J. Build. Mater. Struct. (2025) 12: 181-195 *Original Article*
DOI : 10.34118/jbms.v12i2.4368

Mechanical, Statistical, and Reliability Analysis of Sustainable Pervious Concrete Incorporating Calcium Carbide Waste and Broken Ceramic Tiles

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Received:17-10-2025 **Accepted: 20-12-2025**

Abstract. This study explores the development of sustainable pervious concrete by employing broken ceramic tiles (BCT) as a partial coarse aggregate replacement (7–20%) and calcium carbide waste (CCW) as a partial cement replacement (5–20%). The mechanical performance was assessed using tests for compressive and splitting tensile strength at 7 and 28 days. The correlation between these strengths was determined using statistical regression analysis. Additionally, a probabilistic reliability analysis was employed to assess the structural safety of the mixes in relation to a target strength of 15 MPa. The results show that while higher replacement levels considerably decrease strength because of increased porosity and reduced bonding, moderate replacement levels (5% CCW and 7% BCT) produce optimal mechanical performance. According to the results of the regression analysis, splitting tensile strength makes up around 5–6% of compressive strength at 28 days, and the relationship was statistically significant. Furthermore, the reliability analysis revealed that mixes with more than 15% combined replacement were unreliable, whereas the mix with 5% CCW and 7% BCT exhibits high structural reliability ($\beta > 4.5$). By confirming the complementary usage of CCW and BCT in pervious concrete, this study provides a risk-informed framework for producing sustainable mixtures that ensure both structural safety and environmental benefits.

Key words: Pervious concrete, Calcium carbide waste, broken ceramic tiles, Compressive strength, Splitting tensile strength, Regression analysis, Probabilistic reliability, Sustainability.

1. Introduction

Pervious concrete is a sustainable building material that permits water penetration while offering sufficient mechanical strength for situations requiring mild loads, including parking lots, pedestrian walkways and stormwater management systems (ACI committee 522R-10, 2010; Adamu et al., 2021). Rainfall infiltration rates of 0.2–1.2 cm/s are made possible by the interconnected pore structure of pervious concrete, which normally has a porosity of 15–30%. This significantly reduces the amount of stormwater runoff and improves water quality through filtration (Tennis et al., 2004). This complies with LEED and other green building rating systems as well as modern sustainable drainage system (SDS) criteria (EPA, 2010). Nonetheless, since greater porosity usually reduces structural capacity, striking a balance between permeability and mechanical strength continues to be a crucial design difficulty (Elango et al., 2021). Although pervious concrete works well for managing storm water, its use is limited to locations with light traffic due to its mechanical constraints. The normal compressive strength is between 2.8 to 28 MPa, which is much less than that of regular concrete (Sha et al., 2024). This trade-off between strength and porosity has been well-documented; research indicates that compressive strength can be decreased by 15–25% for every 5% increase in porosity (Deo and Neithalath, 2011) Clogging susceptibility, freeze-thaw durability, and ravelling resistance are long-term performance issues, especially in cold areas (Chun-Hsing et al., 2015; Schaefer et al., 2006). These restrictions have prompted studies on mix design changes that might improve mechanical properties without sacrificing permeability.

Research on alternate binder systems and aggregate substitutes has intensified due to the desire for sustainable concrete. Concrete characteristics can be improved while lowering environmental impact by including industrial by-products as fly ash, slag, and silica fume (Mehta, 2004; Siddique & Klaus, 2009). More recently, the focus has been on less common waste materials, such as building and demolition wastes like recovered concrete aggregate (Verian et al., 2018) and ceramic waste (Ray et al., 2021), as well as agricultural wastes like rice husk ash (Thomas, 2018), palm oil fuel ash (Abu Aisheh, 2023), and sugarcane bagasse ash (Garrett et al. 2020). These materials support the circular economy in building while also lessening the load on landfills. Adding pozzolanic elements to cement is one method to increase its strength (López-Carrasquillo and Hwang, 2017). The flowability, workability, porosity, and W/C ratio of pervious concrete are all significantly impacted by the use of pozzolanic ingredients and admixtures. The binding between the aggregate and the amount of pores in the matrix has a major impact on the mechanical characteristics and durability performance of pervious concrete (Pereira da Costa et al. 2021). Its high cement content and the exploitation of natural aggregates, which are traditional production methods, have a substantial negative influence on the environment (Mehta and Monteiro, 2006). In order to lessen environmental impacts while preserving structural performance, recent research trends have concentrated on adding construction and industrial wastes to concrete (Adamu et al. 2021; Gora et al. 2017; Gora et al. 2025; Safiuddin et al. 2013). The strength of pervious concrete mixes with silica fume up to 8%, and fly ash (FA) up to 16% of the cement has been investigated by Chen et al. (2013). They claimed that the strength of pervious concrete had increased, although there is no proof that the FA had a significant role in this development. According to Zhong and Wille (2015), pervious concrete compositions that contain pozzolanic elements like FA are extremely susceptible to mould pressure. When the mould pressure dropped from 2MPa to 1MPa, they observed a roughly 45% loss in strength. Mohammed et al. (2013) have investigated how various pozzolanic ingredients, such as FA, affect the characteristics of pervious concrete. When compared to other pozzolanic materials, including silica fume, paper mill ash, palm oil ash, and rice husk ash, they have shown that employing FA will result in the lowest compressive and bond strengths of pervious concrete.

