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EFFECT OF RECYCLED SUGARCANE BAGASSE AS AN INTERNAL CURING ADDITIVE ON MECHANICAL STRENGTH, ABRASION RESISTANCE, AND DRYING SHRINKAGE OF PAVING CONCRETE

Dinh-Thang Nguyen[a,b], Phuong N. Pham[a], Trong-Phuoc Huynh[c,*]

[a] *Faculty of Road and Bridge Engineering, The University of Danang - University of Science and Technology,*
54 Nguyen Luong Bang, Danang City, Vietnam
[b] *Faculty of Automotive Engineering Technology, Vinh Long University of Technology Education,*
73 Nguyen Hue Street, Long Chau Ward, Vinh Long Province, Vietnam
[c] *Faculty of Civil Engineering, College of Engineering, Can Tho University,*
Campus II, 3/2 Street, Ninh Kieu Ward, Can Tho City, Vietnam

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Abstract

The utilization of agricultural by-products in paving concrete (PC) has been increasingly explored as a strategy to reduce material-related environmental impacts in pavement construction. This study investigates the influence of recycled sugarcane bagasse (RSB), incorporated into PC at volume fractions ranging from 0 to 2.5 vol.%, on mechanical strength, abrasion resistance, and drying shrinkage behavior. Compressive, flexural, and splitting tensile strengths, surface abrasion loss, and drying shrinkage were evaluated up to 56 days in accordance with relevant Vietnamese standards. Test results indicate that increasing RSB content significantly affects concrete's properties. At 56 days, the compressive strength of the control mixture reached 48.2 MPa, whereas the mixture containing 2.5 vol.% RSB exhibited a substantially reduced strength of 8.9 MPa. Surface abrasion loss increased progressively with RSB addition, rising from 0.42 g/cm^2 for the control mixture to 0.98 g/cm^2 at 2.5 vol.% RSB. A strong inverse linear relationship was observed between compressive strength and surface abrasion loss across all mixtures and curing ages ($R^2 = 0.88$), highlighting the dominant role of matrix compactness in controlling abrasion resistance. Drying shrinkage exhibited a non-monotonic response to RSB incorporation. Mixtures containing 0.5–1.0 vol.% RSB showed shrinkage comparable to or lower than that of the control mixture, whereas higher RSB contents resulted in increased shrinkage at later ages. Although higher RSB dosages caused a noticeable reduction in flexural performance, the mixture containing approximately 0.5 vol.% RSB satisfied the 28-day flexural strength, compressive strength, and surface abrasion requirements specified for level-IV road, while providing measurable shrinkage mitigation. Further mixture optimization is required to enable the use of higher RSB contents while maintaining adequate mechanical performance for pavement applications.

Keywords: Recycled sugarcane bagasse; paving concrete; mechanical strength; abrasion resistance; drying shrinkage.

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1. Introduction

Paving concrete (PC) remains a primary material for rigid pavement due to its high load-carrying capacity, high stiffness, and durability under repetitive traffic loading. However, PC is also resource- and emission-intensive, which has led to increasing efforts to incorporate renewable or recycled constituents into PC, provided that key performance requirements related to load transfer, abrasion resistance, and crack control are not compromised, particularly (i) mechanical properties (compressive,

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[*] Corresponding author. *E-mail address:* htphuoc@ctu.edu.vn (Huynh, T.-P.)

flexural, and splitting tensile strengths), (ii) surface durability against traffic-induced abrasion, and (iii) dimensional stability associated with drying shrinkage and the resulting cracking risk that governs serviceability and long-term maintenance demand. In this context, recycled sugarcane bagasse (RSB), a lignocellulosic by-product generated in significant quantities by the sugar industry, has been increasingly explored in cementitious matrices, predominantly in fibrous form, because its low density, rough surface texture, and moisture affinity can potentially contribute to crack-bridging and moisture buffering, if the dosage and dispersion are adequately controlled. In the present study, the environmental relevance of RSB lies primarily in the utilization of an agricultural by-product within a performance-critical concrete system, rather than in high-volume replacement of conventional constituents. Accordingly, the investigation focuses on identifying a technically compatible dosage range in which RSB can provide measurable serviceability benefits without compromising structural and durability performance.

