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Performance and RSM-based optimization of eco-friendly concrete incorporating seashell powder and bamboo chips

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Abstract

The depletion of natural fine and coarse aggregates due to rapid urbanization poses a significant threat to environmental sustainability. This study explores the performance of eco-friendly concrete incorporating seashell powder (fine aggregate) and treated bamboo chips (coarse aggregate) at replacement levels of 0%, 10%, 20%, and 30% by volume. A total of 111 cylindrical and 12 prism beam specimens were tested in a two-stage experimental program. In Stage I, 18 mix ratios were evaluated based on 28-day compressive strength, identifying the optimal combination (20% seashell powder + 10% bamboo chips, labelled S2B1). In addition to experimental work, Response Surface Methodology (RSM) was employed to statistically optimize replacement levels, with the cubic model predicting 21.6% seashell powder and 0.2% bamboo chips as the mathematical optimum (desirability = 1.0), thereby validating the experimental choice of S2B1 as the practical optimum mix. In Stage II, S2B1 was assessed for compressive strength, split tensile strength, flexural strength, modulus of elasticity, stress-strain response, mass loss, and toughness at 28 and 90 days under ambient and elevated temperatures (200°C, 400°C, 600°C). S2B1 achieved 25.37 MPa compressive strength at 90 days, only 11.9% lower than the control, while also demonstrating improved toughness, ductility, and thermal resilience after extended curing. The synergistic use of these sustainable

materials offers a promising alternative for normal-strength concrete applications, with the added advantage of statistical optimization to support experimental findings.

Keywords: *Eco friendly concrete; Aggregate replacement; Seashell powder; Bamboo chips; Elevated temperature; Mechanical properties; Response Surface Methodology (RSM).*

1. Introduction

Concrete, a composite material of cement, water, and aggregates, remains the most widely used construction material worldwide. Rapid urbanization and infrastructure growth have accelerated global concrete consumption, rising from 1.1 billion tons to 3.27 billion tons in just two decades, and forecasts project a staggering 18 billion tons by 2050 [1]. Consequently, cement demand has surged, reaching 1.62 billion tons annually, amplifying environmental concerns including carbon emissions, natural resource depletion, and ecological degradation [2].

Aggregates constitute 70 - 80% of concrete volume, and their extraction is increasingly unsustainable. In 2015, global aggregate demand reached 48.3 billion tons, surpassing 51.7 billion tons by 2019 and expected to exceed 80 billion tons by 2030 [3]. Sand, the second most consumed resource on Earth, is being mined at an annual rate of 50 billion tons, double the natural replenishment by rivers [4]. Its extraction contributes to the destruction of riverbeds, coastal erosion, noise pollution, and carbon emissions from transportation [5]. Furthermore, the conventional “take-make-dispose” economic model in construction escalates waste production, projected to rise by 70% by 2050 [6].

The sustainability challenge demands innovative concrete materials that minimize ecological harm without compromising performance. To address the depletion of traditional aggregates, researchers have explored renewable and waste-based materials. Among these, seashells - a major marine byproduct from fisheries - are generated in massive quantities, often ending up in landfills or polluting coastlines [7]. Seashells are rich in calcium carbonate (~95%), making them suitable for use in concrete, especially as a fine aggregate replacement [8]. Their use not only manages marine waste but enhances insulation, durability, and thermal resistance [9].

Numerous studies have validated the incorporation of seashells in concrete. Liao et al. observed that 10% replacement of sand with oyster shells retained compressive strength while higher ratios reduced workability and increased shrinkage [10]. Panda et al. reported that 10–20% crushed seashell substitution yields acceptable strength and fire resistance [11].

Bamigboye et al. found seashell concrete exhibited reduced modulus of elasticity but acceptable durability under water absorption and shrinkage metrics [12]. In self-compacting mortars, seashells maintained flowability and bond performance [13].

Simultaneously, bamboo chips have emerged as a sustainable alternative to coarse aggregates. As a fast-growing, renewable plant with high tensile strength, bamboo presents a viable solution to mitigate resource exhaustion [14]. Studies by Tahara et al. showed that up to 10% bamboo chip replacement yields good-quality concrete, although workability and strength decline beyond that point [15]. Similarly, Park et al. concluded that the reduced bond between bamboo and mortar contributes to strength loss at higher substitution levels [16]. Still, chemical treatment and dimensional control improve its utility in structural applications.

Pakistan, with a 1,050 km coastline and expanding bamboo cultivation, faces escalating construction material demand amid rapid urbanization. Over 36% of the population resides in urban centres, and this is projected to rise above 50% by 2025 [17]. Yet, seashell waste remains unmanaged, and bamboo is underutilized due to misconceptions about its structural capacity [18]. Therefore, leveraging these abundant resources supports Sustainable Development Goal 12 by reducing material footprints, conserving biodiversity, and offering affordable alternatives to conventional materials [19].

Although prior research has independently validated the use of crushed seashells and bamboo chips in concrete, their combined effect, particularly under elevated temperature exposure, has not been comprehensively explored. Moreover, most studies rely solely on experimental trial-and-error mix designs, which can be resource-intensive and may overlook optimal combinations. To overcome this limitation, statistical optimization techniques such as Response Surface Methodology (RSM) have been increasingly adopted in concrete research [20,21]. RSM enables efficient modelling of multi-factor interactions (e.g., CSS and TBC levels) and identifies the optimum mix proportions with reduced experimental effort [22]. In this study, RSM was employed in Phase I to analyse 18 different mix combinations and predict the optimal mix design before advancing to Phase II detailed mechanical and thermal evaluations.

By evaluating the synergistic behaviour of these two sustainable materials, this study presents an innovative and scalable approach to eco-friendly concrete that aligns with national priorities and global environmental goals, while maintaining mechanical integrity and offering resilience to fire-related scenarios in normal-strength concrete.

2. Materials and Methods

98 2.1 Materials

99 2.1.1 Material Properties

100 The primary binder used in this study was ordinary Portland cement Type I, conforming
 101 to ASTM C150 [23]. Locally sourced river sand was used as the natural fine aggregate, and
 102 crushed stone of nominal size 19 mm was used as coarse aggregate. The fine aggregate was
 103 clean, well-graded, and passed through a 4.75 mm sieve as per ASTM C33 [24]. Sieve analysis
 104 revealed that the sand fell in Zone II, meeting grading requirements for concrete production.
 105 The fineness modulus, specific gravity and water absorption were 2.67, 2.71 and 1.1%,
 106 respectively. The coarse aggregate had a specific gravity of 2.78 and water absorption of 1.75%.
 107 The sieve analysis data for both fine and coarse aggregates are shown in Figure 1 and Figure
 108 2, respectively.

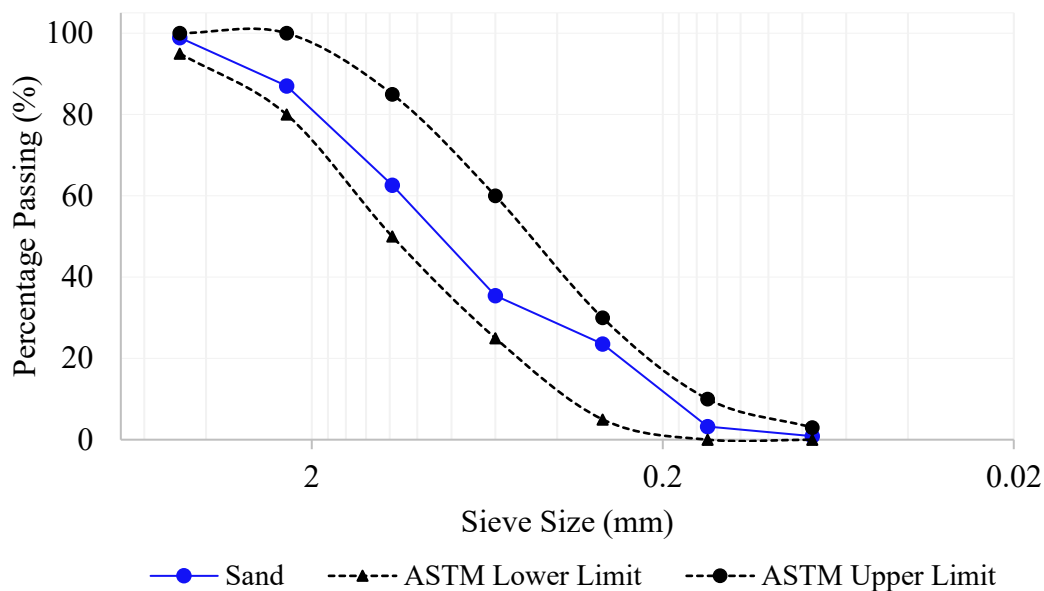


Figure 1. Gradation curve of fine aggregate including ASTM limits as per ASTM C33 [24].

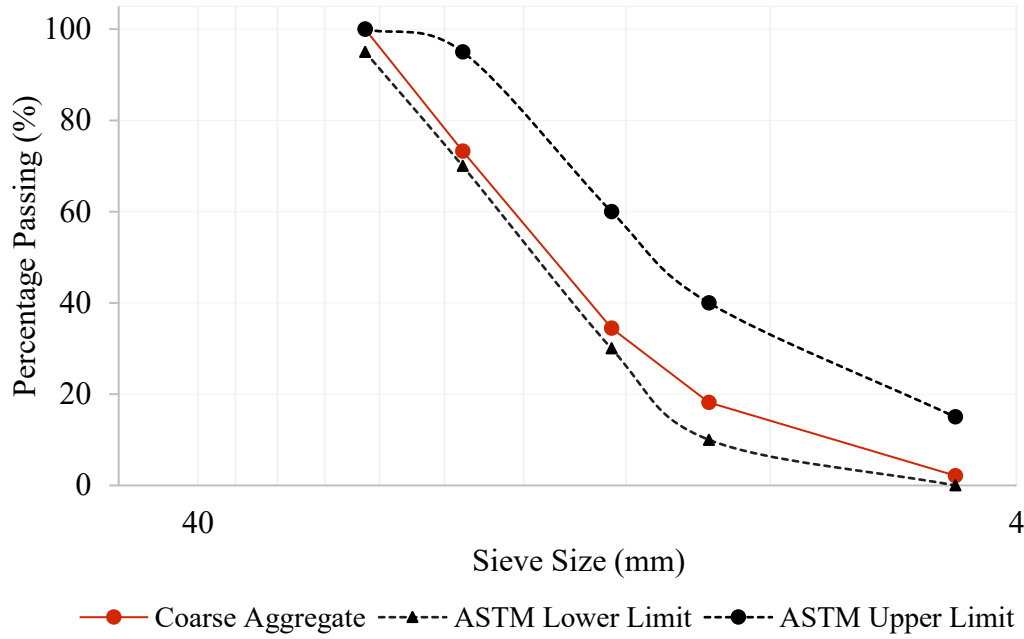


Figure 2. Gradation curve of coarse aggregates with ASTM C33 limits [24].