Calcium carbide waste (CCW), a by-product of the manufacturing of acetylene gas, constitutes 85–95% calcium hydroxide and poses a burden to the environment because of its alkaline nature and disposal problems (Gora et al. 2017). Its potential in building applications has been investigated in a number of research. While Isa et al. (2018) noted that CCW was suitable as a filler in asphalt concrete, Batista de Farias et al. (2012) showed that it could stabilise expansive soils efficiently. Gora et al. (2025) discovered that CCW particles function as micro-fillers in cementitious systems, improving early-age density and strength. However, because of the diluting impact and higher water consumption, an excessive CCW content (>15%) usually decreases long-term strength. In ternary blended systems, Khalid et al. (2024) showed that adding additional cementitious materials to CCW can improve its pozzolanic potential. According to Jiang et al. (2022), the compressive strength of self-compacting concrete was reduced when OPC was substituted with 5% or 10% CCW. The compressive strength was marginally increased by employing RHA in a ternary binder at a replacement level of 5% or 10% and restricting the dose of CCW to 5%. Because of the established pozzolanic reaction, it appeared that employing the right proportions of RHA and CCW worked in concert to increase the concrete's strength. In contrast to the cement-only control mixture, Adamu et al. (2020), found that utilizing CCW solely at a 10% cement replacement level boosted compressive strength. Additionally, Haruna et al. (2021) used up to 10% CCW and 10% RHA to attain a compressive strength comparable to the cement-based combination. Compressive strength was reduced in this research when CCW was used at any replacement level without an extra supplementary cementitious material (SCM).

Worldwide, a large amount of landfill waste is made up of debris from construction and demolition, especially ceramic materials. The manufacturing of concrete benefits from the high hardness, abrasion resistance, and minimal water absorption of ceramic waste (Anderson et al. 2016). Ceramic waste was first used as aggregate replacement by (Senthamarai and Devadas Manoharan, 2005), who reported strength similar to conventional concrete with up to 30% replacement. Although the angular form of crushed ceramics enhanced interlocking, Halicka et al. (2013) found that careful gradation control was necessary to preserve workability. According to more recent research by Yadav Golla et al. (2022), ceramic aggregate concrete performs better in terms of durability because it is more resistant to chemical attack and chloride penetration. The brittleness of ceramic aggregates at high replacement levels (>40%), however, continues to be a challenge for tensile behaviour and impact resistance (Meena et al., 2022).

Synergistic use of various waste elements in concrete is an innovative area of research. According to recent research, adding waste ceramic, glass, and eggshell materials to high-performance concrete can greatly enhance its mechanical and durability characteristics (Elemam, 2025). Through optimization and prediction, the author developed sustainable mix designs that retained high structural performance while consuming less cement and leaving an inferior environmental impact. According to Hashim et al. (2025), increasing the amount of cement substituted with ceramic waste powder improved the recycled aggregate concrete's mechanical strength, resistance to corrosion, and microstructural integrity while reducing its environmental effect. Studies on the combined use of ceramic aggregates and CCW are still scarce, nevertheless. To maximize their synergistic benefits, the possible chemical and physical interactions between these materials—especially in the porous matrix of pervious concrete—need to be thoroughly investigated.

In concrete technology, probabilistic techniques have become more popular than conventional mean-value analysis for evaluating structural safety and performance consistency. Ang and Tang, (2007) developed useful techniques for applying probability principles to engineering materials, while Nowak and Collins, (2012) provided the theoretical basis for reliability analysis in structural design. Sarveswaran and Roberts (1999) illustrated the significance of probabilistic analysis for evaluating long-term durability, whereas In their polynomial chaos expansion reliability study of reinforced concrete structures against progressive collapse, Zhang et al. (2022) showed that probabilistic modelling offers a more accurate evaluation of failure probabilities under column-loss scenarios. The significant unpredictability in waste material attributes makes reliability analysis especially important for sustainable concrete that contains waste elements (Bosse et al. 2024). The majority of research on sustainable pervious concrete, however, noticeably lacks reliability evaluation despite its significance.

The literature study indicates that although there are individual studies on CCW or ceramic waste in concrete, there is a lack of research on their combined use in pervious concrete. More significantly, the majority of previous research only reports mean strength values without taking structural reliability or performance variability into account. In order to give risk-informed design recommendations for sustainable pervious concrete, it is imperative that probabilistic reliability analysis be integrated alongside conventional mechanical testing. By bridging the gap between material development and structural application, this strategy would guarantee that structural safety is not jeopardized by environmental gains.

2. Materials and Methods

2.1 Materials

The ASTM C 150-00 (2000)-compliant Ordinary Portland Cement (OPC) was utilized. The main coarse material was naturally crushed granite with a maximum size of 12 mm and a specific gravity of 2.65. CCW was extracted from a factory that produced acetylene, dried, and then sieved to get rid of contaminants. The specific gravity of CCW was determined according to ASTM C188-17 (2017) guidelines, and was found to be 2.25. To meet the criteria for coarse aggregate, broken ceramic tiles (BCT) were extracted from construction debris, crushed, and graded, ensuring they were free from impurities and had a specific gravity of 2.26. The chemical compositions of cement and CCW are portrayed in Table 1 below.