The literature shows that sugarcane bagasse fibers (SBF) can be incorporated into cement-based composites, yet the resulting properties are highly dosage- and processing-dependent. Early foundational work clarified that botanical constituents and extractives of bagasse can markedly influence cement setting, and that the composite response is strongly dependent on fiber dosage and water availability, indicating that sugarcane bagasse must be considered an active constituent that interacts with cement hydration rather than an inert filler during mix design [1]. Subsequent studies on SBF cement composites expanded the discussion, including physical/thermal implications and control of mixture density/porosity, further reinforcing that the benefits of bagasse addition are conditioned by matrix compactness and fiber–matrix compatibility rather than fiber presence alone [2]. More recent work has continued to confirm a beneficial effect across cement-based systems: moderate SBF contents can improve tensile-related performance indicators and crack control, whereas higher amounts often penalize compressive strength due to increased entrapped air/porosity, fiber balling/agglomeration, and weak interfacial bonding when fibers are insufficiently treated or dispersed. This dosage sensitivity is explicitly documented in recent studies on cement-based composites, including lightweight foamed concrete incorporating treated SBF, where the mixture performance is evaluated alongside sustainability considerations, consistently demonstrating that fiber content must be optimized rather than maximized [3, 4]. In parallel, chemically/physically assisted approaches have been explored to improve fiber–matrix interaction. For example, a prior study reports that alkali-treated SBF in lightweight foamed concrete exhibits an optimal fiber range (3–4 wt.%), improving strength-related properties while highlighting the need for careful control of fresh-state workability and fiber saturation [5]. In another direction, micro-/nano-engineering strategies have been investigated to stabilize the fiber surface and enhance composite performance; notably, cellulose-fiber-reinforced cementitious materials have been shown to exhibit modified early-age autogenous and drying shrinkage behavior due to the water uptake–release capability of hygroscopic fibers, highlighting the relevance of moisture buffering mechanisms in fiber-containing cement matrices [6]. Beyond conventional concrete, SBF has been extended to other cement-based products (blocks/earth-cement units), again reiterating that SBF content must be optimized because moisture transport/void structure and fiber distribution largely govern mechanical and durability outcomes [7, 8]. Beyond sugarcane bagasse, numerous studies have demonstrated that a wide range of natural and agricultural wastes can be incorporated into cementitious materials as part of sustainability-oriented concrete design. Comprehensive review studies report that agro-waste ashes and plant-derived materials (e.g., rice husk ash, palm oil fuel ash, wheat straw ash, coconut shell-derived materials, and other agricultural by-products) have been successfully used as supplementary cementitious materials or fillers, contributing to reduced clinker consumption and improved environmental performance when appropriately processed and proportioned [9, 10]. These studies consistently indicate that the performance of agro-waste-based concretes is controlled by two competing mechanisms: on the one hand, certain agricultural wastes may provide beneficial effects related to internal curing, crack mitigation, or microstructural refinement; on the other hand, excessive contents or inadequate processing often lead to increased porosity, weakened interfacial transition zones, and reduced mechanical performance.

Recent investigations focusing on the use of agricultural wastes as partial aggregate substitutes or volumetric additions further indicate that volumetric control and mixture compactness are critical for maintaining mechanical integrity, particularly when such materials are introduced as lightweight or porous constituents rather than as cement replacements [11, 12]. However, while many agro-waste-based concretes demonstrate acceptable compressive or tensile performance at low replacement levels, durability- and serviceability-related properties (e.g., abrasion resistance, shrinkage development, and long-term surface performance) are far less consistently evaluated, especially in the context of pavement concrete subjected to traffic-induced wear [10, 12]. This broader literature context motivates pavement-oriented studies that jointly assess mechanical performance, abrasion resistance, and drying shrinkage when agricultural wastes are incorporated into concrete, and directly supports the scope and experimental design of the present study.

Despite these advances, most studies only focus on the use of RSB in cement paste, mortar, foamed concrete, or earth-cement units, primarily evaluating strength and selected durability indicators. In contrast, surface abrasion resistance, a governing functional property of PC under tyre–aggregate interaction and polishing wear, is rarely quantified alongside mechanical performance and drying shrinkage. Also, although lignocellulosic fibers are inherently hygroscopic and may act as internal moisture reservoirs, pavement-oriented evidence explicitly framing RSB as an internal curing or moisture-buffering addition under volumetric mixture control remains limited. Recent studies provide clearer experimental evidence that natural or bio-based porous inclusions can serve as internal water reservoirs that regulate moisture gradients and internal relative humidity (RH) evolution in cementitious systems. For instance, plant-based fibers have been reported to induce internal curing effects by storing mixing water and releasing it during drying, resulting in measurable changes in shrinkage development and internal RH profiles [13]. Similarly, prewetted biochar has been increasingly investigated as a bio-based internal curing medium, where the internal curing benefit is attributed to water absorption–desorption within the char pore network and the resulting RH stabilization, including recent demonstrations in conventional concrete and ultra-high-performance concrete-type systems [14, 15]. In parallel, internal curing concepts and their governing kinetics (e.g., water uptake–release, RH buffering, and transport–mechanical coupling) have been summarized in recent literature, further supporting the mechanistic basis for moisture-reservoir additions in cementitious composites [16]. While fiber–cement composite research has shown that cellulose-based fibers can mitigate drying shrinkage and shrinkage-induced cracking through moisture uptake–release and fiber-bridging mechanisms when properly dispersed [17], these findings are seldom reported in PC mixture design, where constituents should be proportioned by concrete volume to preserve paste content, aggregate skeleton integrity, and air structure. These gaps motivate a systematic evaluation of RSB incorporation in pavement concrete with simultaneous consideration of strength, abrasion resistance, and shrinkage behavior.

Accordingly, RSB not only acts as a fibrous reinforcement but may also function as a moisture-buffering inclusion with plausible internal curing behavior, although RSB is introduced as particulate fragments rather than continuous fibers in PC. In this study, the internal curing concept is considered in an inferred sense, primarily based on drying shrinkage behavior and supported by previous literature, and is therefore interpreted as a moisture-buffering effect rather than a directly verified internal curing mechanism. Owing to its hygroscopic nature, RSB may absorb part of the mixing water and subsequently release it within the hardened matrix, thereby moderating drying shrinkage and reducing the propensity for shrinkage-induced cracking when proper RSB content is incorporated. Mechanistically, this moisture-buffering concept is consistent with the internal curing principle, whereby an internal water reservoir partially stabilizes internal relative humidity (RH) during drying and reduces capillary-stress-driven shrinkage, provided that the reservoir does not excessively increase pore connectivity or compromise matrix compactness. Such a mechanism is expected to enhance the crack resistance and serviceability of PC, provided that the RSB dosage remains within a range that neither excessively increases pore connectivity nor compromises matrix compactness. This conceptual framework is consistent with broader evidence indicating that SBF strongly interacts with cement hydration and the mixture water balance [1], that composite performance is governed by porosity and fiber–matrix compatibility [2], and that shrinkage-related cracking indicators can be mitigated through the formation of effective fiber networks [17]. Accordingly, when RSB is introduced into PC as a controlled volume fraction of concrete, rather than as an aggregate replacement, it can be systematically assessed as an internal moisture reservoir that influences shrinkage behavior. At the same time, the resulting changes in matrix compactness are expected to be reflected in both mechanical capacity and surface abrasion resistance, the two performance domains that ultimately govern pavement serviceability under traffic loading.