2.1.2 Crushed Seashell Powder

The seashells used in this study were collected from the coastal region of Karachi, Pakistan. After collection, the shells were thoroughly washed to remove adhering impurities and sand, then sun-dried for 48 hours. The dried shells were crushed at a marble factory and further crushed using a Los Angeles abrasion machine to achieve the size comparable to natural fine aggregates. Sieve analysis of CSS was performed according to the guidelines of ASTM C33 [24] and compared with its natural counterpart as shown in Figure 3. The results showed that gradation curves of both materials are within the ranges defined by ASTM C33. The CSS powder was white in colour and had a fineness modulus, specific gravity, and water absorption of 3.19, 2.81, and 16.82% respectively. CSS powder is rich in calcium carbonate (CaCO_3), which contributes to better cementitious bonding and thermal stability. The replacement percentages for CSS powder were chosen as 0%, 10%, 20%, and 30% by volume of fine aggregate. Previous literature [25,26] supports up to 20% replacement without major compromise in strength, especially for normal-strength concrete applications.

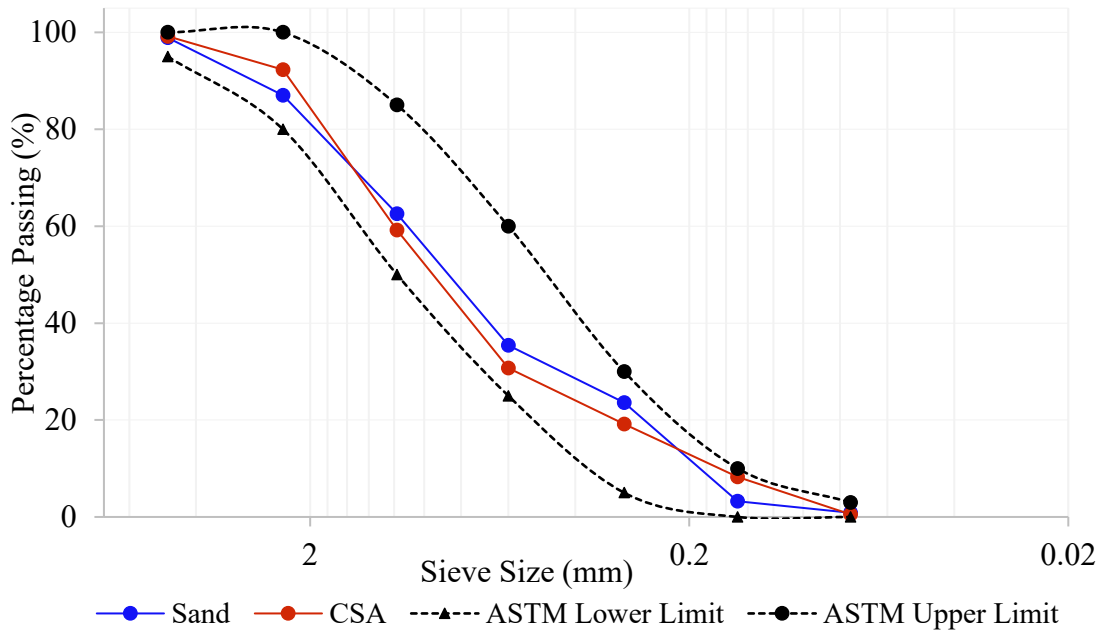


Figure 3. Gradation curve of sand and CSS with ASTM C33 limits [24]

2.1.3 Bamboo Chips

Bamboo, a renewable, fast-growing natural material, was used in this study as a partial coarse aggregate replacement. Locally grown bamboo was manually cut into chips of 19 mm in length using mechanical cutters. These pieces were further manually broken into small fragments in order to ensure its suitability for partial replacement of coarse aggregates and satisfy the sieve analysis limits laid by ASTM C33 [24]. The bamboo chips (BC) were tested to determine their initial water absorption, which was found to be 110.41% prior to treatment. Studies [27–29] indicate that bamboo chips require pretreatment before incorporation into composites to mitigate high water absorption, weak bonding, flammability, and poor composite performance. Common treatment methods documented in literature are shown in Figure 4.

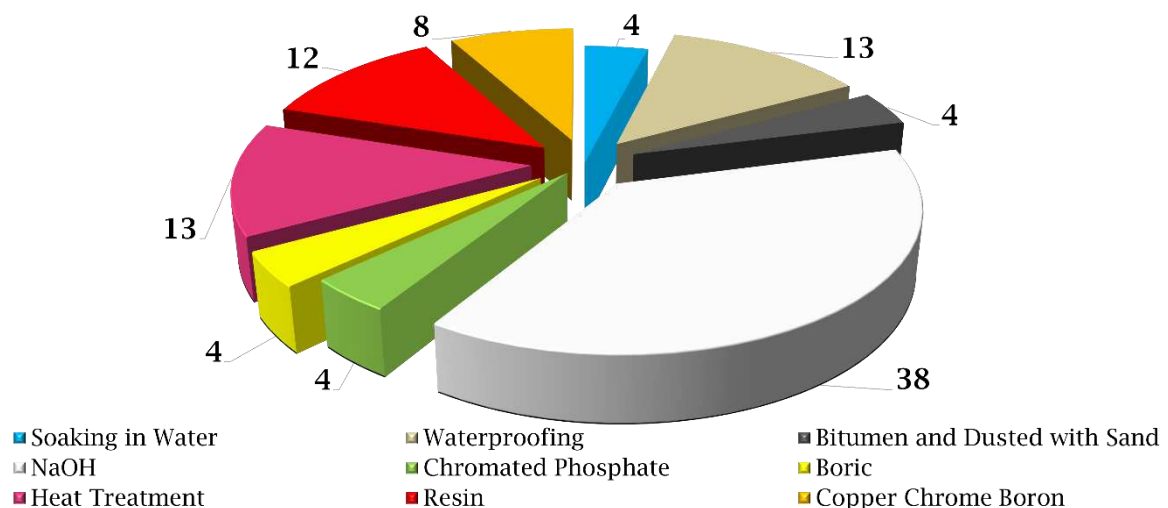


Figure 4. Chemical treatment methods used in studies for bamboo [30].

Among various treatment methods (e.g., thermal modification, chemical impregnation, or oil coating), water soaking was selected for this study due to its cost-effectiveness, local availability, and proven efficacy in enhancing dimensional stability while minimizing cracking, as demonstrated in prior research [15,30]. BC was immersed in a 5% sodium hydroxide (NaOH) solution by weight of water for 30 minutes, then sun-dried and incorporated into the mix in a saturated surface-dry (SSD) condition. NaOH treatment modifies the surface properties of BC by dissolving hemicellulose and lignin, which reduces hydrophilicity. This chemical reaction decreases pore volume and forms a deposited layer on the fiber surface, ultimately lowering the water absorption capacity from 110.41% to 72.37%. The gradation of treated bamboo chips (TBC) was analysed and compared with natural coarse aggregates, as illustrated in Figure 5.

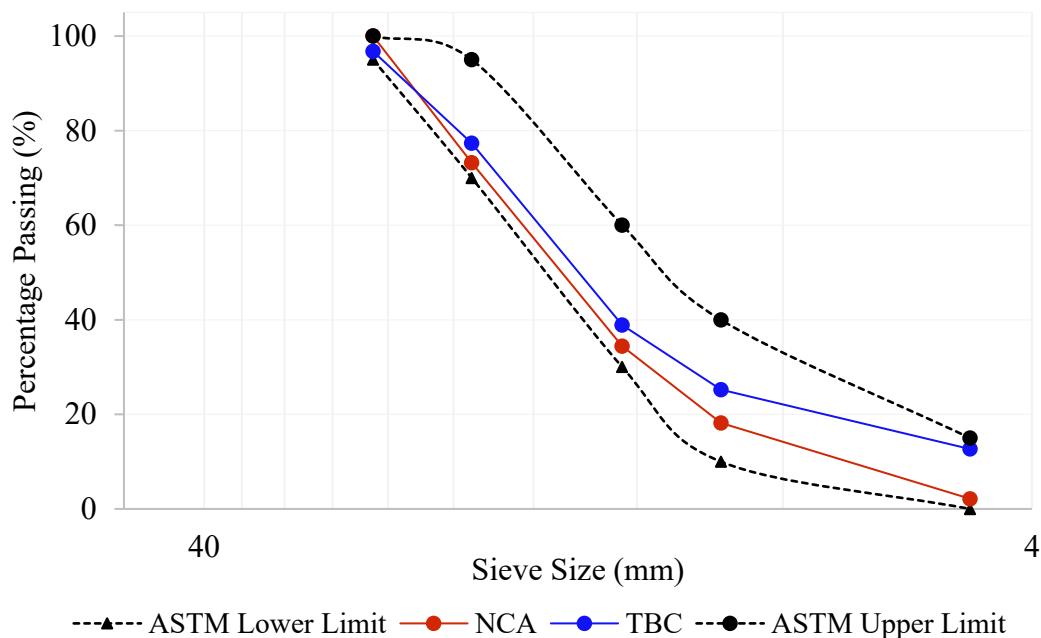


Figure 5. Gradation curve of natural aggregates (NA) and treated bamboo chips (TBC) with ASTM C33 limits [24].

2.2 Mix Design

The experimental program was conducted in two phases. In Phase I, initially 16 mix design combinations were prepared to determine the optimal combination of CSS powder and TBC based on 28 days compressive strength test results. The mixes were labelled based on replacement levels: S0 to S3 for CSS powder at 0%, 10%, 20%, and 30%, and B0 to B3 for TBC at corresponding replacement levels. Mix combinations like S2B1 indicate 20% CSS powder and 10% TBC. The water-cement ratio was kept constant at 0.45 across all mixes. Detailed mix proportions for each combination are shown in Table 1 and test matrix of Phase I

& II is shown in Table 2 & 3. Based on the compressive strength test results of Phase I combinations and RSM optimization, S2B1 was identified as the optimal mix. To validate this finding, two additional ratios (S1.5B0.5 and S2B0.5) were tested, selected through analysis of compressive strength trends observed in single-component specimens (S1B0 and S0B1).