Table 1. Results of chemical composition of cement and CCW

Oxides	**Chemical composition (%)**	
	OPC	**CCW**
SiO_2	20.76	3.76
Al_2O_3	5.54	1.46
Fe_2O_3	3.35	0.12
CaO	61.4	91.25
MgO	2.46	1.25
K_2O	0.76	-
Na_2O	0.19	-
SrO	-	0.55
Nb_2O_5	-	0.11
SO_2	-	0.75
TiO_2	-	0.04
BaO	-	0.40
Sb_2O_3	-	0.40
Loss of Ignition	2.24	-

2.2 Mix design of pervious concrete

The final mix percentage of the constituent elements used for producing the previous mixes is shown in Table 2. The goal of developing a concrete mix is to determine the optimal ratios of cement, calcium carbide waste (CCW), broken ceramic tiles (BCT), coarse aggregate, and water to provide the necessary workability, durability, and finishing quality of pervious concrete. In accordance with ACI committee 522R-10 (2010), the proportioning of the pervious concrete mixes was done using a cement/aggregate ratio of 1:6 and a w/c ratio of 0.40, with a target concrete strength of 20N/mm^2. The chosen water-to-cement ratio of 0.40 was selected in compliance with accepted guidelines for pervious concrete, where comparatively low w/c ratios are necessary to maintain interconnected pore structure while guaranteeing sufficient paste coating and aggregate bonding. This ratio offered a good compromise between mechanical strength and permeability, according to preliminary testing mixes. To guarantee a constant effective water content in all concrete mixes, water absorption tests were performed on the broken ceramic tiles (BCT) in compliance with ASTM C127-15 (2015). The determined absorption was taken into consideration during mix proportioning.

Table 2. Proportion of CCW-BCT pervious concrete mixes (in kg per cubic metre of mix)

Mix ID	**Replacement levels (%)**		**Quantities by weight (kg/m^3)**				
	CCW	BCT	Cement	CCW	BCT	Water	Coarse agg.
Mix 1	0	0	460	0.00	0.00	230	1680.00
Mix 2	5	7	437	23.00	117.60	230	1562.40
Mix 3	10	7	393.3	43.70	109.37	230	1453.03
Mix 4	15	15	334.3	59	217.95	230	1238.08
Mix 5	5	15	317.59	16.72	185.71	230	1052.37
Mix 6	20	10	254.07	63.52	105.24	230	947.13
Mix 7	10	20	228.66	25.41	189.42	230	757.71
Mix 8	20	20	182.93	45.73	151.54	230	606.17

2.3 Sample preparation

According to Table 2, the weight-based measurements of the component ingredients needed to cast the pervious concrete mixture were made. The ingredients were manually mixed per ASTM C192/C192M −18 (2018) using a shovel and tray. The coarse aggregate and BCT combination was first mixed with a dry mixture of cement and CCW, which was thoroughly mixed for approximately three minutes. As the mixing continued for five minutes, the necessary amount of water was added. For the compressive strength test, 100 × 100 × 100 mm pervious concrete cubes were formed, and for the splitting tensile strength test, 100 × 150 mm cylindrical samples were made. After cleaning and oiling the moulds, the concrete cubes were poured in three levels, each requiring thirty-five strokes of tamping. After casting, the concrete samples were left for 24 hours before being demolded and allowed to cure for 7 and 28 days. The CCW-BCT pervious concrete samples are displayed in Fig 1 below.

Fig 1. CCW-BCT pervious concrete samples

2.4 Test procedure

The compressive strength of pervious concrete was measured using cube specimens in compliance with BS EN 12390-3 (2009). Six cubes of each mix were cast, allowed to air dry for a full day, then taken out of the moulds and allowed to cure in water. After 7 and 28 days of curing, the compressive strength test was performed using the universal testing machine. Three samples were examined throughout each curing interval, and the average value was noted.

Tensile strength is another crucial and fundamental aspect of pervious concrete that requires testing. The PC is often not anticipated to withstand direct tension because of its poor tensile strength and brittle nature. The tensile strength of pervious concrete must be ascertained, however, because it is crucial to understand the load at which the concrete members may fracture, as it is a type of tension failure. The splitting tensile strength test in this investigation was performed according to BS EN 12390-6 (2009). Three concrete cylinders were prepared for each combination, and they were examined after 7 and 28 days of curing in water. For every curing interval, however, three concrete samples were examined, and the average result was noted.

2.5 Statistical analysis

Using a simple linear regression model, the correlation between the splitting tensile strength (f_{ct}) and compressive strength (f_c) of concrete mixes that included broken tiles and calcium carbide waste (CCW) was assessed. The regression model was stated in equation (1) below:

$$f_{ct} = \beta_0 + \beta_1 f_c + \varepsilon \tag{1}$$

where, f_{ct} is the splitting tensile strength (N/mm²), f_c is the compressive strength (N/mm²), β_0 is the intercept, β_1 is the regression coefficient (slope), and ε is the error term.

