Luan et al., 2023).

Stone wearing courses, particularly cobblestone pavements, represent an alternative surfacing system that has historically been applied in urban streets subjected to heavy braking and low-speed traffic. Unlike asphalt mixtures, which behave as viscoelastic continua with temperature- and rate-dependent response, cobblestone pavements function as rigid modular systems in which load transfer occurs primarily through direct stone-to-stone contact. Numerical and field-based investigations have demonstrated that this structural configuration leads to distinct stress distribution and deformation mechanisms compared with asphalt pavements under urban traffic loading (Fiorentini et al., 2023). Long-term field observations further suggest that natural stone pavements can maintain structural integrity and surface durability under urban traffic conditions when appropriately designed and constructed (Majer et al., 2024).

The mechanical performance of wearing courses is commonly evaluated using laboratory-based strength indicators that reflect dominant stress modes under traffic loading. For asphalt mixtures, parameters such as Marshall stability, indirect tensile strength, and compressive strength are widely used to assess load-bearing capacity, resistance to cracking, and deformation behaviour (Luan et al., 2023). Recent experimental studies have confirmed that these indicators provide meaningful insight into the mechanical response and moisture susceptibility of asphalt mixtures under traffic loading (Zinnurain et al., 2025). In contrast, stone materials are typically characterised using aggregate crushing, impact, and abrasion tests, which describe resistance to compressive loading, mechanical degradation, and surface wear. Although these test methods differ in form, they each represent strength-related properties that govern wearing course performance under high-stress traffic conditions.

Despite these established testing approaches, most existing studies evaluate asphalt and stone wearing courses independently using material-specific performance indicators, with limited attempts to integrate the results within a unified, mechanics-based comparative framework. Consequently, decisions regarding the application of cobblestone as an alternative wearing course material in low-speed urban environments are often based on empirical practice or functional considerations rather than on quantitative strength-based evaluation (Majer et al., 2024). This limitation is particularly relevant for urban road sections where dominant distress mechanisms are governed by compressive stress, shear loading, and abrasion rather than tensile cracking alone (Deng & Shi, 2023).

To address this gap, the present study proposes a strength-normalised, performance-based framework for comparative evaluation of cobblestone and dense-graded asphalt concrete wearing courses for low-speed urban applications. Laboratory indicators representing compressive, tensile or impact, and abrasion-related resistance are normalised into dimensionless performance indices and combined into composite strength measures based on equivalent stress modes. The objective is to provide an objective, mechanics-based basis for selecting appropriate wearing course materials in low-speed, high-stress urban road environments where conventional asphalt surfaces are prone to premature distress.

2. METHODOLOGY

Materials

The cobblestone consisted of naturally occurring stone units sourced from CICO Quarry in the Mbeya Region, Tanzania, a supplier of aggregates commonly used for road construction in the region. The physical properties of the stone were determined in the laboratory in accordance with ASTM C97/C97M, yielding a bulk density of 2650 kg/m³ and water absorption of 0.8%.

The asphalt material consisted of a conventional dense-graded asphalt concrete wearing course (AC-WC) prepared using penetration grade 60/70 bitumen. The mixture was produced using crushed coarse aggregates, natural fine aggregates, and mineral filler following standard asphalt mixture preparation procedures. Mixture proportions were determined using the Marshall mix design method in accordance with ASTM D6927, and the compacted specimens exhibited an air void content of 4%, which is typical for dense-graded asphalt wearing course mixtures used in surface layers.

Mechanical characterization tests

The mechanical performance of the cobblestone and asphalt concrete materials was evaluated using laboratory tests representing mechanical resistance mechanisms relevant to pavement wearing course performance. Separate test methods were applied to characterize the mechanical behavior of the cobblestone aggregates and the asphalt concrete mixture. All tests were conducted using three replicate specimens, and the reported values represent the arithmetic mean.