In addition to the experimental evaluation, Phase I data was analysed using RSM to statistically optimize the replacement levels of CSS and TBC. RSM, performed in Design-Expert 13, CSS (A) and TBC (B) as continuous variables in the 0–30% range, while 28-day compressive strength was used as the response. A cubic model was fitted based on ANOVA significance ($p < 0.05$), with adequacy confirmed through R^2 , adjusted R^2 , predicted R^2 , and lack-of-fit statistics. Two-dimensional contour and three-dimensional surface plots were generated to illustrate the interactive effects of CSS and BC, and desirability optimization identified the statistically optimal replacement levels. Ultimately, 17 mix combinations were evaluated and compared against 28-day control samples before advancing to phase II. In phase II, this optimum combination was subsequently evaluated at 28-day and 90-day curing periods under both ambient and elevated temperatures.

Table 1. Mix design proportions for different types of concrete mixes.

Type	Material Details (kg)				
	Cement	Sand	Coarse Aggregate	CSS	TBC
Control Sample	8.65	12.12	17.49	0.00	0.00
10% Replacement	8.65	10.93	15.75	0.95	0.23
20% Replacement	8.65	9.72	14	1.91	0.46
30% Replacement	8.65	8.5	12.25	2.86	0.7

**Note: CSS stands for crushed seashell aggregates and TBC means treated bamboo chips utilized as partial replacement of sand and coarse aggregates respectively.*

Table 2. Detailed test matrix for phase I.

Ser	Sample Group	Sample ID	No of Samples (Cylinders)	Partial Replacement (%)	
				CSS	TBC
1.	Control 1	C-28	3	0	0
2.	Combination 1	S0B1	3	0	10
3.	Combination 2	S0B2	3	0	20
4.	Combination 3	S0B3	3	0	30
5.	Combination 4	S1B0	3	10	0

6.	Combination 5	S1B1	3	10	10
7.	Combination 6	S1B2	3	10	20
8.	Combination 7	S1B3	3	10	30
9.	Combination 8	S2B0	3	20	0
10.	Combination 9	S2B1	3	20	10
11.	Combination 10	S2B2	3	20	20
12.	Combination 11	S2B3	3	20	30
13.	Combination 12	S3B0	3	30	0
14.	Combination 13	S3B1	3	30	10
15.	Combination 14	S3B2	3	30	20
16.	Combination 15	S3B3	3	30	30
17.	Combination 16	S1.5B0.5	3	15	5
18.	Combination 17	S2B0.5	3	20	5

**Note: CSS stands for crushed seashells and BC stands for bamboo chips. In samples IDs, C stands for control, S stands for crushed seashells and B stands for bamboo chips.*

Table 3. Detailed test matrix for phase II.

Ser	Sample Group	Sample IDs		No of Samples (Cy / PB)	
		28 Days	90 Days	28 Days	90 Days
1.	Control 1 (Ambient Temperature)	C-28-CS-AT	C-90-CS-AT	3 Cy	3 Cy
		C-28-ST-AT	C-90-ST-AT	3 Cy	3 Cy
		C-28-FS-AT	C-90-FS-AT	3 PB	3 PB
2.	Control 2 (Elevated Temperature)	C-28-CS-200	C-90-CS-200	3 Cy	3 Cy
		C-28-CS-400	C-90-CS-400	3 Cy	3 Cy
		C-28-CS-600	C-90-CS-600	3 Cy	3 Cy
3.	Combination 9 (Ambient Temperature)	S2B1-CS-28	S2B1-CS-90	3 Cy	3 Cy
		S2B1-ST-28	S2B1-ST-90	3 Cy	3 Cy
		S2B1-FS-28	S2B1-FS-90	3 PB	3 PB
4.	Combination 9 (Elevated Temperature)	S2B1-28-CS-200	S2B1-90-CS-200	3 Cy	3 Cy
		S2B1-28-CS-400	S2B1-90-CS-400	3 Cy	3 Cy
		S2B1-28-CS-600	S2B1-90-CS-600	3 Cy	3 Cy

**Note: Cy stands for cylinders (150 mm × 300 mm) and PB stands for prism beams (100 mm × 100 mm × 400 mm). Sample IDs followed these conventions: C for control specimens, CS for compressive strength tests, ST for split tensile tests, FS for flexural strength tests, and AT for ambient temperature (25°C) conditions. This standardized notation system ensured consistent identification throughout all experimental phases.*

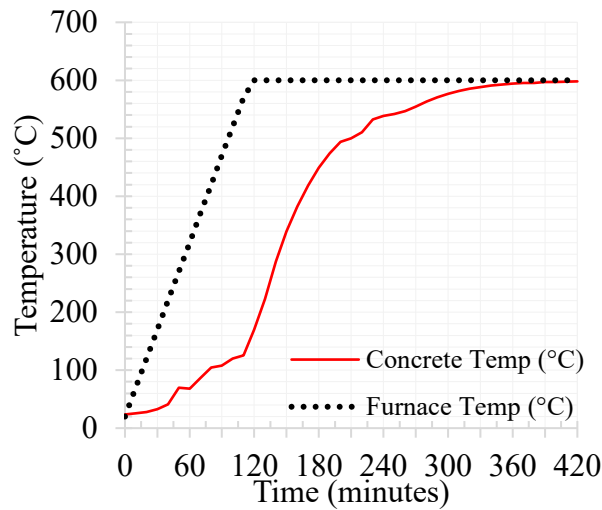
2.3 Casting of Samples

For each mix in Phase I, fifty-four cylindrical specimens of 150 mm diameter and 300 mm height were cast in steel moulds, following ASTM C192 [31] for different concrete mixes as shown in table 2. The dry materials were first mixed for 2 minutes in a rotating drum mixer, after which water was gradually added, and the entire mix was blended for an additional 3 minutes. After mixing, fresh concrete was poured into moulds in three layers and compacted using a vibratory table. Moulds were covered with plastic sheets and demoulded after 24 hours. The specimens were then placed in a water tank for 28 days for curing of specimens. In Phase II, 60 cylindrical specimens and 12 prism beams were prepared for detailed testing as shown in table 3. The same casting and curing procedure of phase I were followed in phase II.

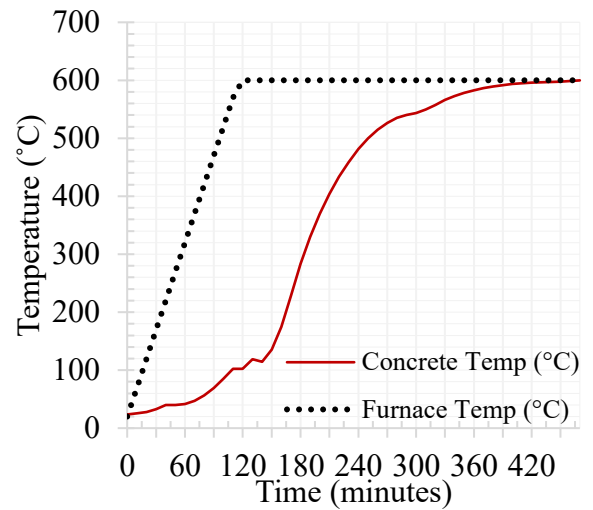
2.4 Fire Loading Conditions

To assess thermal resistance, samples were subjected to elevated temperatures using a digital electric muffle furnace. Target temperatures were set at 200°C, 400°C, and 600°C. The heating rate was maintained at 10°C/min, and specimens were held (dwell time) at the target temperature for 2 hours to simulate fire exposure conditions. Dwell time is defined as the duration for which the furnace maintained its target temperature to allow the core temperature of the concrete specimen to reach equilibrium with the furnace environment. To monitor core temperature, a K-type thermocouple was embedded at the centre of selected cylindrical specimens during the casting process. The thermocouple was connected to a data logger to continuously record temperature evolution.

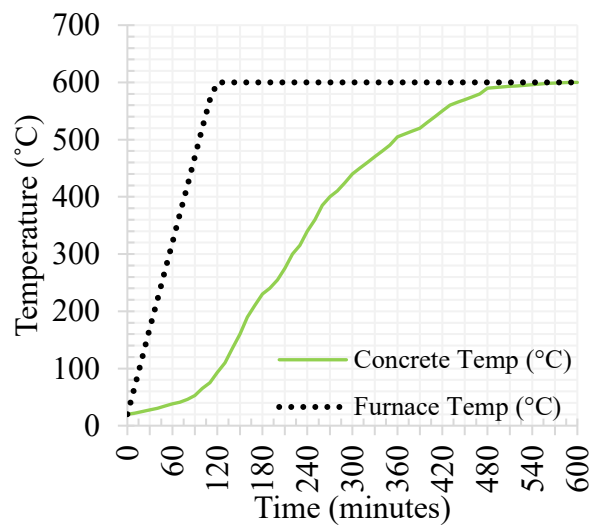
The Stage II specimens, including control and S2B1, exhibited varying heating rates due to differences in thermal conductivity, specific heat capacity, and internal moisture content - parameters strongly influenced by material composition and degree of hydration. Such variations in heat transfer behaviour among concrete mixes have also been reported in previous studies [32]. The corresponding time-temperature profiles are presented in Figure 6. After heating, the specimens were allowed to cool in air for 24 hours before mechanical testing. Visual observations for colour change, cracking, and surface degradation were also recorded.



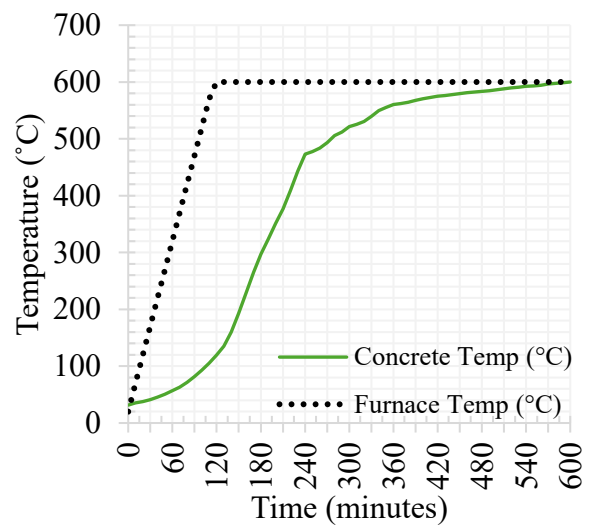
(a)



(b)



(c)



(d)

Figure 6. Time–temperature curves showing core and furnace temperature profiles during fire exposure for (a) Control specimen at 28 days, (b) Control specimen at 90 days, (c) S2B1 specimen at 28 days, and (d) S2B1 specimen at 90 days.