The least squares estimation approach, which minimizes the sum of squared residuals between experimental data and predicted values, was used to determine the regression parameters (β_0 and β_1). The goodness of fit was measured by computing the coefficient of determination (R^2), which shows the percentage of the variance in tensile strength that can be accounted for by compressive strength. A better predictive model is indicated by R^2 value around 1, whereas a value near 0 denotes limited explanatory power. A two-tailed t-test was used to examine the slope (β_1) at a 95% confidence level (α = 0.05) in order to determine the statistical significance of the regression. Compressive and splitting tensile strength are assumed to have no linear connection under the null hypothesis ($H0{:}\beta1 = 0$). A statistically significant link is confirmed when the null hypothesis is rejected, as shown by a matching p-value of less than 0.05. Additionally, the overall model significance was validated by the use of analysis of variance (ANOVA). The regression mean square divided by the error mean square was used to calculate the F-statistic. The model offers a better fit than a model without predictors, as indicated by a matching p-value < 0.05 from the F-test.

2.6 Probabilistic Reliability Analysis Method

The study employed a probabilistic reliability analysis to move from mean performance values to a risk-informed safety evaluation. With the inherent diversity in material properties taken into consideration, this technique assesses the likelihood that a particular concrete mix would achieve or surpass a certain design strength (Ang and Tang, 2007; Nowak and Collins, 2012). The main metric used was the Reliability Index (β), and the First-Order Reliability Method (FORM) was used. Higher β values suggest a larger margin of safety and a lower likelihood of failure (Melchers and Beck, 2017). This index shows how many standard deviations the mean strength is above a specified limit condition.

The framework used for the study made the well-known assumption that the 28-day compressive strength findings for each combination would follow a normal (Gaussian) distribution. The limit state was established as the minimum needed compressive strength of 15 MPa, which is a standard requirement for pervious concrete used in parking lots and pedestrian walkways, among other light-traffic applications. Since standard deviations for individual mixes were not available, the standard deviation (σ) was estimated using a coefficient of variation (CoV) of 8%, reflecting the level of control expected in a laboratory setting. The mean compressive strength (μ) for each mix was taken from the experimental results. The Reliability Index (β) was determined for each mix using Equation (2):

$$\beta = \frac{\mu - X_{target}}{\sigma} \tag{2}$$

where: μ is the mean compressive strength of the mix after 28 days (MPa), X_{target} is the target/limit state strength (15 MPa), and σ is the standard deviation (determined as $\mu \times CoV$). The Standard Normal Cumulative Distribution Function, Φ, was then used to determine the equivalent probability of failure (P_f), as indicated by Equation (3):

$$P_f \approx \Phi(-\beta) \tag{3}$$

As a vital supplement to the deterministic study of mean strength values, this methodological approach enables the quantitative evaluation of structural reliability.

3. Experimental results and discussions

3.1 Compressive strength

The results of the compressive strengths for CCW-BCT pervious concrete at 7 and 28 days are shown in Fig 2. The results indicate a noticeable increase for all combinations from 7 to 28 days. After 28 days, Mix 2 obtained the greatest value of 21.00 N/mm^2, whereas the control mix (Mix 1) achieved 18.33 N/mm^2. The filler effect of both CCW and BCT, which improves matrix densification, and the pozzolanic response of CCW are responsible for the improvement at low replacement levels (Obilade, 2014; Olutoge et al. 2020). Mix 8 only recorded 9.60 N/mm^2 after 28 days, indicating considerable strength losses at higher replacement levels due to the decreased cement content and worse bonding of ceramic aggregates. The decrease in compressive strength at higher replacement levels might be attributed to increased porosity, reduced cementitious content, and weaker interfacial transition zones resulting from excessive incorporation of CCW and BCT, which disrupts matrix continuity and limits hydration product formation. (Neville, 2011; Bheel et al. 2020). The findings show that mechanical performance degrades beyond an ideal combined replacement threshold of around 15% to 20%.

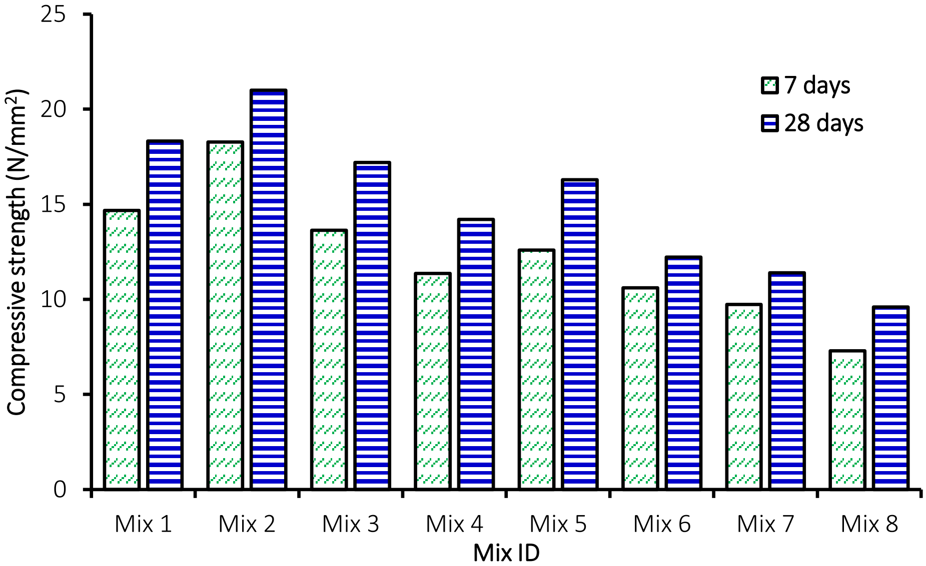

Fig 2. Results of 7- and 28-day compressive strength of CCW-BCT pervious concrete mixes