Distinct from prior studies that mainly address SBF in general cement composites and report strength responses without a pavement-functional triad, this study provides a pavement-oriented, performance-coupled dataset for PC incorporating RSB by volume control. Rather than seeking to maximize biomass incorporation, the objective of this study is to identify a dosage range in which RSB can provide serviceability-related benefits (e.g., shrinkage mitigation) without compromising the structural and surface durability requirements of paving concrete. From a pavement engineering perspective, defining such a feasible dosage window is critical because excessive incorporation of porous lignocellulosic materials may rapidly deteriorate matrix compactness and mechanical performance. Mechanical strength, drying shrinkage development, and surface abrasion loss are concurrently quantified, and the influence of RSB-induced changes in compactness on abrasion performance is examined, thereby generating design-relevant evidence for the use of RSB as a practical internal-curing constituent in PC.

2. Materials and methods

2.1. Materials

A ternary binder system was employed to produce PC, consisting of ordinary Portland cement, ground granulated blast-furnace slag (GGBFS), and fly ash (FA). The cement complied with the requirements of TCVN 2682:2020 [18], providing the primary source of early-age strength. GGBFS was incorporated as a latent hydraulic material, in accordance with TCVN 11586:2016 [19], contributing to matrix densification and improved later-age performance. FA satisfying the requirements of TCVN 10302:2014 [20] was used to enhance workability and support long-term pozzolanic reactions [21].

Crushed sand with a particle size range of 0.14–5 mm was used as fine aggregate, selected for its angular particle shape and adequate surface roughness, which are beneficial for strength development and surface texture in PC. The sand has a fineness modulus of 3.26, a density of 2.77 g/cm^3, and a water absorption of 1.3%. Crushed stone coarse aggregates with a nominal maximum size of 19 mm have a density of 2.75 g/cm^3 and water absorption of 1.1%. The fine and coarse aggregates also complied with TCVN 7570:2006 [22] and were selected to ensure mechanical stability, abrasion resistance, and compatibility with PC applications.

RSB (Fig. 1(a)) was incorporated as an additional constituent in the concrete mixtures by volume. The RSB was processed to ensure repeatable material characteristics and stable particle geometry before its incorporation in PC. Owing to its lignocellulosic and porous nature (Fig. 1(b)), RSB exhibits a high water absorption capacity, which may influence internal moisture distribution and drying behavior in PC. In this study, RSB was introduced without replacing fine or coarse aggregates, allowing its effects on matrix compactness, moisture buffering, and shrinkage behavior to be evaluated independently. The RSB was obtained through a recycling process adapted from previously reported methodologies [23, 24], with minor modifications to suit the objectives and scale of the present work. Raw sugarcane bagasse was collected from local sources, thoroughly cleaned to remove residual sugars and impurities, and cut into smaller fragments. The material was then subjected to boiling and alkaline treatments to partially remove soluble components and surface contaminants. Specifically, the RSB was immersed in 3% NaOH solution for 24 hours at ambient laboratory temperature. After treatment, the material was washed with clean water to remove residual alkali, followed by drying, mechanical grinding, and sieving. This process yielded RSB particles with controlled size suitable for volumetric incorporation into concrete mixtures, while preserving the intrinsic lignocellulosic and porous features required for moisture-buffering behavior. After sieving, the RSB particles used in this study were within the size range of 0.15–2.5 mm, which was selected to ensure stable dispersion and minimize fiber balling.

(a) RSB (b) SEM image

Figure 1. RSB and its SEM image

A type-G high-range water-reducing admixture (superplasticizer–SP) conforming to TCVN 8826:2011 [25] was used to achieve a consistent slump of approximately 4 cm measured according to TCVN 3106:2022 [26] while maintaining a constant water-to-binder (w/b) ratio across all concrete mixtures. The SP dosage was adjusted to ensure adequate dispersion of binder constituents and RSB without adversely affecting strength development. For all mixtures, the SP dosage was varied as needed to maintain a target slump of approximately 4 cm, ensuring comparable fresh-state consistency rather than representing a fixed dosage for each mixture.

2.2. *Mix proportioning*

A control PC mixture was designed using a ternary binder system and conventional aggregates. The concrete proportions were established based on the authors' prior experience with PC mixture design, supported by preliminary laboratory trials and subsequent adjustments to ensure compliance with fundamental performance requirements for pavement applications, particularly workability and strength. The final control mixture consisted of 223.4 kg of cement, 173.9 kg of GGBFS, 99.4 kg of FA, 657.4 kg of crushed sand, 1112.4 kg of crushed stone, 173.8 kg of water, and 5.5 kg of SP per cubic meter of concrete. This mixture served as the reference composition for evaluating the effects of RSB incorporation under comparable mechanical strength and workability conditions.