209

210 2.5 Test Methodology

211 2.5.1 Compressive Strength Testing

212 Compressive strength tests were carried out in accordance with ASTM C39 [33]. After
 213 curing and post-fire cooling, the cylindrical specimens were wiped to remove excess surface
 214 water and tested under uniaxial compression using a 2000 kN digital compression testing
 215 machine. Load was applied at a uniform rate of 0.25 MPa/s until failure, and the maximum
 216 load was recorded. The comparison confirmed that the S2B1 mix performed consistently well,
 217 while RSM optimization predicted ~21.6% CSS and a very low level of TBC (~0.2%) as the

mathematical optimum with desirability = 1.0. Although the statistical model emphasized minimal TBC for maximizing compressive strength, the experimental results demonstrated that incorporating 10% TBC (S2B1) still maintained adequate strength while offering greater sustainability benefits. Hence, S2B1 was retained as the practical optimum for detailed Phase II testing.

2.5.2 Split Tensile Strength Testing

Split tensile strength was evaluated using ASTM C496 [34]. Cylinders were placed horizontally between the platens of the compression testing machine, with steel strips used to distribute load uniformly along the length. The purpose was to determine the tensile resistance indirectly, which is critical in evaluating crack propagation behaviour in concrete.

2.5.3 Flexural Strength Testing

Flexural strength was tested using the third-point loading method in accordance with ASTM C78 [35]. Beams were supported over a span of 400 mm and loaded at the third points to simulate uniform bending. The maximum load at failure was used to compute the modulus of rupture. This test also provided load-deflection data for analysing ductility and post-crack energy absorption.

3. Results and Analysis

3.1 Phase I testing

3.1.1 Compressive Strength Analysis

The 28-day compressive strength results for all 18 mixes investigated in Phase I are presented in Figure 7. The control mix achieved the highest compressive strength of 27.77 MPa. As the replacement percentages of both CSS powder and TBC increased, compressive strength exhibited a progressive decline. Among the mixes, S2B1 (20% CSS + 10% TBC) demonstrated the most favourable performance, achieving 23.61 MPa, corresponding to a 17% reduction relative to the control. This mix offered the best balance between mechanical strength and sustainability by incorporating substantial volumes of eco-friendly materials. In contrast, mixes containing 20 to 30% TBC exhibited more pronounced strength reductions, underscoring the negative impact of excessive bamboo replacement on structural performance, primarily due to bamboo's lower stiffness and weaker interfacial bonding with the cementitious matrix.

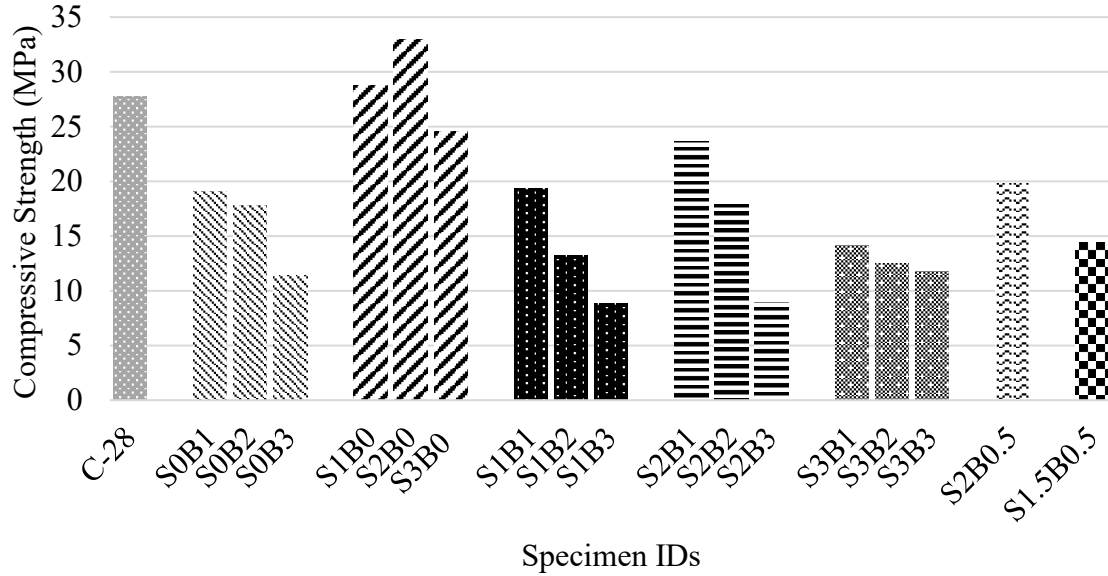


Figure 7. Compressive Strength at 28 days for all Mixes (Phase I).

3.1.2 RSM Optimization

To complement the experimental findings, Phase I results were analysed using RSM. The analysis was performed in Design-Expert 13 with CSS powder (Factor A) and TBC (Factor B) as continuous variables in the range of 0–30%, while the 28-day compressive strength was set as the response variable. A cubic model was identified as the best fit based on ANOVA results ($p < 0.05$), with adequacy confirmed through R^2 , adjusted R^2 , and predicted R^2 values, as well as a non-significant lack-of-fit test. Diagnostic plots (normal probability of residuals, predicted vs. actual values, and Box–Cox transformation) confirmed the validity of the statistical model.

The RSM analysis provided both two-dimensional contour plots and three-dimensional response surface plots as shown in figure 8, which clearly illustrated the interactive effects of CSS and TBC on compressive strength. The surfaces indicated that strength decreased significantly with increasing bamboo replacement beyond 10%, while seashell powder contributed positively up to ~20%. The desirability function optimization predicted ~21.6% CSS and ~0.2% TBC as the mathematical optimum, corresponding to a maximum compressive strength of 24.1 MPa. Although the statistical model emphasized minimal TBC content for maximizing compressive strength, the experimental data demonstrated that incorporating 10% TBC (S2B1) maintained adequate mechanical performance while achieving higher sustainability benefits by utilizing bamboo waste. Based on both experimental and statistical optimization, S2B1 was retained as the practical optimum for detailed Phase II testing, which evaluated mechanical and thermal performance at both ambient and elevated temperatures.

Factor Coding: Actual

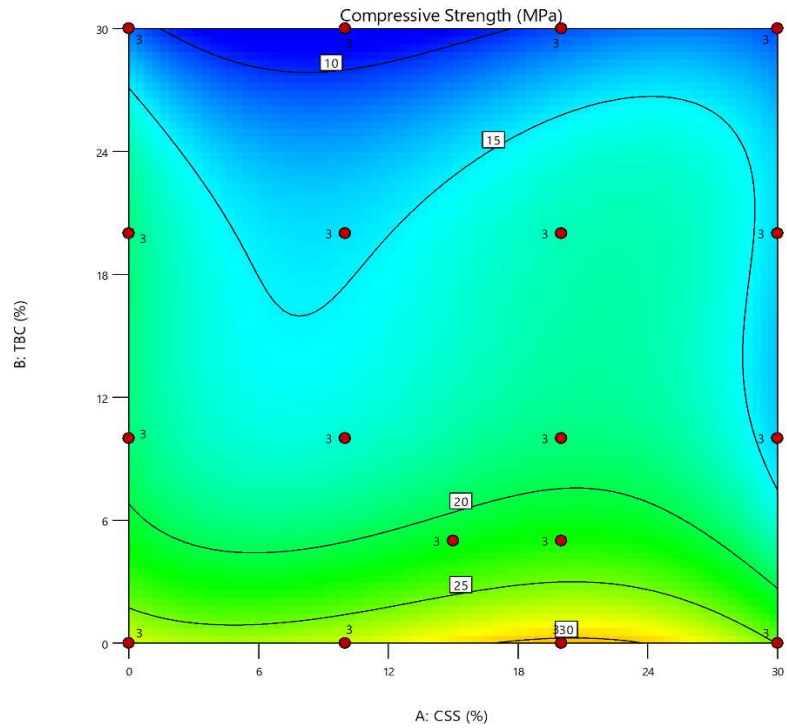
Compressive Strength (MPa)

● Design Points

8.64 34.76

X1 = A

X2 = B



(a)

Factor Coding: Actual

Compressive Strength (MPa)

Design Points:

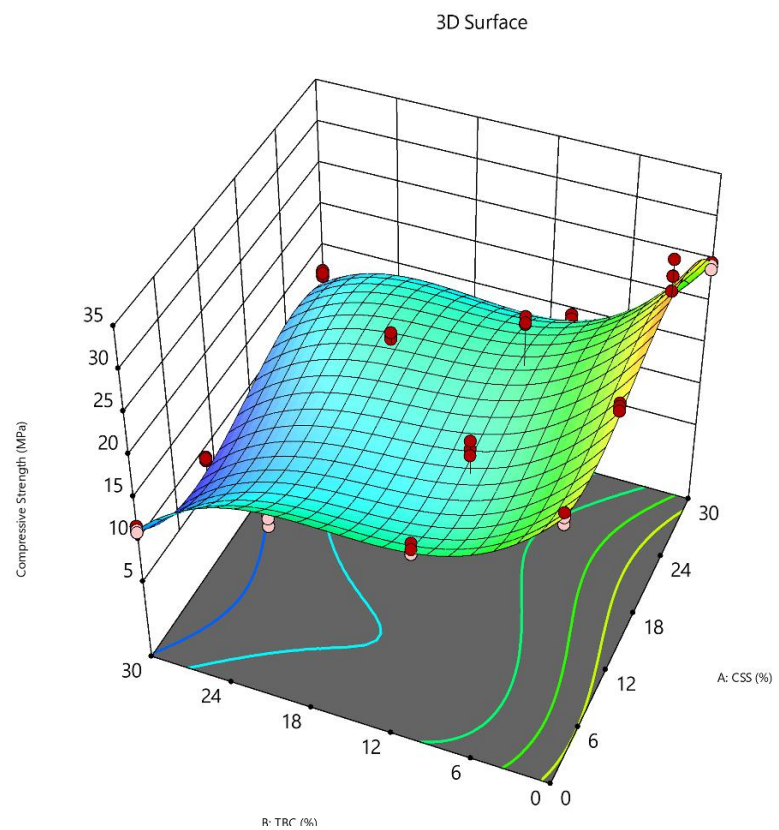
● Above Surface

○ Below Surface

8.64 34.76

X1 = A

X2 = B



(b)

Fit Statistics

	Std. Dev.	2.83	R ²	0.8623
	Mean	18.15	Adjusted R ²	0.8341
	C.V. %	15.58	Predicted R ²	0.8239
			Adeq Precision	19.0338

(c)

Figure 8. RSM analysis of 28-day compressive strength: (a) 2D contour plot, (b) 3D surface plot, and (c) fit statistics.

3.2 Phase II testing

Concrete, while not a refractory material, is inherently non-combustible and offers considerable fire resistance due to its ability to retain strength and resist spalling under thermal exposure [32]. The fire performance of concrete is influenced by its mechanical stability, cracking behaviour, thermal conductivity, and coefficient of thermal expansion. In this study, Stage II testing was performed on four specimen types - C-28, C-90, S2B1-28, and S2B1-90 - evaluated at both ambient and elevated temperatures (200°C, 400°C, and 600°C).