1. Cobblestone Tests

The mechanical resistance of the cobblestone material was characterized using aggregate property tests representing compressive, impact, and abrasion-related behavior relevant to pavement surface performance. Resistance to compressive loading was evaluated using the Aggregate Crushing Value (ACV) test conducted in accordance with BS 812-110, while resistance to sudden impact loading was determined using the Aggregate Impact Value (AIV) test following BS 812-112. Abrasion resistance and durability under mechanical wear were assessed using the Los Angeles Abrasion (LAA) test performed in accordance with ASTM C131/C131M, which determines the percentage mass loss of aggregates subjected to abrasion and impact in a rotating steel drum containing steel spheres.

2. Asphalt Concrete Tests

The mechanical performance of the asphalt concrete mixture was evaluated using standard laboratory tests commonly applied for asphalt mixture characterization. Load-bearing capacity and resistance to deformation were determined using the Marshall stability test conducted in accordance with ASTM D6927. Tensile resistance of the mixture was evaluated using the Indirect Tensile Strength (ITS) test performed following ASTM D6931, in which diametral compression of cylindrical specimens induces tensile stresses within the specimen. Compressive resistance was assessed using the Unconfined Compressive Strength (UCS) test under axial loading conditions.

3. Stress Mode Representation

To enable comparison between cobblestone and asphalt concrete wearing courses, the laboratory tests employed in this study were grouped according to the dominant mechanical stress modes they represent in pavement surface behavior. Pavement surfaces are subjected to compressive, tensile, and shear stresses induced by traffic loading and tyre–pavement interaction, which contribute to distress mechanisms such as rutting, cracking, and surface degradation (Liu et al., 2025; Wang et al., 2024). For the cobblestone material; As per BS 812-110, the Aggregate Crushing Value (ACV) test represents resistance to compressive loading through progressive particle crushing. The Aggregate Impact Value (AIV) test reflects aggregate toughness under impact loading, while the Los Angeles Abrasion (LAA) test evaluates resistance to abrasion and particle degradation under repeated mechanical interaction (ASTM C131/C131M).

For asphalt concrete mixtures, comparable mechanical behavior was characterized using commonly applied mixture strength tests. The Unconfined Compressive Strength (UCS) test represents the compressive resistance of asphalt mixtures under axial loading conditions, reflecting the ability of the material to sustain compressive stresses (Xia et al., 2019). The Indirect Tensile Strength (ITS) test is widely used to evaluate tensile resistance and cracking susceptibility of asphalt mixtures subjected to traffic loading (ASTM D6931; Seitllari et al., 2022). Marshall stability represents the load-bearing capacity and resistance of asphalt mixtures to plastic deformation under compressive loading conditions typical of pavement surface layers (ASTM D6927). Based on these mechanical interpretations, the indicators were grouped into compressive, tensile or impact, and abrasion or shear resistance categories for the strength normalization and composite performance evaluation.

Although the laboratory tests applied to cobblestone aggregates and asphalt concrete mixtures differ in procedure and material scale, the indicators were selected to represent equivalent mechanical resistance mechanisms relevant to pavement surface performance. The tests were therefore grouped according to dominant stress modes compressive, tensile or impact, and abrasion or shear and subsequently converted into dimensionless normalized indices. This approach enables comparison of mechanically dissimilar materials within a unified evaluation framework and is consistent with normalization practices used in multi-criteria performance assessment (Malefaki et al., 2025; Nardo et al., 2005).