Table 1. Quantity of RSB for each concrete mixture

Mix ID.	RSB (vol.%)	RSB (kg)
R0.0	0	0
R0.5	0.5	7.5
R1.0	1.0	15.0
R1.5	1.5	22.6
R2.0	2.0	30.1
R2.5	2.5	37.6

RSB was subsequently incorporated into the reference mixture as an additional constituent at 0, 0.5, 1.0, 1.5, 2.0, and 2.5 vol.%. The corresponding mixtures were designated R0.0, R0.5, R1.0, R1.5, R2.0, and R2.5, respectively, with exact quantities for each mixture shown in Table 1. The corresponding RSB masses were calculated from the target volumetric fractions using the measured saturated surface-dry (SSD) density of RSB, and the reported values are rounded to one decimal place. Notably, RSB was added without replacing either fine or coarse aggregates, allowing the aggregate skeleton and binder content to remain unchanged across all mixtures. In this study, the base mixture was proportioned per 1 m^3 of reference concrete, and RSB was then introduced at the specified volumetric fraction relative to that reference volume. Accordingly, the fresh yield of RSB-containing mixtures may be slightly higher than 1 m^3, but all mixtures were compared on the same reference-mixture basis rather than on a strict constant-yield redesign. The w/b ratio was kept constant, and SP dosage was adjusted to maintain comparable workability. RSB was added in an SSD condition to prevent its porous nature from affecting the effective water content and slump of the mixtures. In this context, the reported w/b ratio refers to the mixing water added for the binder system (cement–GGBFS–FA), while RSB is introduced in SSD condition to minimize unintended withdrawal of paste water during mixing. The SSD conditioning is intended to control the initial water exchange between RSB and the cementitious matrix; nevertheless, local water redistribution and entrapped air associated with porous organic inclusions cannot be fully eliminated, and the resulting strength loss is interpreted primarily through compactness/porosity and interfacial discontinuity effects rather than through a direct verification of hydration enhancement. For volumetric-to-mass conversion (Table 1), an SSD bulk density measured for the processed RSB was used; this value represents the packed material in SSD condition rather than the true density of the lignocellulosic solid.

2.3. *Sample preparation and test programs*

All concrete mixtures were prepared in the laboratory following a consistent mixing and specimen preparation procedure to ensure repeatability and comparability among mixtures. Before mixing, all concrete ingredients were weighed according to the designed mixture proportions. RSB was prepared in advance and added to the mixtures according to the specified volume fractions. Prior to mixing, processed RSB was brought to an SSD state to control its initial moisture condition; the material was soaked to saturation and then surface-dried to remove free water while retaining absorbed water within its porous structure. To promote full saturation of the internal pore structure, the processed RSB particles were pre-soaked in water for approximately 24 h. After soaking, the excess water was removed by draining the material through a sieve until no visible surface water remained. The SSD condition was verified by ensuring that no free water accumulated during weighing and that no moisture transfer occurred when the particles were briefly placed on dry filter paper.

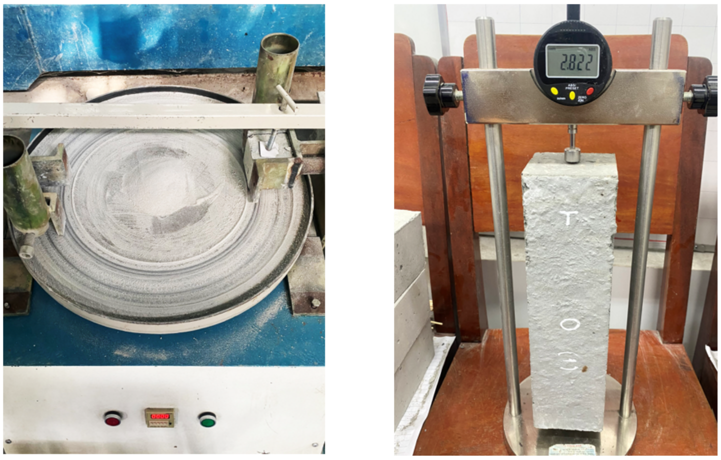
The mixing process began with dry mixing of cement, GGBFS, FA, crushed sand, and crushed stone until a uniform dry blend was obtained. Subsequently, approximately three-quarters of the total mixing water and SP were gradually introduced, and mixing was continued to ensure thorough wetting and uniform dispersion of all constituents. RSB was then added to the mixer, followed by the remaining portion of water and SP. Mixing was further continued until a homogeneous, workable concrete mixture was achieved. The fresh concrete was poured into molds corresponding to each test method (Table 2), and specimens were prepared and cured in accordance with TCVN 3105:2022 [27]. The preparation, curing conditions, and testing schedule were kept identical across all mixtures, allowing the observed differences in PC performance to be attributed primarily to the incorporation of RSB.