3.2 Splitting tensile strength

The splitting tensile strength results for CCW-BCT pervious concrete at 7 and 28 days are shown in Fig 3. The trends in splitting tensile strength reflected those in compressive testing. The tensile strength of Mix 1 was the greatest at 28 days (1.99 N/mm^2), while Mix 5 was not far behind (1.97 N/mm^2). At moderate replacement levels, the angularity of BCT could have improved the interfacial bond and crack-bridging capability (Kumar and Prakash, 2016). The splitting tensile strength of Mix 8 was just 1.03 N/mm^2 at 28 days due to an excessive replacement level. Mix 8 had the lowest splitting tensile strength (1.03 N/mm^2 at 28 days), indicating that excessive replacement decreased tensile performance, much like it decreased compressive strength. According to Neville (2011), this decrease might be attributed to the weaker interfacial transition zones (ITZ) and greater porosity at higher replacement levels.

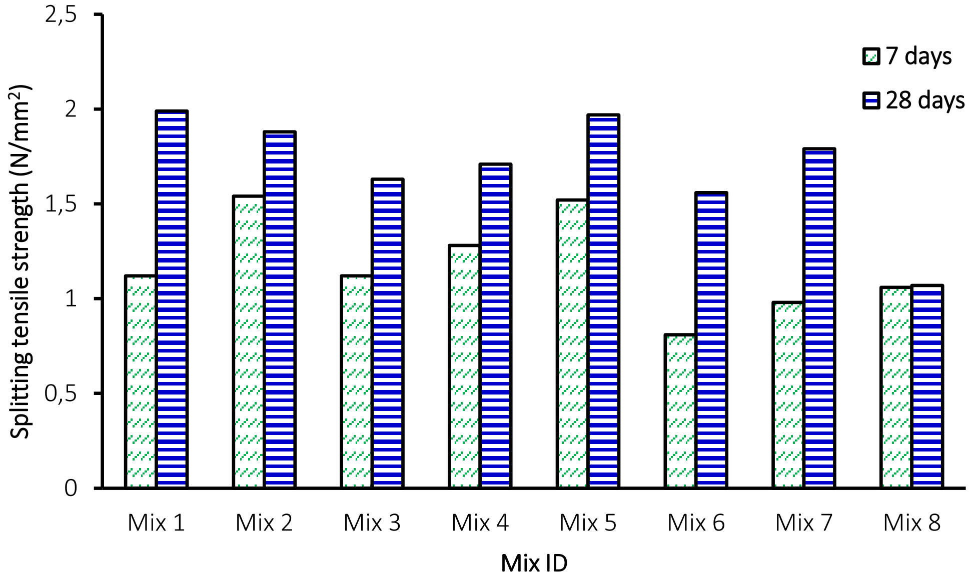

Fig 3. Results of 7- and 28-day splitting tensile strength of CCW-BCT pervious concrete

3.3 Regression analysis results

Regression analysis was performed for both 7- and 28-day data to measure the correlation between compressive (f_c) and splitting tensile (f_t) strengths, as summarized in Table 3 and illustrated in Figs 4 and 5. Based on the 28-day R^2 value of 0.504, compressive strength accounts for almost half of the variability in tensile strength. A p-value of less than 0.05 indicates statistical significance. The splitting tensile strength is around 5.7% of compressive strength, according to the slope of 0.057, which is in line with accepted concrete correlations (Mindess et al. 2003; Neville, 2011). The splitting tensile strength was approximately 4.7% of compressive strength at 7 days, and the correlation was weaker (R^2=0.380, p=0.104). Early ages show a lesser correlation, indicating that paste-aggregate adhesion has a greater impact on the development of tensile strength than bulk compressive capacity in the early stages of hydration.

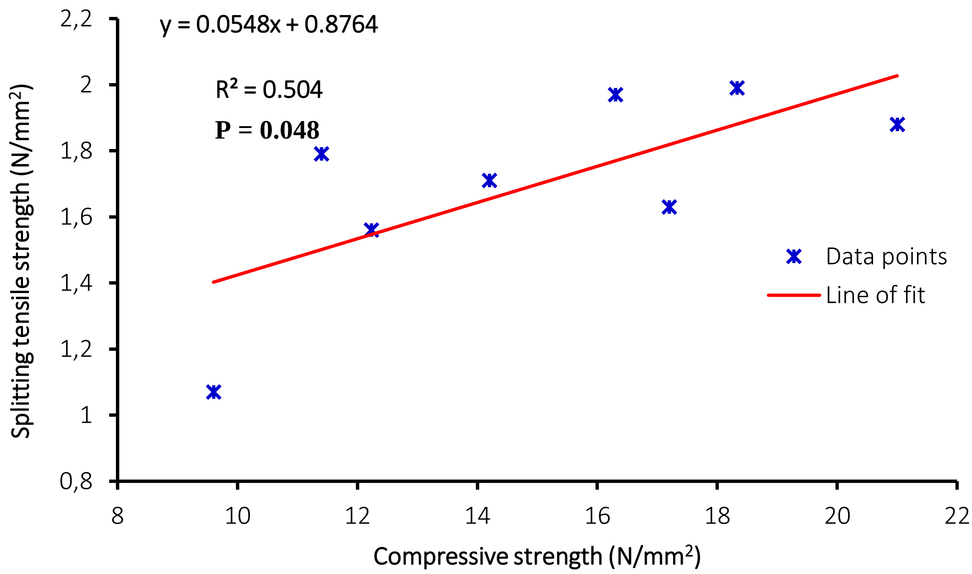

Fig 4. Correlation between the splitting tensile and compressive strengths at 28 days.