Strength normalization

1. Indicator Normalization

Mechanical indicators obtained from laboratory tests differ in magnitude, units, and performance direction. To enable consistent comparison, the measured values were transformed into dimensionless performance indices through normalisation. Normalisation techniques are widely used to convert heterogeneous indicators into a comparable scale while preserving relative performance relationships (Malefaki et al., 2025; Nardo et al., 2005). For strength-based indicators, where higher values represent improved mechanical performance, including Marshall stability, indirect tensile strength, and unconfined compressive strength, the normalised index (I_i) was calculated from the measured value (P_i) and the corresponding specification limit from relevant pavement material standards (P_{limit}) using Equation 1. This procedure is standard in multi-criteria evaluation to maintain comparability across strength indicators (Triantaphyllou, 2000).

$$I_i = \frac{P_i}{P_{limit}} \quad (1)$$

For degradation-based indicators, where lower values indicate better resistance to mechanical damage, including aggregate crushing value, aggregate impact value, and Los Angeles abrasion loss, the ratio was inverted as per Equation 2.

$$I_i = \frac{P_{limit}}{P_i} \quad (2)$$

This transformation ensures all indicators follow the same performance direction, with higher index values representing superior mechanical resistance. Directional adjustment of indicators with opposite preference directions is a common practice in multi-criteria decision-making (Linh et al., 2025; Triantaphyllou, 2000).

2. Composite Strength Index (CSI)

After the individual indicators were normalized, they were aggregated into a Composite Strength Index (CSI) to represent the overall mechanical performance of the wearing course material across all evaluated indicators. Composite indices provide a systematic framework for integrating multiple heterogeneous performance measures into a single comparative metric in engineering evaluations (Malefaki et al., 2025). Following common practice in multi-criteria evaluation, the normalized indicators were aggregated using equal weighting, as no experimentally justified weighting scheme is typically available for such indices (Linh et al., 2025). The CSI was computed as the arithmetic mean of the normalized indicators as per Equation 3.

$$CSI = \frac{1}{n} \cdot \sum_{i=1}^{n} I_i \quad (3)$$

Where I_i is the normalised index for each mechanical indicator, and n is the total number of indicators considered. The resulting CSI provides a unified, dimensionless measure for comparing the relative mechanical performance of cobblestone and asphalt wearing courses under the considered loading mechanisms. Performance index approaches have also been applied in cementitious material studies to integrate heterogeneous mechanical and durability indicators into a unified evaluation framework, providing a practical precedent for this methodology (Mlodi & Djayaprabha, 2025).

3. RESULTS AND DISCUSSION

Cobblestone performance

Cobblestone aggregates from CICO Quarry were evaluated using standardized mechanical tests representing compressive resistance, impact toughness, and abrasion durability. Normalized indices were calculated by relating measured results to relevant specification limits, following widely accepted material evaluation practices as shown in

Table **1**. However, Previous studies, such as (Chan et al., 2023), reported that aggregate abrasion values remain nearly unchanged under wet and dry conditions. Therefore, it was considered reasonable to assume the same abrasion index for the soaked condition in this study, particularly since the ASTM C131 specifies the test under dry conditions only.

Table 1. Cobblestone Test Results and Normalized Indices

Test	Mechanical Stress Mode	Condition	Measured Result	Standard	Specification Limit	Normalized Index (I)
Aggregate Crushing Value (ACV, %)	Compressive resistance	Dry	20.7	BS 812-110:1990	≤ 30 %	1.449
Aggregate Crushing Value (ACV, %)	Compressive resistance	Wet	23.1	BS 812-110:1990	≤ 30 %	1.299
Aggregate Impact Value (AIV, %)	Impact / tensile resistance	Dry	22.7	BS 812-112:1990	≤ 30 %	1.322
Aggregate Impact Value (AIV, %)	Impact / tensile resistance	Wet	35.9	BS 812-112:1990; soaked)	≤ 35 %	0.975
Los Angeles Abrasion (LAA, %)	Abrasion / shear resistance	Dry	25.4	ASTM C131/C535	≤ 30 %	1.181

The distribution of the normalized performance indices across the evaluated stress modes is illustrated in Figure 1.