Table 2. Test methods used to evaluate concrete's properties

Test name	Age (day)	Sample size (mm)	Reference
FS	28, 56	100 × 100 × 400	TCVN 3119:2022 [28]
CS	28, 56	100 × 100 × 100	TCVN 3118:2022 [29]
TS	28, 56	100 × 100 × 100	TCVN 3120:2022 [30]
SA	28, 56	70 × 70 × 70	TCVN 3114:2022 [31]
DS	0, 3, 7, 14, 28, 56	75 × 75 × 285	TCVN 3117:2022 [32]

(a) Flexural strength (b) Compressive strength (c) Splitting tensile strength

The mechanical strength (e.g., flexural strength–FS, compressive strength–CS, and splitting tensile strength–TS), surface abrasion (SA), and drying shrinkage (DS) of the PC were evaluated in accordance with the Vietnamese standards summarized in Table 2. Fig. 2 presents representative photographs of the test setups used in this study. For each test and curing age, at least three specimens



(d) Surface abrasion (e) Drying shrinkage

Figure 2. Experimental setups for mechanical, abrasion, and drying shrinkage tests

were tested, and the reported values represent the average result.

3. Results and discussion

3.1. Flexural strength

Fig. 3 shows that including RSB in PC results in a clear dosage-dependent reduction in FS at both curing ages, with the extent of the reduction heavily influenced by the RSB volume. At 28 days, the control mixture (R0.0) had an FS of 4.39 MPa, whereas mixes containing 0.5 vol.% RSB showed only a minor drop (4.18 MPa). However, additional increases in RSB content resulted in a significant decrease in FS, which dropped to 3.58 MPa (R1.0), 3.11 MPa (R1.5), 2.11 MPa (R2.0), and 1.35 MPa (R2.5).

At 56 days, the control mixture reached 5.35 MPa, while R0.5 maintained a comparable value (5.04 MPa). However, mixtures with ≥ 1.0 vol.% RSB experienced rapid strength deterioration, with FS decreasing to 3.88 MPa, 3.49 MPa, 2.54 MPa, and 1.95 MPa for R1.0–R2.5, respectively. The results indicate that at low RSB contents (≤ 0.5 vol.%), the porosity and localized defects introduced by RSB remain limited and do not significantly impair FS. In contrast, when the RSB content reaches ≥ 1.0 vol.%, these mechanisms–together with reduced paste–aggregate load transfer–become dominant, leading to a pronounced deterioration in the FS response of PC. This behavior is consistent with broader observations on SBF/particle incorporation in cementitious composites, where crack-bridging benefits are typically confined to a dosage optimum at very low biomass contents (generally below about 0.5–1.0 vol.%), beyond which strength gains are rapidly offset by inadequate dispersion, weak interfacial bonding, and a pronounced increase in porosity at higher biomass contents [33]. Furthermore, investigations on bagasse-based natural fiber concrete typically indicate that increasing fiber/biomass content leads to agglomeration and poor compaction, resulting in larger interfacial defects and a faster decline in bending-related strength [3, 4]. The results suggest that RSB contents above 1.0 vol.% may rapidly compromise pavement-relevant bending performance, unless specific mitigation measures are adopted to control water uptake, improve dispersion, and enhance matrix compactness, such as fiber pre-conditioning, grading control, dispersion strategies, or paste densification. This reduction in FS is crucial for PC because flexural capacity controls slab fatigue performance and crack propagation under wheel loading.