3.2.1 Surface Characteristics and Visual Damage Evolution

Visual inspection remains an essential method for evaluating the serviceability of fire-exposed concrete, providing immediate insight into surface damage, cracking, and colour changes [36]. Figure 9 presents the physical condition of both control specimens (C-28, C-90) and eco-friendly specimens (S2B1-28, S2B1-90) at ambient, 200°C, 400°C, and 600°C.

At ambient temperature, control specimens exhibited uniform, smooth surfaces without visible cracking. The S2B1 mixes displayed a slightly rougher and more porous texture, attributed to the presence of TBC and CSS powder. At 200°C, all specimens showed minor discoloration and surface roughness, with no significant cracking. In S2B1 mixes, early degradation of organic components led to localized surface changes. At 400°C, surface cracking became evident, especially in the control specimens. S2B1 samples exhibited more pronounced roughness and discoloration, though crack density remained lower than in control samples - likely due to the increased pore network formed by CSS and shrinkage of TBC, which enhanced vapor pressure dissipation and delayed matrix failure [37]. At 600°C, severe cracking and material disintegration was observed in all specimens. However, S2B1 samples demonstrated relatively fewer and finer cracks than the controls, suggesting improved thermal

stability. This can be attributed to the open pore system generated by CSS decomposition and bamboo shrinkage, which reduced internal stresses and mitigated explosive spalling [38].

Colour changes were also consistent with literature [39]: specimens transitioned from light grey at 200°C, to dark grey at 400°C, and pinkish hues at 600°C, especially in S2B1 samples - indicating progressive dehydration and microstructural breakdown. Overall, the visual assessment highlights that the eco-friendly concrete (S2B1) exhibited enhanced thermal stability due to its modified pore structure, which contributed to improved fire performance relative to the control mix.

Temperature (°C)	C-28	S2B1-28	C-90	S2B1-90
AT				
200				
400				
600				

Figure 9. Visual assessment of control (C-28, C-90) and eco-friendly BCSC (S2B1-28, S2B1-90) specimens at ambient temperature and after exposure to elevated temperatures (200°C, 400°C, and 600°C).

3.2.2 Failure Modes

Failure modes provide insight into the structural degradation mechanisms of concrete under elevated temperatures [40]. In this study, both control (C-28, C-90) and eco-friendly (S2B1-28, S2B1-90) specimens were tested at ambient, 200°C, 400°C, and 600°C. Typical failure patterns are shown in Figure 10.

At ambient temperature, control specimens exhibited classic brittle failure with sharp vertical cracks, while S2B1 samples displayed more ductile behaviour due to the presence of BC and CSS powder. At elevated temperatures, thermal cracking and matrix degradation progressively intensified across all specimens. Extended curing (C-90, S2B1-90) consistently improved thermal resistance, resulting in finer, less severe cracks compared to 28-day counterparts. At 600°C, severe degradation was observed in all mixes, with extensive cracking

and material loss. However, S2B1-90 maintained relatively better integrity than S2B1-28, likely due to improved matrix densification from extended curing.

Overall, while eco-friendly concretes exhibited more ductile failure modes, the degradation of organic components at high temperatures limited their performance. These trends align with recent findings on thermally exposed modified concretes [41,42].



Figure 10. Failure modes of control and BCSC specimens at ambient and elevated temperatures.

3.2.3 Compressive and Residual Compressive Strength

The compressive strength of all specimens was evaluated at ambient and elevated temperatures (200°C, 400°C, 600°C), with residual strength calculated relative to their ambient values [43]. The compressive strength test results are shown in table 4 and residual strength trends are presented in Figure 11.

For C-28, compressive strength decreased progressively from 27.77 MPa (ambient) to 23.14 MPa (200°C, -16.7%), 18.73 MPa (400°C, -32.5%), and 9.74 MPa (600°C, -64.9%). These reductions are consistent with expected matrix degradation due to dehydration, microcracking, and C-S-H decomposition at high temperatures. S2B1-28 followed a similar trend but exhibited greater sensitivity at higher temperatures, decreasing from 23.61 MPa to 18.73 MPa (-16.5%), 14.19 MPa (-39.9%), and 7.15 MPa (-69.7%). The presence of organic materials (bamboo, seashell powder) accelerated strength loss at elevated temperatures.

C-90 displayed improved thermal resistance due to extended curing, with strength decreasing from 28.78 MPa to 24.94 MPa (-13.3%), 20.40 MPa (-29.1%), and 11.05 MPa (-

332 61.6%). Similarly, S2B1-90 showed better performance than S2B1-28, retaining 25.37 MPa at
333 ambient, and decreasing to 20.73 MPa (-18.3%), 15.90 MPa (-37.3%), and 8.24 MPa (-67.5%).
334 The overall trends are consistent with literature, where typical strength losses in NSC range
335 from 15–20% at 200°C, 30–40% at 400°C, and 60–70% at 600°C [44]. In eco-friendly
336 concretes, greater reductions were observed, attributable to the decarbonation of CaCO_3 (from
337 CSS) and thermal degradation and shrinkage of bamboo, which weaken the interfacial
338 transition zone (ITZ) at elevated temperatures. Above 400°C, $\text{Ca}(\text{OH})_2$ decomposition and C-
339 S-H breakdown become dominant mechanisms of strength loss. Beyond 600°C, degradation is
340 largely irreversible, with CSS decarbonation and bamboo shrinkage contributing to maximum
341 loss in BCSC specimens.

Table 4. Compressive stress vs strain values of control and BCSC specimens at ambient and elevated temperatures.

Sample ID	Compressive Stress (MPa)	Compressive Strain	Difference (%)
CS-28-AT	27.74	0.002436	-
CS-28-200	23.139	0.002357	-16.688
CS-28-400	18.733	0.002287	-32.550
CS-28-600	9.738	0.002387	-64.938
CS-90-AT	28.775	0.002380	-
CS-90-200	24.941	0.002252	-13.324
CS-90-400	20.398	0.002173	-29.112
CS-90-600	11.048	0.002304	-61.606
S2B1-CS-28-AT	23.612	0.002506	-
S2B1-CS-28-200	18.728	0.002387	-20.686
S2B1-CS-28-400	14.191	0.002245	-39.901
S2B1-CS-28-600	7.153	0.002134	-69.705
S2B1-CS-90-AT	25.374	0.002631	-
S2B1-90-200	20.733	0.002427	-18.288
S2B1-90-400	15.898	0.002286	-37.345
S2B1-90-600	8.241	0.002198	-67.523

**Note: C-28-AT refers to the compressive strength of the control specimen after 28 days of curing at ambient temperature. The values 200, 400, and 600 indicate the respective exposure temperatures (in °C). The suffix 90 denotes a 90-day curing period. Similarly, S2B1-28-AT refers to the compressive strength of the eco-friendly mix containing 20% seashell powder (CSS) and 10% treated bamboo chips (TBC), measured after 28 days of curing at ambient temperature. The subsequent 200, 400, and 600 labels indicate exposure temperatures applied to this mix.*

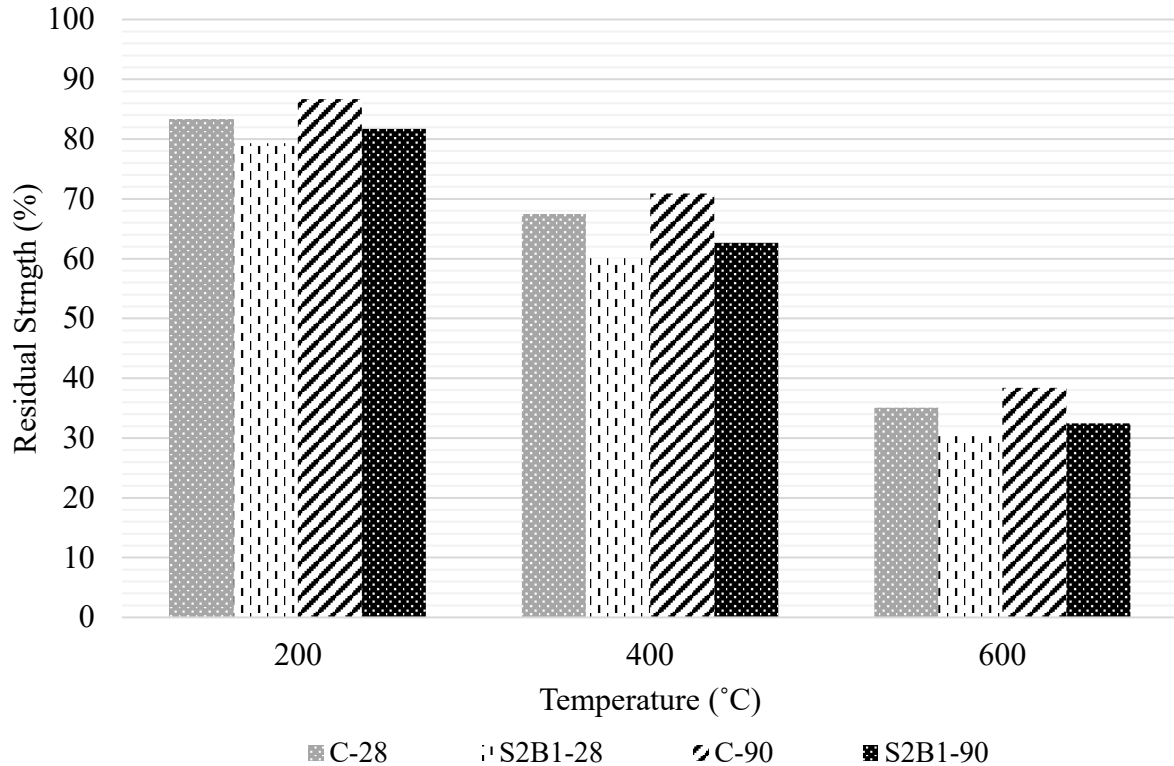


Figure 11. Residual compressive strength of control and BCSC specimens at elevated temperatures.

3.2.4 Split Tensile Strength

The split tensile strength results for control and eco-friendly BCSC specimens at ambient temperature are summarized in Figure 12. The control mix (C-90) exhibited the highest tensile strength at 3.52 MPa, establishing the baseline for performance. C-28 recorded a slightly lower value of 3.21 MPa, 8.8% lower than C-90, which reflects the beneficial effects of extended curing (90 days) in enhancing tensile resistance through continued hydration and matrix densification.