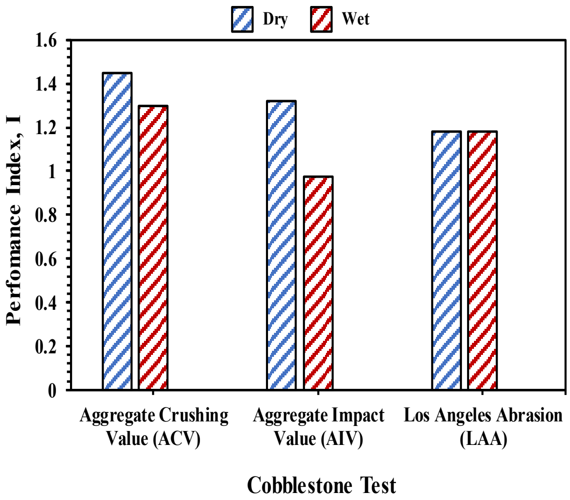

Figure 1. Normalized Performance of Cobblestone Tests

The Aggregate Crushing Value (ACV) results under both dry and soaked conditions are well below the commonly applied specification limit of 30 %, indicating that the cobblestone aggregates provide reliable resistance to crushing under gradually applied compressive loads. Studies on coarse aggregate mechanical behaviour indicate that lower ACV values correspond to stronger resistance to particle crushing and are widely used as indicators of aggregate suitability for surface and wearing course applications (Jiang et al., 2022). The slight increase in ACV under soaked conditions is consistent with reported moisture effects on aggregate compressive behaviour, where the presence of water may reduce interparticle friction and slightly weaken compressive resistance without substantially compromising structural capacity under static loading. The Aggregate Impact Value (AIV) results indicate reduced impact resistance in the presence of moisture. While the dry AIV remains within typical specification limits, the soaked value slightly exceeds common guidance levels. This behaviour is consistent with findings reported by Yadava & Aqeel, (2020), who observed that moisture can reduce aggregate toughness by weakening internal grain contacts, thereby increasing the proportion of fines generated during impact loading.

The Los Angeles Abrasion (LAA) value of 25.4 % indicates strong resistance to mechanical wear and fragment generation. Aggregates with lower LA abrasion loss are generally considered more resistant to abrasion and degradation under repeated tyre–surface interactions and traffic-induced wear (Tunc & Kursat, 2019).When expressed through the normalised performance indices, the cobblestone demonstrates strong compressive and abrasion resistance, with ACV indices ranging from 1.449 (dry) to 1.299 (wet) and an abrasion index of 1.181. Impact resistance remains satisfactory under dry conditions (1.322) but decreases under wet conditions (0.975), indicating moderate moisture sensitivity (Jiang et al., 2022).
Overall, the results suggest that the material maintains robust compressive and abrasion performance with only limited reduction in impact resistance, supporting its suitability for low-speed urban environments where pavement distress is primarily governed by compressive loading and surface wear mechanisms.

Asphalt performance

The mechanical performance of the Asphalt Concrete Wearing Course strength parameters evaluated using Marshall Stability (MS), Indirect Tensile Strength (ITS), and Unconfined Compressive Strength (UCS) from the core specimens, and normalised indices were calculated based on the ratio of measured value to the corresponding Construction Materials Laboratory (CML), (2000) minimum limit with Equation 2, as summarized in Table 2.

Table 2. Asphalt concrete (AC-WC) mechanical performance and normalized indices.

Test	Mechanical Stress Mode	Unit	Strength Parameter	Result Obtained	CML Limit	Normalized Index (I)	Standard Reference
Marshall Stability (Ms)	Abrasion / Shear	kN	Shear / load-bearing capacity	17.1	≥15	1.14	ASTM D6927 / BS 598-107
Indirect Tensile Strength (ITS)	Tensile / Impact	MPa	Tensile resistance	0.45	≥0.40	1.12	ASTM D6931 / BS EN 12697-23
Unconfined Compressive Strength (UCS)	Compressive	MPa	Compressive stiffness	0.52	≥0.50	1.04	ASTM D1074

The normalized mechanical performance indices for the asphalt concrete mixture are illustrated in Figure 2.