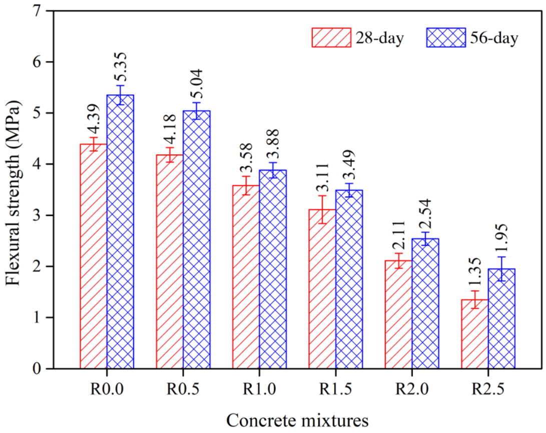


Figure 3. FS of concrete

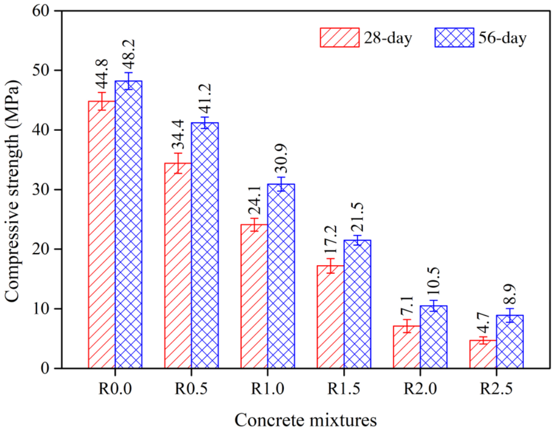


Figure 4. CS of concrete

3.2. Compressive strength

As illustrated in Fig. 4, CS decreases markedly with increasing RSB content, with a more severe reduction than that observed in flexural strength. This trend indicates that CS is predominantly controlled by matrix compactness and load-transfer continuity, rather than by tensile crack-bridging mechanisms [34]. At 28 days, the control mixture (R0.0) exhibited a CS of 44.8 MPa, whereas RSB incorporation led to progressive reductions in strength of approximately 23.2–89.5% relative to the control. At 56 days, the CS of the control increased to 48.2 MPa; however, mixtures containing RSB still showed notable strength losses, with reductions ranging from about 14.5% to 81.5% compared to the reference mixture. The relatively stronger strength recovery observed at 56 days for mixtures R0.5–R1.5, compared to 28 days, indicates a limited benefit from continued hydration; however, this improvement remains insufficient to compensate for the pronounced increase in void volume and interfacial discontinuities associated with volumetric incorporation of RSB. Mechanistically, the porous lignocellulosic nature of RSB increases void content and weakens the interfacial transition zone. Comparable strength-loss trends with increasing bagasse-derived biomass content have been consistently reported in the literature when fiber or particle dosages exceed the compatibility and dispersion capacity of the cementitious matrix [3, 4, 33]. From a pavement engineering perspective, the control mixture already falls within a CS range commonly associated with Portland cement concrete applications. In contrast, the sharp decline in CS at RSB contents of 1.0 vol.% and higher suggests that any sustainability- or shrinkage-mitigation benefit must be carefully weighed against the structural performance requirements of rigid pavements. Accordingly, the practically feasible RSB content for PC applications is likely limited unless the mixture design is further optimized, for example, through improved particle packing, mitigation of entrapped air, controlled pre-saturation of RSB, or enhanced synergy with SCMs [35].

3.3. Splitting tensile strength

TS exhibits the same monotonic degradation trend as CS (Fig. 5), indicating that RSB does not provide effective tensile reinforcement to offset the porosity increase and weak interfacial zones in the matrix. At 28 days, the control mixture (R0.0) achieved a TS of 1.81 MPa, whereas RSB incorporation led to progressive reductions in TS of approximately 6.6–81.8% relative to the control. At 56 days, the TS of the control increased slightly to 1.87 MPa; however, mixtures containing RSB continued to show notable losses, with reductions ranging from about 3.2% to 64.7% compared with the reference mixture. Given that TS is highly sensitive to interfacial transition zone quality and early microcrack initiation, the pronounced strength losses at higher RSB dosages support the interpretation that RSB primarily acts as a porous inclusion and defect initiator rather than as an effective crack-bridging reinforcement in this Portland cement system. Similar tensile performance degradation has been widely reported for bagasse-based cementitious composites when their contents exceed the workable dispersion and compaction threshold, leading to pull-out-dominated failure and reduced tensile-related indices [3, 4, 33]. From a pavement design perspective, the concurrent reduction in TS and FS implies a lower crack initiation threshold and diminished post-cracking load-transfer capacity, which is unfavorable for fatigue resistance and joint or crack performance. Consequently, any use of RSB for serviceability-related benefits (e.g., shrinkage mitigation) must be restricted to a dosage range that does not significantly compromise tensile-related properties, which appears to be limited to approximately 0.5–1.0 vol.% based on the present results.

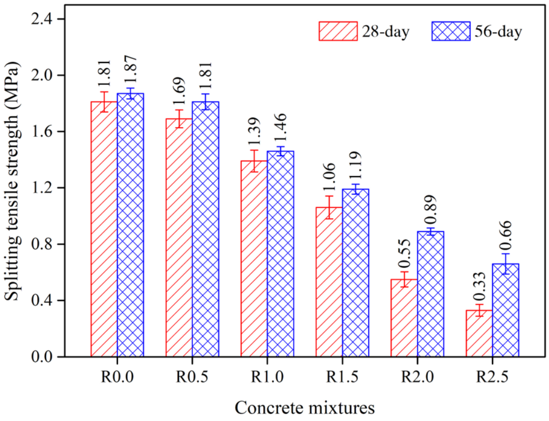


Figure 5. TS of concrete

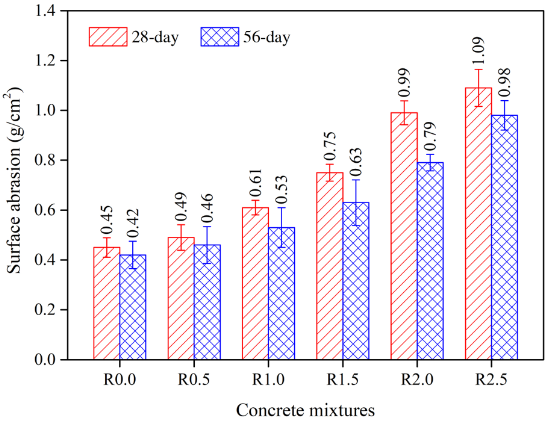


Figure 6. SA of concrete

3.4. Abrasion resistance

SA is a critical functional property for PC, as it governs long-term skid resistance and surface integrity under traffic-induced polishing and wear. A steady decline in surface durability is indicated by Fig. 6, which shows that abrasion loss increases consistently with increasing RSB content at both curing ages. At 28 days, the control mixture (R0.0) exhibited an abrasion loss of 0.45 g/cm^2, whereas RSB incorporation resulted in successive increases of approximately 8.9–142.2% relative to the control. At 56 days, abrasion loss of the control decreased slightly to 0.42 g/cm^2 due to continued hydration and surface densification; however, mixtures containing RSB still showed higher abrasion losses, with increases ranging from about 9.5% to 133.3% compared to the reference mixture, and the ranking among mixtures remained unchanged. The pronounced sensitivity of SA to RSB content indicates that surface wear resistance in PC is primarily governed by near-surface paste hardness, aggregate–paste bonding, and microstructural continuity. As RSB content increases, the introduction of porous inclusions and weak interfacial regions promotes preferential paste removal and aggregate debonding under abrasive action, thereby accelerating surface material loss. This behavior aligns with the concurrent reductions observed in CS, FS, and TS, confirming that abrasion performance is closely linked to overall matrix integrity rather than isolated surface phenomena.