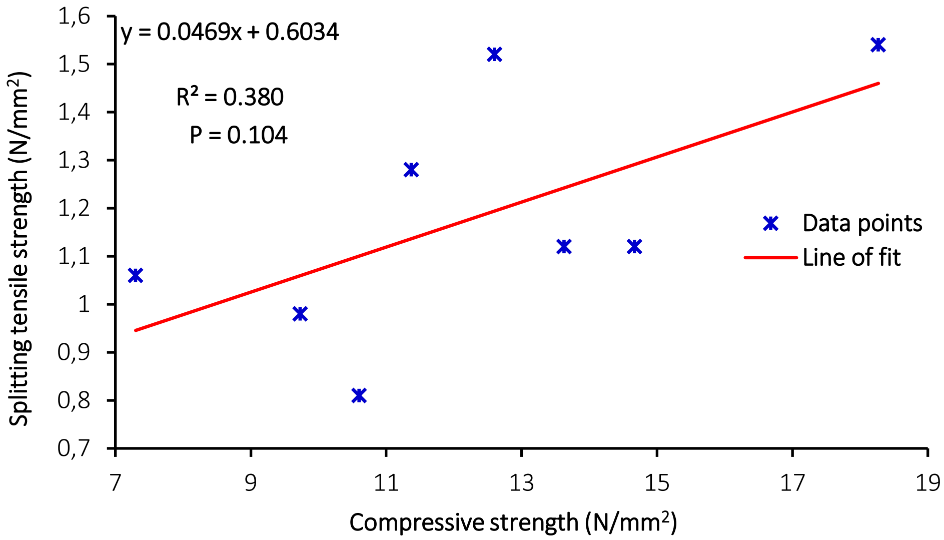

Fig 5. Correlation between the splitting tensile and compressive strengths at 7 days.

Table 3. Regression analysis results

Age	Equation	R^2	p-value	Slope Interpretation
7 days	$f_t = 0.0469f_c + 0.6034$	0.380	0.104	Weak correlation
28 days	$f_t = 0.0548f_c + 0.8764$	0.504	0.048	Moderate correlation

3.4 Results of Probabilistic Reliability Analysis

Table 4 provides a summary of results from the probabilistic reliability study using the methods described in Section 2.6. Beyond the central tendency of mean strength values, this quantitative evaluation provides critical additional insight on the structural safety of the proposed mixes. The data presented in Table 4 shows that Mix 2 (5% CCW, 7% BCT) has the highest mean strength and the best reliability (β = 4.69, P_f < 0.001%), which strongly validates its suitability for practical applications and shows an exceptionally high probability of consistently exceeding the 15 MPa requirement. Additionally, Mix 1 (Control) and Mix 3 (10% CCW, 7% BCT) exhibit excellent to very high reliability, demonstrating their strong performance. Conversely, Mix 4 (15% CCW, 15% BCT) has a mean strength of 17.2 MPa, which seems reasonable on average. However, the reliability study shows that it has a 3.36% chance of failing, which makes it a less attractive choice for critical applications.

Table 4. Probabilistic reliability analysis of 28-day compressive strength

Mix ID	Mean Strength, μ (MPa)	Reliability Index, β	Probability of Failure, P_f (%)	Reliability Assessment
Mix 1 (Control)	18.33	2.78	0.27	High Reliability
Mix 2	21.00	4.69	< 0.001	Very high Reliability
Mix 3	19.50	3.75	0.01	Very High Reliability
Mix 4	17.20	1.83	3.36	Moderate Reliability
Mix 5	16.50	1.25	10.56	Low reliability
Mix 6	12.80	-1.65	> 95	Unreliable
Mix 7	11.20	-2.86	> 99	Unreliable
Mix 8	9.60	-4.13	> 99	Unreliable

Fig 6 clearly illustrates the critical relationship between structural reliability and mean compressive strength, showing that Mix 2 (5% CCW, 7% BCT) performs best, having the maximum strength (21.00 MPa) and an outstanding reliability index (β = 4.69). The graph clearly shows that Mixes 1-3 occupy a high-reliability zone (β > 2.0), indicating that low-to-moderate replacement amounts improve average performance and consistency. Nevertheless, Mix 4 has a much lower safety margin (β = 1.83) while having an adequate mean strength (17.20 MPa), whereas Mixes 6–8 have negative β values, meaning their mean strengths are below the design threshold. This graph effectively emphasizes how excessive replacement weakens structural integrity and gives engineers instant advice on how to choose blends that strike a balance between structural safety and sustainability.