In comparison, S2B1-28 demonstrated a significantly lower tensile strength of 2.12 MPa, 33% lower than C-28. The reduction is primarily attributed to the weaker bond characteristics of BC and CSS powder compared to conventional aggregates. Despite this reduction, the value falls within the acceptable range defined by ASTM C78 standards for split tensile strength (typically 8–14% of compressive strength) [35]. S2B1-90 exhibited a modest improvement, achieving 2.45 MPa - an increase of approximately 9% over S2B1-28. This gain is linked to the beneficial effects of prolonged curing, which fosters the development of additional hydration products and improves interfacial bonding, even though the tensile strength remains lower than the control specimens. These trends are consistent with prior

studies, where organic aggregate replacements generally lead to reduced tensile strength, although extended curing can partially mitigate this effect [45].

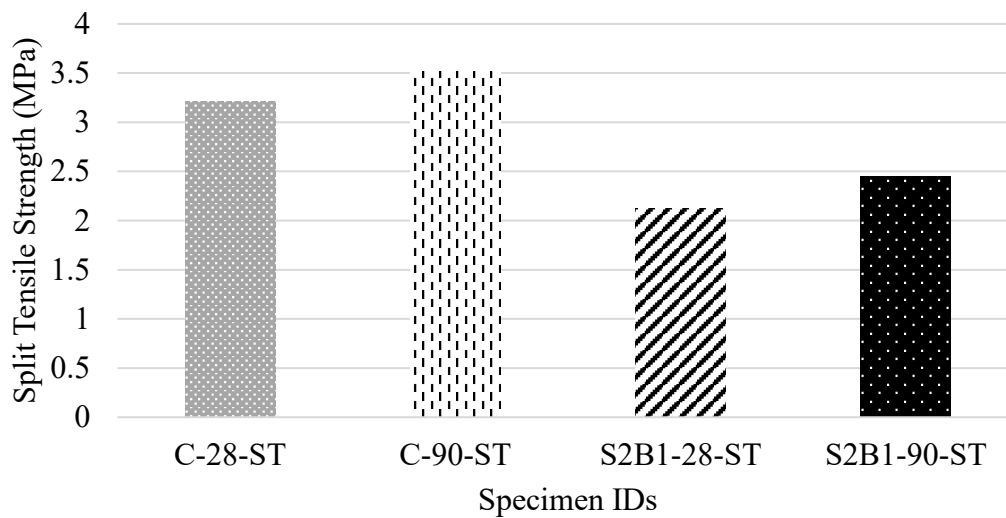


Figure 12. Split tensile strength of control and eco-friendly BCSC samples.

3.2.5 Flexural Strength

The flexural strength results of control and BCSC specimens at ambient temperature are presented in Figure 13. The control mix C-90 exhibited the highest flexural strength of 4.59 MPa, establishing the reference benchmark. C-28 recorded a slightly lower value of 4.22 MPa (8.06% lower), with the strength gain in C-90 attributed to improved matrix densification through extended curing.

In comparison, S2B1-28 showed a flexural strength of 3.62 MPa, approximately 14.21% lower than C-28, reflecting the influence of bamboo chips and seashell powder on reducing flexural capacity at early age. However, S2B1-90 demonstrated a notable improvement, reaching 4.19 MPa (13.6% higher than S2B1-28), highlighting the beneficial effect of prolonged curing in enhancing flexural performance of the eco-friendly mix. Importantly, both S2B1 specimens exhibited flexural strength values well within the ASTM-defined range (10–20%) of corresponding compressive strengths, confirming structural acceptability. Overall, extended curing significantly improved flexural behaviour in S2B1, consistent with trends observed in the control specimens.

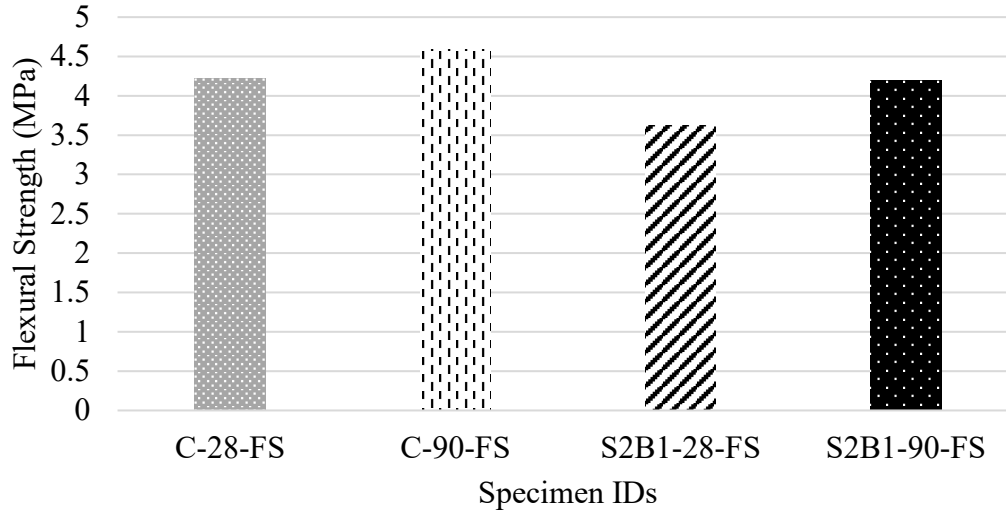


Figure 13. Flexural strength of control and BCSC specimens at ambient temperature.

3.2.6 Mass loss

Mass loss at elevated temperatures reflects the release of moisture and thermal degradation of the concrete matrix, including loss of free, adsorbed, absorbed, and chemically bound water [46,47]. The percentage mass loss for control and BCSC specimens is presented in Table 5. For C-28, mass loss increased from 6.37% at 200°C to 6.9% at 400°C, and 8.63% at 600°C, consistent with progressive dehydration and matrix degradation. C-90 exhibited lower mass loss across all temperatures, with 5.78% at 200°C, reflecting its denser microstructure from extended curing, though at 600°C it reached 7.5%, approaching the levels of C-28.

In comparison, S2B1-28 displayed higher mass loss at all temperatures, reaching 10.05% at 600°C, due to the thermal degradation of TBC and CSS powder. Similarly, S2B1-90 showed the highest mass loss at 200°C (8.63%) and 400°C (8.83%), driven by early degradation of the organic components, with only a marginal increase to 8.93% at 600°C, indicating most volatile losses occurred below 400°C. Across all specimens, BCSC mixes consistently exhibited greater mass loss than controls, particularly at moderate temperatures where the decomposition of bamboo fibres and CaCO_3 decarbonation of seashells contributed significantly to matrix breakdown [48].

Table 5: Mass loss (%) of control and BCSC specimens at elevated temperatures.

Specimen type	Mass Loss (%)		
	200 °C	400 °C	600 °C
C-28	6.37	6.9	8.63
C-90	5.78	6.3	7.5
S2B1-28	6.56	7.78	10.05
S2B1-90	8.63	8.83	8.93

3.2.7 Stress vs strain response

The stress vs strain behaviour of control and BCSC specimens was analysed under ambient and elevated temperatures to evaluate the evolution of mechanical performance and ductility with thermal exposure. The comparative ambient temperature curves for all specimens are shown in Figure 14, while the temperature-wise progression for each individual mix is presented in Figure 15 (a–d).

At ambient temperature as shown in Figure 14, both control specimens (C-28 and C-90) exhibited higher peak stress and steeper slopes, indicating higher stiffness, when compared to the BCSC specimens (S2B1-28 and S2B1-90). In contrast, the eco-friendly concretes showed broader curves and more ductile behaviour, primarily due to the incorporation of BC and CSS powder, which reduce stiffness but enhance deformability.

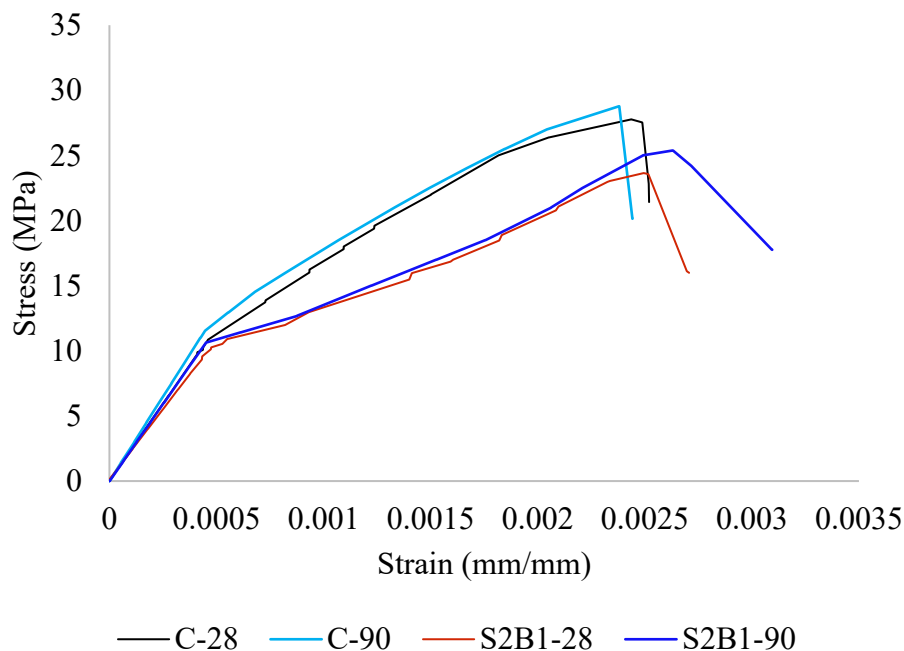
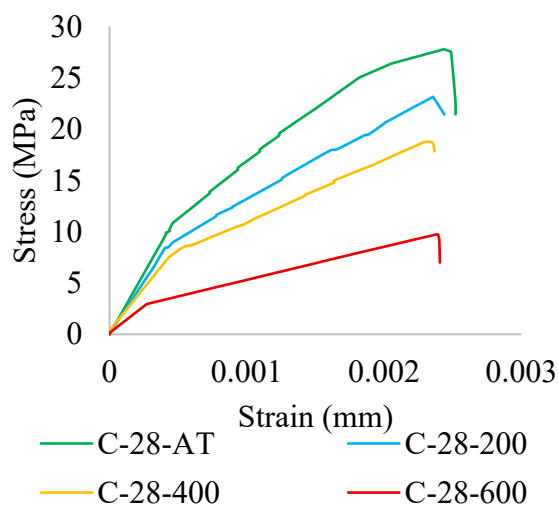


Figure 14. Stress vs strain curves of control and BCSC specimens at ambient temperature.