The simultaneous deterioration of CS, TS, and abrasion resistance indicates that these properties are governed by the same mechanism, namely the loss of matrix compactness caused by RSB inclusion. The incorporation of RSB primarily introduces additional porosity and interfacial discontinuities, which disrupt load-transfer continuity under compression, lower crack initiation resistance under tensile stress, and weaken near-surface cohesion under abrasive action. Although limited strength recovery at later ages suggests some continued hydration, this effect is insufficient to offset the structural discontinuities induced by volumetric RSB inclusion. Consequently, the mechanical performance of the system transitions from a dense, load-bearing cementitious matrix to a defect-controlled composite, in which strength and durability-related indices become increasingly governed by void connectivity and interfacial quality. From a structural performance perspective in rigid pavements, these coupled trends highlight that any serviceability-oriented benefit of RSB incorporation must be carefully balanced against the simultaneous loss in structural capacity, thereby constraining the practically viable RSB dosage to a narrow range unless comprehensive mixture re-optimization is implemented.

Fig. 7 further confirms this mechanism by showing a clear inverse relationship between CS and SA loss. Based on the combined dataset at 28 and 56 days, the CS–SA relationship can be well approximated by a linear trend, expressed as SA (g/cm^2) = 1.04 − 0.01CS (MPa), with a coefficient of determination of $R^2 = 0.88$, indicating that mixture compactness and strength are reliable indicators of abrasion resistance in the present PC system. When interpreted together with the FS results, this finding aligns with previous reports on fiber-reinforced concretes, which suggest that abrasion resistance is closely related to overall mechanical integrity and matrix continuity rather than to CS alone [36]. Importantly, while some fiber systems can enhance abrasion resistance by limiting microcrack growth and surface raveling, these benefits generally require strong fiber–matrix bonding and controlled porosity; otherwise, the porosity penalty dominates, as observed in this study for mixtures with higher RSB contents.

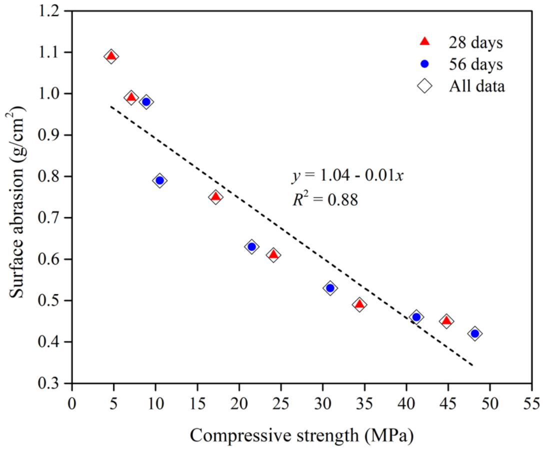


Figure 7. Correlation between CS and SA of concrete

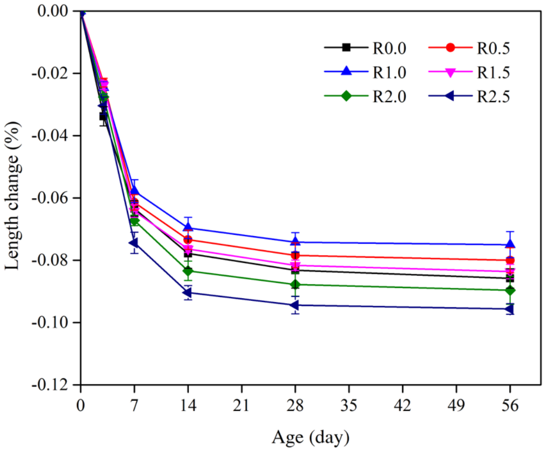


Figure 8. DS of concrete

3.5. *Drying shrinkage*

Fig. 8 demonstrates a non-monotonic effect of RSB on DS, a critical serviceability-related parameter for PC because shrinkage-induced cracking accelerates increases in permeability, joint deterioration, and long-term maintenance demand [37]. At early ages (3–14 days), all mixtures exhibited rapid development of negative strain; however, the magnitude was strongly dependent on RSB content. At 3 days, low RSB dosages (0.5–1.0 vol.%) clearly reduced early-age shrinkage relative to the control, whereas higher dosages tended to approach or exceed the control level. This dosage-dependent response became more evident at 56 days, with RSB contents of 0.5 and 1.0 vol.% resulting in DS reductions of approximately 6.8% and 12.6%, respectively, while mixtures with ≥ 2.0 vol.% RSB exhibited DS magnitudes comparable to or greater than those of the control. This non-monotonic behavior reflects two competing mechanisms introduced by RSB. At low dosages, the hygroscopic pore network of RSB (added in SSD condition) can buffer moisture loss by temporarily storing and gradually releasing water, which moderates internal RH gradients and delays the development of capillary tension. However, as the volumetric fraction increases, the RSB-induced voids become more frequent and connected, which facilitates moisture transport and accelerates drying, thereby diminishing (or reversing) the shrinkage-mitigation effect. This behavior supports a dual governing mechanism. At low RSB contents (0.5–1.0 vol.%), RSB acts as a hygroscopic reservoir, moderating internal RH gradients during drying, thereby delaying capillary stress development and reducing net shrinkage, analogous to an internal curing effect.