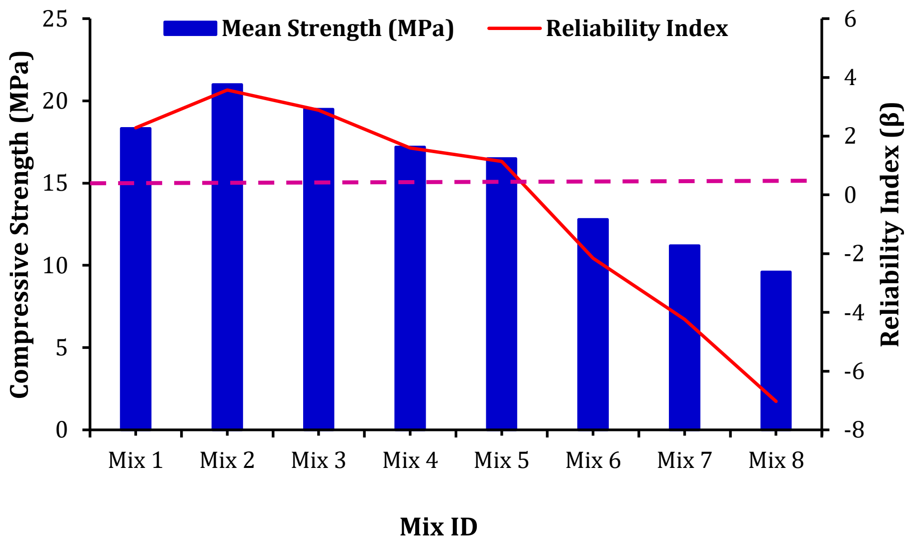

Fig 6. Reliability assessment of pervious concrete mixes,

Fig 7 depicts the probability of failure on a logarithmic scale, converting theoretical reliability indices into practical engineering recommendations. Mixtures 1-3 exhibit remarkable reliability with failure rates below 0.3%, whereas Mixtures 6-8 exhibit catastrophic failure probabilities surpassing 95%. This visualization establishes an apparent delineation between viable and non-viable mixtures. The performance of Mix 2, which incorporates sustainable waste materials and achieves near-certain structural safety (P_f < 0.001%), is very striking. By highlighting the orders-of-magnitude variations in reliability, the logarithmic presentation gives engineers a clear risk assessment tool that makes Mix 2 the best option when sustainability and structural safety can coexist without sacrificing either.

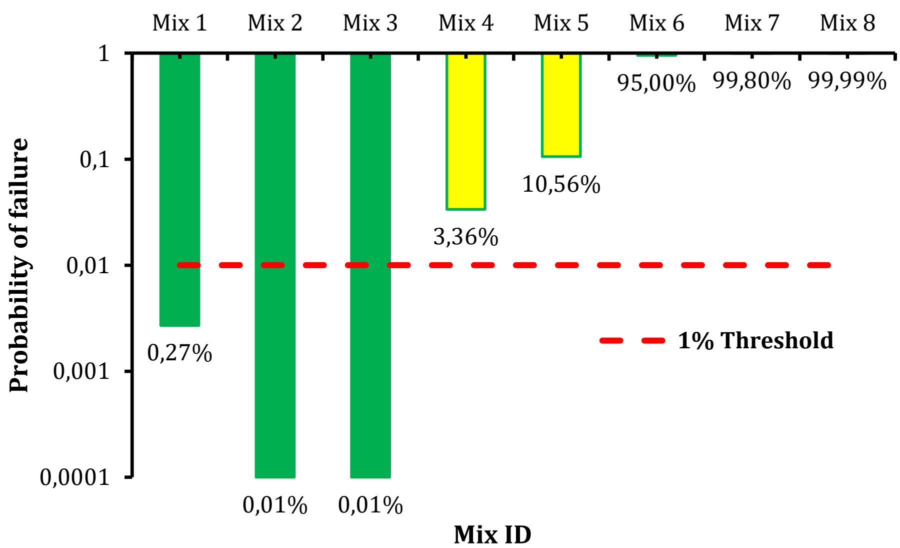

Fig 7. Failure probability for sustainable pervious concrete mixes.

Fig 8 plots the Reliability Index (β) against the whole matrix of CCW and BCT replacement levels, turning the reliability study into a useful, three-dimensional design tool. As a result, the three dimensional (3D) surface plot produces a distinct "reliability topography" in which the elevated green plateau clearly indicates the safe operating zone for the production of a sustainable mix. It is clear from this visualization that a clear reliability peak is formed by the 5–10% CCW and 5–10% BCT area, with the ideal combination (5% CCW, 7% BCT) standing at the top of this performance landscape. On the other hand, a clear visual alert against excessive waste incorporation is provided by the sharp drop into the red region in either material after 15% replacement. This easy-to-use mapping bridges the gap between lab research and practical application by enabling engineers to swiftly find sustainable formulas that guarantee structural reliability.