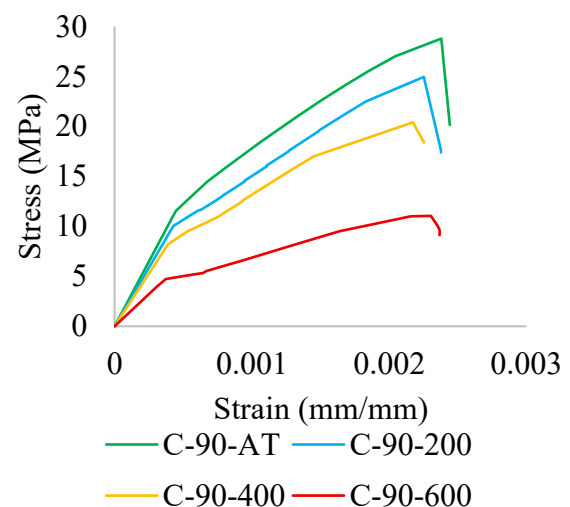
The evolution of stress vs strain behaviour with increasing temperature was evident in all mixes, as illustrated in Figure 15 (a–d). For C-28 shown in Figure 15(a), there was a

progressive reduction in both strength and stiffness with rising temperature, with significant flattening of the curve at 600°C, reflecting advanced matrix degradation and early strain softening. C-90 (Figure 15b) displayed better retention of mechanical performance across all temperatures, owing to its denser microstructure achieved through extended curing, which improved both stiffness and thermal stability. The S2B1-28 (Figure 15c) specimen exhibited the most pronounced reduction in stiffness and strength at elevated temperatures. At 600°C, its stress vs strain curve became substantially flatter with delayed peak stress, indicating substantial loss of mechanical integrity as a result of organic material degradation and microstructural weakening. Conversely, S2B1-90 (Figure 15d) demonstrated improved performance over S2B1-28, with more gradual stiffness reduction and better post-peak behaviour, further confirming that prolonged curing enhances the thermal stability of eco-friendly concretes.

Overall, elevated temperature exposure resulted in a progressive reduction in load-carrying capacity, matrix degradation, and a transition toward more ductile failure modes in all specimens, consistent with literature findings on fire-exposed concretes [49,50]. The comparative results suggest that S2B1-90 offers improved thermal resilience relative to its 28-day counterpart, highlighting the significance of curing in optimizing the performance of eco-friendly concrete under fire scenarios.



(a)



(b)

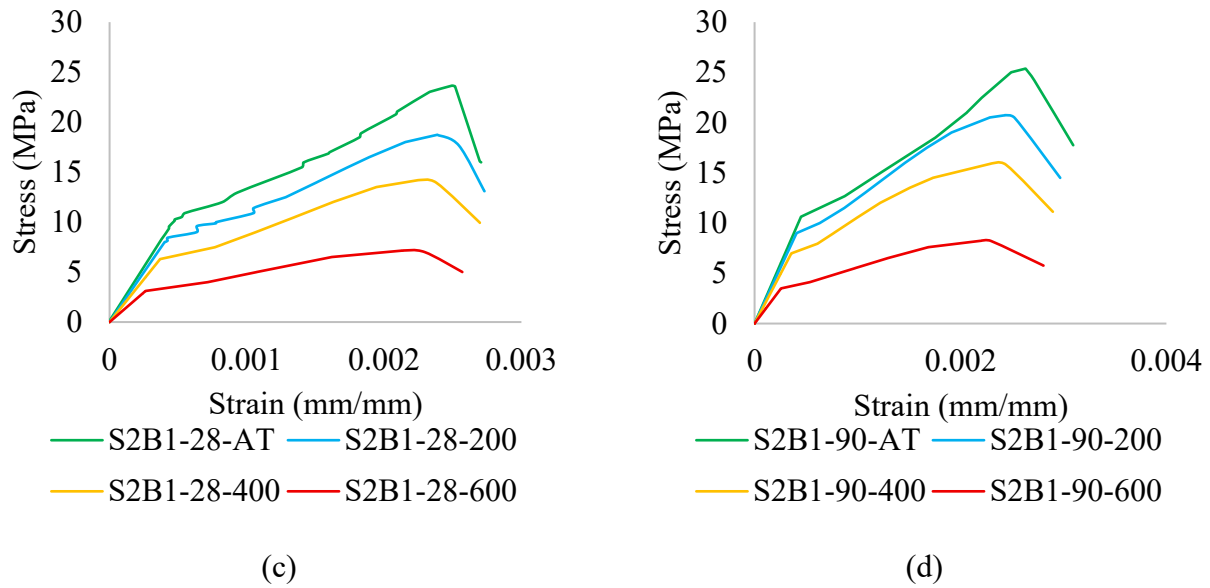


Figure 15. Stress vs strain response of individual specimens at various temperatures: (a) C-28, (b) C-90, (c) S2B1-28, (d) S2B1-90.

3.2.8 Elasticity modulus

The elasticity modulus (E_c) of all specimens was evaluated both experimentally from the initial slope of the stress vs strain curves and analytically using the ACI formula ($4700\sqrt{f'_c}$). The comparative results for all mixes and temperatures are presented in Table 6.

At ambient temperature, the control mixes exhibited the highest stiffness. C-90-AT recorded an experimental modulus of 25.85 GPa, closely matching the ACI-predicted value of 25.22 GPa, with a difference of only -2.53% , confirming the accuracy of the ACI model for conventional concrete. C-28-AT showed an experimental modulus of 23.71 GPa, also in close agreement with ACI predictions ($+4.28\%$). The higher modulus in C-90 reflects the densification from extended curing. In the BCSC specimens, the incorporation of BC and CSS powder resulted in lower stiffness. S2B1-28-AT recorded 21.85 GPa versus 22.56 GPa (ACI), showing a 3.43% difference. S2B1-90-AT displayed improved stiffness (23.57 GPa) with a minimal deviation of $+0.44\%$, again highlighting the positive effect of extended curing on stiffness recovery in eco-friendly mixes.

As temperature increased, all mixes exhibited a progressive decline in elasticity modulus. For C-28, the modulus dropped from 23.71 GPa (AT) to 10.89 GPa at 600°C , with an increasing divergence from ACI predictions ($+25.75\%$). Similarly, C-90 showed superior retention, maintaining 17.5 GPa at 600°C , though with a larger deviation (-12.02%) as the empirical model does not account for elevated temperature effects. In S2B1-28, the modulus reduced more sharply, from 21.85 GPa (AT) to 10.96 GPa at 600°C . In S2B1-90, stiffness

463 remained better, with 17.4 GPa at 600°C, but divergence from ACI reached –28.96%,
464 emphasizing the vulnerability of eco-concretes at high temperatures due to organic degradation
465 and weaker interfacial transition zones.

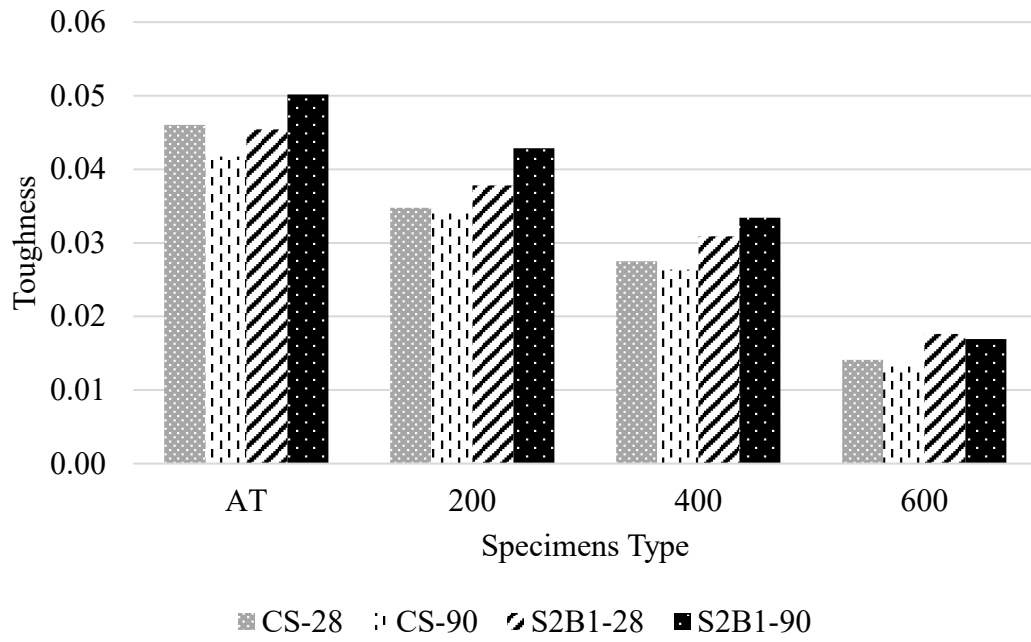
466 Across all specimens, ACI predictions remained valid at ambient conditions, but
467 diverged progressively with temperature rise aligned with the findings reported in literature
468 [47,48,49]. The eco-friendly mixes consistently exhibited lower modulus values, due to the
469 lower inherent stiffness of bamboo fibres and porous microstructure induced by seashell
470 powder.

Table 6. Experimental and ACI-calculated modulus of elasticity for control and BCSC specimens at ambient and elevated temperatures.