In contrast, at higher RSB volumes (≥ 2.0 vol.%), the increased porosity and pore connectivity introduced by RSB dominate moisture transport, promoting faster drying and higher shrinkage while simultaneously weakening the load-bearing skeleton, consistent with the pronounced losses observed in CS, TS, and FS. In addition to moisture transport, the stiffness reduction associated with higher RSB contents may also contribute to larger measured shrinkage strains, because a more compliant load-bearing skeleton offers less restraint to volumetric contraction of the cementitious matrix. This coupled transport–stiffness effect is consistent with the concurrent deterioration in abrasion resistance observed in Section 3.4, where increased porosity/connectivity governs surface raveling under wear. The proposed moisture-buffering/internal-curing interpretation is in agreement with previous studies reporting that cellulosic or natural fibers can mitigate shrinkage and cracking by storing and gradually releasing water within the cement matrix, provided that fiber dosage and moisture conditioning are adequately controlled and do not excessively increase pore connectivity [38]. It is noted that direct measurements of internal RH evolution or pore-structure descriptors (e.g., sorptivity/permeability indices) were not conducted in this study; therefore, the mechanism is discussed as a plausible interpretation supported by the coupled DS–strength–abrasion trends and prior literature. Similarly, investigations on early-age cracking mitigation have shown that natural fibers can reduce shrinkage-crack formation by redistributing moisture and hindering microcrack coalescence, again within a limited dosage range [39]. From a pavement engineering perspective, these results indicate that RSB incorporation at 0.5–1.0 vol.% offers a tangible shrinkage-mitigation benefit while maintaining acceptable abrasion and mechanical performance. In contrast, higher dosages are incompatible with the serviceability and durability requirements of rigid pavement systems.

3.6. Overall performance with respect to the standard requirements for level-IV road

According to TCCS 39:2022/TCĐBVN [40], TCCS 40:2022/TCĐBVN [41], and the study reported by Hieu [42], the PC of level-IV road is required to satisfy the following key performance criteria at 28 days: (i) a FS not lower than 4.0 MPa and a CS not lower than 32.6 MPa, which govern the structural capacity of rigid pavement slabs; and (ii) a SA loss not exceeding 0.6 g/cm^2, which controls surface durability under traffic-induced wear. Although no explicit numerical limit is specified for DS, shrinkage behavior is closely related to crack control and long-term serviceability and is therefore considered as a complementary performance indicator.

Based on direct comparison with these requirements, both the control mixture (R0.0) and the mixture containing 0.5 vol.% RSB (R0.5) satisfy all three mandatory criteria at 28 days, including FS, CS, and SA resistance. In contrast, concrete mixtures with RSB contents of 1.0 vol.% or higher fail to meet at least one key requirement–specifically, FS, CS, and/or SA–and are therefore not suitable for level-IV road applications from a structural or surface durability standpoint.

From a serviceability perspective, mixtures containing 0.5–1.0 vol.% RSB exhibit reduced DS relative to the control; however, only R0.5 achieves this benefit without violating the strength and abrasion limits specified by the standards. At higher RSB contents, the shrinkage benefit is offset by remarkable losses in mechanical capacity and increased SA. When the combined criteria of structural capacity, surface durability, and shrinkage performance are considered, R0.5 (0.5 vol.% RSB) emerges as the most balanced mixture within the scope of this study. This mixture meets the standard requirements for level-IV road while providing measurable shrinkage mitigation, with only a modest reduction in FS and CS relative to the control mixture.

The abovementioned results indicate that RSB can be incorporated into PC at low volume fractions (approximately 0.5 vol.%) to enhance shrinkage-related serviceability while maintaining full compliance with level-IV road performance requirements at 28 days. For applications requiring higher RSB contents, further mix optimization (e.g., improved particle packing, reduced entrapped air, enhanced synergy with supplementary cementitious materials, etc.) would be necessary to recover mechanical performance while preserving the moisture-buffering benefits.

4. Conclusion

This study evaluated the feasibility of incorporating RSB into PC at volume fractions ranging from 0 to 2.5 vol.%, with emphasis on mechanical strength, SA resistance, and DS behavior. Based on the experimental results and systematic comparison with the performance requirements specified in TCCS 39:2022/TCĐBVN and TCCS 40:2022/TCĐBVN for level-IV road, the following conclusions can be drawn:

- RSB incorporation produces a clear dosage-dependent penalty in mechanical performance; flexural strength governs the practical applicability for pavement slabs, thereby restricting feasible RSB contents to low volumetric fractions.
- Abrasion resistance is highly sensitive to RSB-induced porosity/connectivity; mixtures with elevated RSB contents become unsuitable from a surface durability standpoint, consistent with the coupled strength–abrasion relationship observed in the experimental dataset.
- Drying shrinkage exhibits a non-monotonic response, indicating competing moisture-buffering benefits at low dosages versus transport/connectivity and stiffness penalties at higher dosages. Considering structural capacity, abrasion durability, and shrinkage-related serviceability simultaneously, 0.5 vol.% RSB provides the most balanced overall performance and is the recommended dosage within the scope of this study. These findings indicate that the practical value of RSB incorporation lies not in maximizing its content, but in identifying a narrow compatibility range in which moisture-buffering benefits can be achieved without unacceptable losses in mechanical and durability-related performance.

The present work is limited to laboratory-scale evaluation with one baseline mixture and a fixed binder system. Long-term pavement-relevant performance (e.g., restrained cracking, freeze–thaw durability, and fatigue response) was not examined and should be addressed in future studies, together with RSB grading/control and mixture re-optimization to extend the feasible dosage range.

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