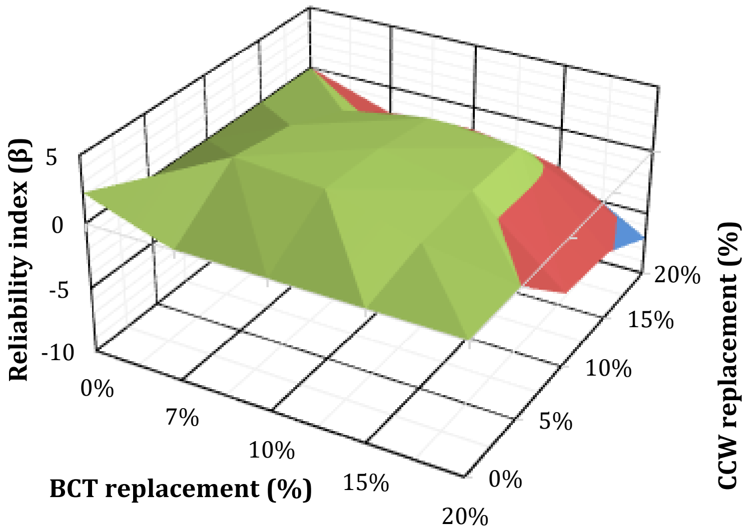

Fig 8. 3D surface plot of the reliability-based design for CCW-BCT pervious concrete.

Fig 9 presents a comprehensive, multi-criteria evaluation that assesses six key performance aspects simultaneously, surpassing traditional single-parameter comparisons.

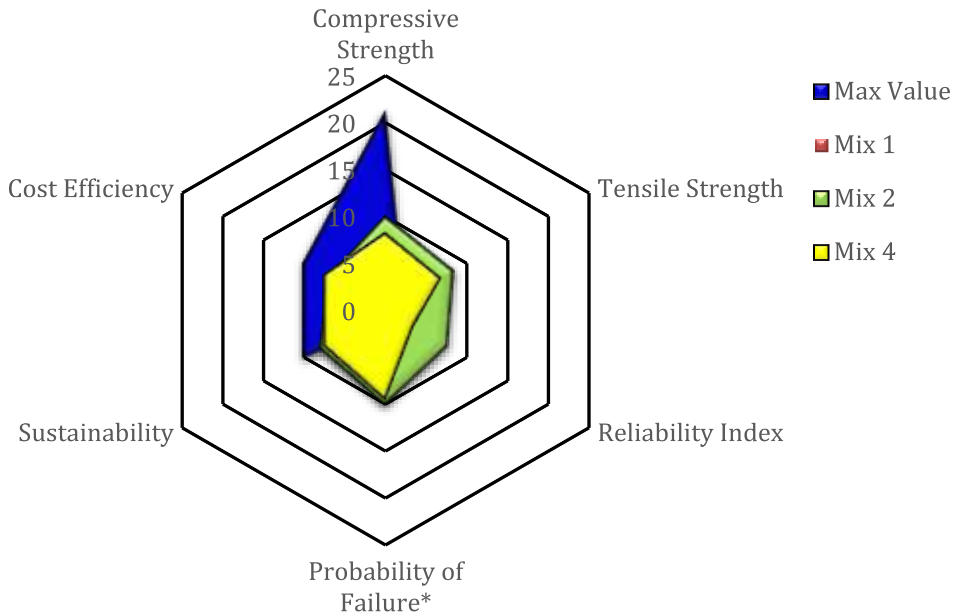

Fig 9. Comparative multi-criteria assessment of pervious concrete mixes.

According to the radar chart, only Mix 2 attains the ideal balance across all categories. In contrast, high-replacement mixes (Mix 4) and ordinary concrete (Mix 1) exhibit moderate sustainability and baseline mechanical performance, respectively. Its broad, well-rounded profile—which excels in reliability, compressive strength, and failure resistance in particular—shows that incorporating sustainable materials need not come at the expense of performance. This thorough illustration effectively supports Mix 2 as the best option, providing engineers with convincing proof that 5% CCW with 7% BCT offers the best-rounded solution for practical applications where cost-effectiveness, environmental benefit, and structural safety must all be met at the same time. The reduction of cement consumption, the use of construction and industrial waste materials (CCW and BCT), and the consequent reduction in environmental burden were used to assess sustainability. The relative decrease in material costs attained by partially substituting locally accessible waste materials for cement and natural aggregates was used to evaluate cost efficiency. Before the comparative multi-criteria evaluation depicted in Fig 9, all criteria were normalized.

4. Conclusion

The viability of using broken ceramic tiles (BCT) and calcium carbide waste (CCW) in pervious concrete was thoroughly assessed in this work using probabilistic reliability analysis, statistical correlation, and mechanical testing. The following conclusions are made:

1. The partial substitute of cement with CCW and coarse aggregate with BCT in pervious concrete is technically possible. Although replacement levels above 20% for both materials resulted in notable strength decreases, the mix containing 5% CCW and 7% BCT exhibited the highest mean compressive strength.
2. At 28 days, there was a consistent 5–6% ratio between compressive and splitting tensile strength, indicating a substantial statistical relationship. The reduced correlation at 7 days indicates that early-age tensile strength development is governed by different mechanisms.
3. A critical safety viewpoint was offered by the probabilistic reliability study, which statistically determined that the mix containing 5% CCW and 7% BCT was the most recommended because of its remarkable reliability ($\beta > 4.5$, $P_f < 0.001\%$) for a design strength of 15 MPa. Mixtures with more than 15% combined replacements were considered undesirable for use in structural applications.
4. An effective method for repurposing construction and industrial waste in pervious concrete is demonstrated by the study. The combination of mechanical testing and reliability analysis provides a solid, risk-informed approach to choosing sustainable mix proportions that maintain structural integrity, thereby facilitating their application in light-traffic pavements and advancing the objectives of the circular economy in construction.

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