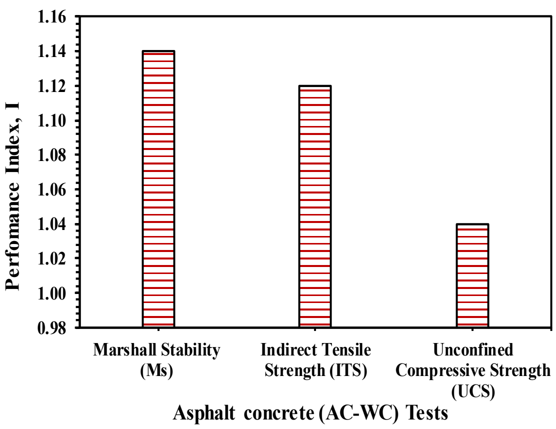

Figure 2. Normalized performance of Asphalt Concrete Tests

The results presented in Figure 2 shows that the AC-WC specimens satisfy the adopted CML strength criteria, with measured values exceeding the specified minimum limits and yielding normalized indices of 1.14, 1.12, and 1.04 for Marshall Stability, ITS, and UCS, respectively. These results indicate that the mixture exhibits adequate mechanical performance across the primary stress modes relevant to pavement surface behavior. The determined Marshall Stability value of 17.1 kN and respective normalized index of 1.14 indicates satisfactory resistance to shear deformation and load-bearing capacity, consistent with expected behavior of dense-graded asphalt mixtures used in surface course layers (Al Kaaf & Ibeabuchi, 2023).

The Indirect Tensile Strength of 0.45 MPa and normalized index of 1.12 reflects the mixture's ability to resist tensile stresses associated with cracking under repeated traffic loading, consistent with the role of ITS as an indicator of tensile integrity and cracking susceptibility in asphalt mixtures (Meqtoof et al., 2024)

The Unconfined Compressive Strength of 0.52 MPa and normalized index of 1.04 confirms that the AC-WC mixture provides compressive stiffness slightly above the minimum requirement, supporting its ability to sustain concentrated wheel loads. Taken together, the normalized indices indicate a balanced mechanical profile across shear, tensile, and compressive resistance, providing a quantitative baseline for subsequent comparison with cobblestone within the composite strength evaluation framework.

Strength-normalized comparison

Following the methodology described in Section 2.3.2, the normalized strength indices were combined to obtain the Composite Strength Index (CSI). This approach integrates compressive, tensile or impact, and abrasion or shear resistance into a single comparative indicator. The calculated indices and corresponding CSI values are presented in

Table **3.**

Table 3. Composite Strength Index (CSI) for Cobblestone and Asphalt Concrete Wearing Courses

Mechanical Stress Mode	Cobblestone Indicator	Normalized Index (Dry)	Normalized Index (Soaked)	Asphalt Concrete Indicator	Normalized Index
Compressive resistance	ACV	1.449	1.299	UCS	1.04
Tensile / Impact resistance	AIV	1.322	0.975	ITS	1.12
Abrasion / Shear resistance	LAA	1.181	1.181	MS	1.14
Composite Strength Index (CSI)	—	**1.317**	**1.152**	—	**1.102**

The variation of the normalised indices across the evaluated mechanical stress mode is illustrated in Figure 3.