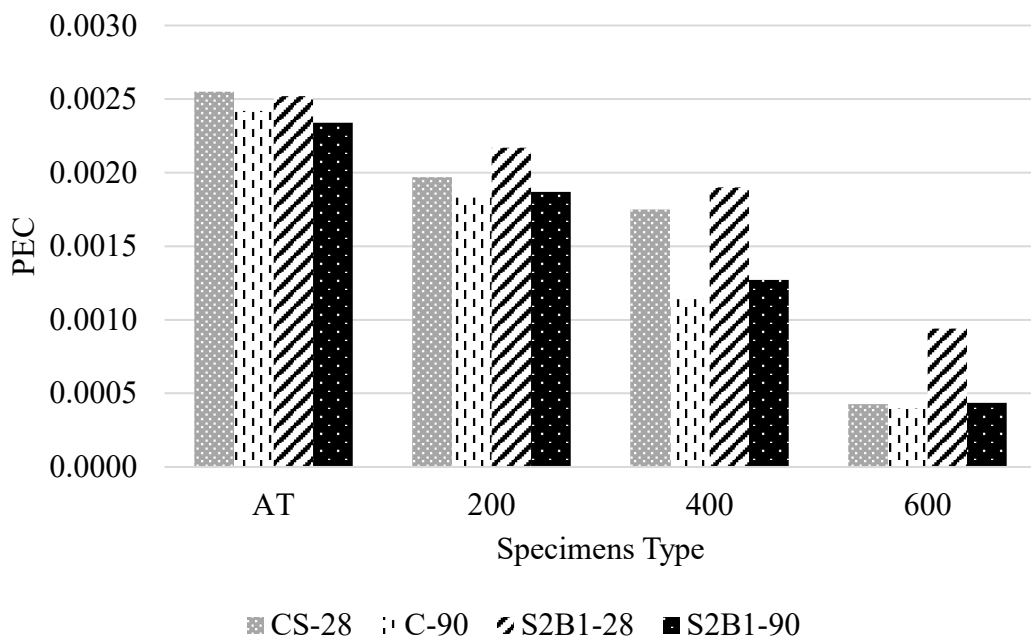
Specimen ID	f'_c (MPa)	Corresponding strain (mm/mm)	Experimental E_c (GPa)	ACI E_c (GPa)	Difference (%)
C-28-AT	27.774	0.002436	23.71	24.77	4.28
C-28-200	23.139	0.002357	20.29	22.61	10.25
C-28-400	18.733	0.002287	17.42	20.34	14.37
C-28-600	9.738	0.002387	10.89	14.67	25.75
C-90-AT	28.775	0.002379	25.85	25.21	-2.53
C-90-200	24.941	0.002252	23.42	23.47	0.22
C-90-400	20.398	0.002173	21.08	21.23	0.69
C-90-600	11.048	0.002304	17.5	15.62	-12.02
S2B1-28-AT	23.612	0.002506	21.85	22.84	4.33
S2B1-28-200	18.728	0.002387	19.95	20.34	1.92
S2B1-28-400	14.191	0.002245	17.11	17.71	3.36
S2B1-28-600	7.153	0.002134	11.87	12.57	5.57
S2B1-90-AT	25.374	0.002631	23.57	23.68	0.44
S2B1-90-200	20.733	0.002427	22.07	21.40	-3.13
S2B1-90-400	15.898	0.002286	19.56	18.74	-4.38
S2B1-90-600	8.241	0.002198	17.4	13.49	-28.96

3.2.9 Toughness and energy absorption

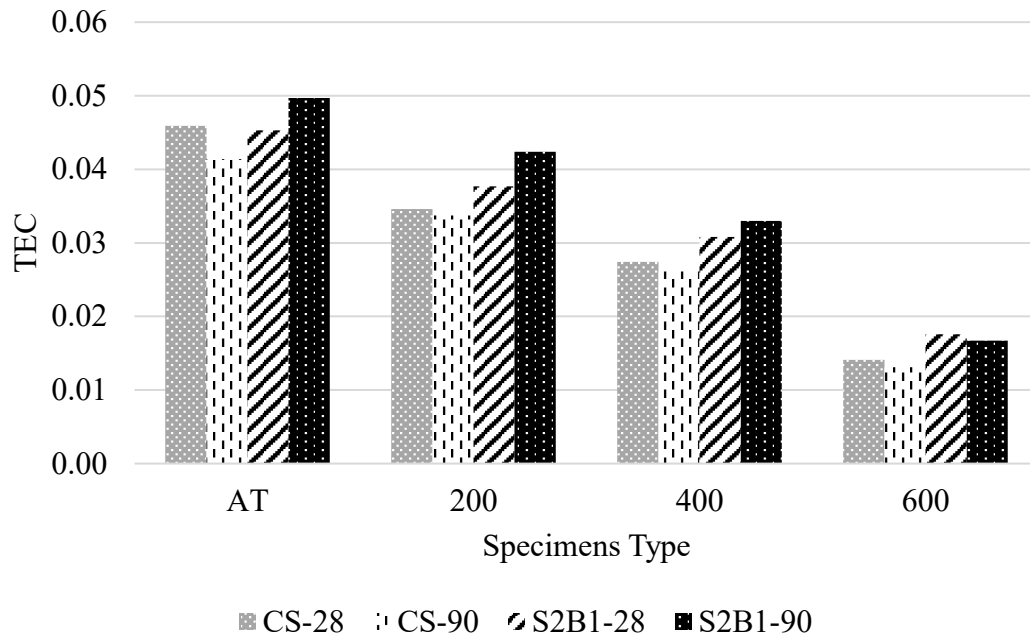
The toughness and energy absorption capacity of the control and BCSC specimens were evaluated under ambient and elevated temperatures, using four key indicators: overall toughness, pre-crack energy in compression (PEC), total energy in compression (TEC), and toughness index (TI). The results are presented in Figure 16 (a–d).



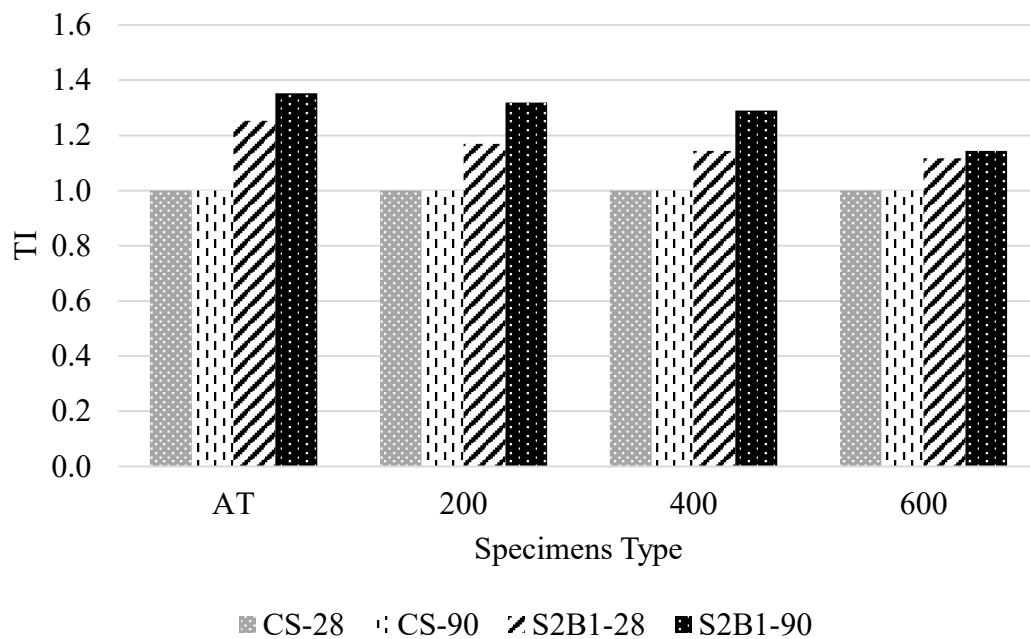
(a)



(b)



(c)



(d)

Figure 16. Toughness and energy absorption parameters of control and BCSC specimens at ambient and elevated temperatures: (a) Toughness; (b) Pre-crack energy in compression (PEC); (c) Total energy in compression (TEC); (d) Toughness Index (TI).

479

480 At ambient temperature, the toughness of S2B1-90 exceeded that of all other mixes,
 481 indicating that the extended curing significantly enhanced the ductility and energy absorption
 482 of the eco-friendly concrete. Figure 16(a) shows that, with rising temperature, all specimens
 483 exhibited progressive reductions in toughness, consistent with the onset of micro-cracking,

matrix degradation, and loss of energy absorption capacity. Notably, S2B1-90 retained higher toughness than both C-90 and S2B1-28 at 200°C and 400°C, demonstrating the positive effects of both material design and curing.

The PEC trends in Figure 16(b) similarly revealed that S2B1-90 performed comparably to C-90 at ambient and moderate temperatures, though at 600°C, all mixes exhibited sharp reductions due to the severe deterioration of the matrix and aggregate bond. The TEC results in Figure 16(c) followed a similar pattern, with S2B1-90 maintaining a slight advantage over its 28-day counterpart, particularly at 400°C, highlighting improved thermal resilience through extended curing.

The TI, shown in Figure 16(d), further illustrates the relative performance of BCSC mixes. While S2B1-28 showed a lower TI at ambient temperature, both S2B1-28 and S2B1-90 exhibited equal or superior TI values to control mixes at 200°C and 400°C, suggesting that the crack-bridging effects of bamboo fibres and the matrix densification of extended curing helped maintain toughness at intermediate temperatures. At 600°C, TI values for all mixes converged, reflecting the universal degradation of the material at extreme temperatures.

Overall, these results demonstrate that the BCSC mixes, particularly S2B1-90, offer competitive toughness and energy absorption properties relative to conventional concrete, with enhanced performance at moderate elevated temperatures due to the synergistic effects of BC, CSS powder, and prolonged curing.

4. Conclusions

This study investigated the mechanical performance and thermal behaviour of an eco-friendly concrete incorporating 20% seashell powder and 10% treated bamboo chips (S2B1) as optimum mix, as partial replacements for fine and coarse aggregates, under ambient and elevated temperatures (200°C, 400°C, and 600°C). Based on the experimental findings, the following key conclusions are drawn:

- The S2B1 mix achieved competitive compressive strength, with only a ~15% reduction compared to control at ambient temperature and retained ~68% of its original strength at 400°C, demonstrating reasonable thermal stability. In parallel, RSM optimization predicted 21.6% CSS powder with negligible TBC (0.2%) as the mathematical optimum, thereby validating the experimental choice of S2B1 as the practical optimum.
- Split tensile and flexural strengths of S2B1 were within the acceptable ASTM limits relative to compressive strength, with performance improvements observed after prolonged

curing (90 days), confirming that extended curing enhances bond development and mechanical properties.

- Mass loss in BCSC mixes was higher than in control specimens, particularly at 200°C and 400°C, due to degradation of organic bamboo fibres and partial decarbonation of seashell components.

- Stress vs strain responses indicated that while all mixes exhibited stiffness degradation at elevated temperatures, S2B1-90 maintained better ductility and post-peak behaviour, demonstrating enhanced thermal resilience after extended curing.

- The modulus of elasticity of BCSC mixes was lower than control at all temperatures, yet the experimental values at ambient conditions remained close to ACI predictions. At elevated temperatures, divergence increased, consistent with the known limitations of ACI models under thermal exposure.

- Toughness and energy absorption analyses showed that S2B1-90 exhibited superior performance compared to both control and S2B1-28 at moderate temperatures (200°C and 400°C), attributed to the crack-bridging capacity of bamboo fibres and enhanced microstructural integrity from prolonged curing.

Overall, the results confirm that eco-friendly concrete utilizing CSS powder and BC can achieve acceptable mechanical performance and thermal stability comparable to conventional concrete, particularly when optimized through extended curing. The combined use of experimental testing and statistical optimization strengthens confidence in the applicability of such eco-concretes, demonstrating that sustainability goals can be achieved without disproportionate loss of structural performance. Future work may explore fiber hybridization, surface modification of bamboo, and high-performance binders to further improve the fire resistance and long-term durability of eco-concretes.

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