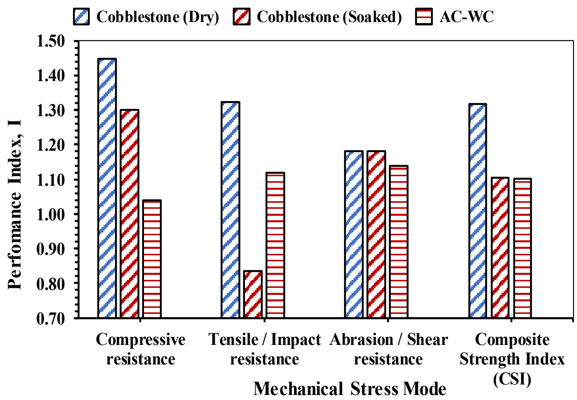

Figure 3. Mechanical stress Modes against Performance Index

As presented in Figure 3, the calculated CSI values for all materials exceed unity, indicating that the measured strength parameters satisfy the adopted minimum performance thresholds. The dry cobblestone condition produced the highest CSI value of 1.317, which may indicate strong resistance to compressive and abrasion-related stresses, as reflected by the low Aggregate Crushing Value and Los Angeles abrasion obtained in Section 3.1. Aggregates exhibiting low crushing and abrasion losses are generally associated with durable mineral structures capable of resisting mechanical degradation under repeated loading (Jiang et al., 2022). Under soaked conditions, the cobblestone CSI decreased to 1.152, which can be attributed primarily to the higher Aggregate Impact Value observed during wet testing. Previous studies have shown that moisture can influence aggregate impact resistance by weakening internal grain contacts and reducing interparticle friction, leading to increased fragmentation under dynamic loading (Yadava & Aqeel, 2020).

The AC-WC mixture produced a CSI of 1.102, which is comparable to the soaked cobblestone condition but slightly lower than the dry cobblestone value. This result may reflect the relatively balanced mechanical response of the asphalt mixture, where Marshall stability, indirect tensile strength, and unconfined compressive strength all exceeded the adopted minimum limits. Asphalt mixtures typically exhibit distributed stress transfer through the binder–aggregate matrix, which can provide balanced resistance to compressive, tensile, and shear-related loading modes within the pavement layer (Wang et al., 2024). In contrast, natural stone materials often demonstrate higher resistance to crushing and abrasion due to their dense mineral composition, although their mechanical response under impact loading may be more sensitive to moisture conditions.

From a comparative perspective, the CSI results suggest that both materials demonstrate mechanical capacities above the adopted performance thresholds within the laboratory testing framework used in this study. The slightly higher CSI value observed for dry cobblestone may indicate stronger resistance to crushing and wear-related stresses, whereas the asphalt mixture demonstrates a more uniform distribution of mechanical resistance across compressive, tensile, and shear-related indicators. However, the CSI should be interpreted as an integrated indicator derived from laboratory strength tests rather than a direct predictor of long-term pavement performance. Field durability can also depend on factors such as structural design, drainage conditions, traffic loading intensity, and maintenance practices (Song et al., 2021).

4. CONCLUSIONS

This study developed a strength-normalized comparative framework to evaluate the mechanical suitability of cobblestone and asphalt concrete wearing courses for low-speed urban road applications. Mechanical properties of cobblestone were characterised using Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion (LAA) tests representing compressive, impact, and abrasion resistance, while asphalt concrete performance was assessed using Marshall Stability, Indirect Tensile Strength (ITS), and Unconfined Compressive Strength (UCS). The measured results were converted into dimensionless normalised indices and combined into composite strength indices (CSI) to enable comparison between materials with different structural behavior.

The results indicate that cobblestone exhibited higher composite mechanical resistance under dry conditions, with a CSI of approximately 1.317 compared with 1.102 for the asphalt concrete mixture. This difference suggests that cobblestone may provide improved resistance to compression- and wear-dominated loading conditions typically occurring in braking and low-speed traffic zones. However, under soaked conditions the cobblestone composite index decreased to approximately 1.152, approaching the asphalt performance level. This trend indicates that moisture exposure can reduce the relative mechanical advantage of cobblestone, particularly in impact-related behaviour. Overall, the proposed strength-normalised framework provides a transparent method for comparing mechanically dissimilar pavement materials and may support material selection for urban road sections where braking, turning, and high contact stresses govern pavement performance.

It should be noted that the comparison presented in this study is based on laboratory-derived strength indicators and a normalization framework intended to facilitate cross-material evaluation. The results therefore represent relative mechanical performance under controlled testing conditions rather than direct predictions of long-term field performance. Factors such as pavement structural design, construction quality, drainage conditions, and traffic loading intensity may also influence the in-service behaviour of wearing course materials.

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