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Research Article

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Posted Date: November 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11633886/v1

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Additional Declarations: No competing interests reported.

Strength reduction and strength-scaling relations of M40 concrete with untreated bamboo chips as partial coarse-aggregate replacement

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Acknowledgments

The authors thank Professor Dr. Sudip Kumar Pal, former Head of the Department of Civil Engineering, CUET, for providing departmental facilities, Professor Dr. Md. Moinul Islam for his support, and the laboratory staff of the Department of Civil Engineering, CUET, for their assistance.

Abstract

Bamboo is cheap and plentiful in Bangladesh. Its use as coarse aggregate has so far been tested mainly in normal-strength concrete (20–31 MPa). Here, untreated, seasoned bamboo chips replaced 0, 4, 8, 12 and 16% by volume of the crushed-stone coarse aggregate in an M40 concrete (40 MPa target strength, water–cement ratio 0.40). Slump and 28-day compressive, splitting tensile and flexural strengths were measured. Compressive strength decreased linearly by 1.79 MPa per 1% of bamboo ($R^2 = 0.996$), from 44.2 MPa to 15.4 MPa at 16% (−65%). Flexural and splitting tensile strengths fell less, by 46% and 41%. Bamboo content had a significant effect on all three strengths in an analysis of variance ($p < 10^{-6}$), but slump changed by only 3.5 mm. Flexural and splitting tensile strengths followed power laws of compressive strength with exponents of 0.56 and 0.45, both statistically consistent with the square-root relation of the American Concrete Institute building code (ACI 318). Measured flexural strengths exceeded the ACI 318 modulus of rupture by 3–13% at every replacement level. The strength losses fall between published values for oven-dried and water-soaked chips, which points to the moisture condition of the chips as the main factor that can be controlled. Replacing 4–8% of the coarse aggregate retained 66–81% of the control compressive strength (29–36 MPa), which is enough for ordinary structural grades. Above 8%, the concrete suits non-structural uses unless the chips are treated.

Keywords: bamboo chips; coarse aggregate replacement; bio-aggregate; flexural strength; strength scaling; sustainable concrete

1. Introduction

Coarse aggregate takes up more of the volume of concrete than any other constituent, and it is quarried from rock that does not renew. In Bangladesh, crushed stone is comparatively expensive, and burnt-clay brick chips are still widely used as an alternative coarse aggregate (Sarker et al., 2017). Bamboo, by contrast, grows fast and costs little anywhere in the country, and rural builders already use it for structural supports. Using bamboo for part of the stone could reduce the demand for quarried rock, but only if the strength loss that comes with it is known and kept within limits.

Most research on bamboo in concrete has used it as reinforcement or as fiber. Bamboo splints and culms have been tested as substitutes for steel bars in beams (Rahman et al., 2011; Rahim et al., 2020), but a critical review concluded that bamboo-reinforced concrete suffers from durability, bond and stiffness problems (Archila et al., 2018); because bamboo is less stiff than concrete, flexural cracks can form in such members at service loads (Ding, 2015). Short bamboo fibers added at low dosages, typically 0.5–2%, have increased splitting tensile strength (Sarker et al., 2017; Gelanew & Demiss, 2023; Asrat & Songa, 2025), and small additions of bamboo chips by cement weight have produced compressive strengths close to that of the control (Dary et al., 2024). In all of these, bamboo is added to the mix rather than used in place of aggregate.

When bamboo does replace aggregate, particle size and volume largely decide the outcome. As a fine-aggregate replacement, 5% bamboo fiber gave a compressive strength of 27.77 MPa against 30.15 MPa for the control (Noh et al., 2021), and small fractions (1–5%) of bamboo in place of sand have also been examined (Rahman et al., 2025). At very high volumes (30–50%), bamboo particles produce bio-concretes with densities below 786 kg/m^3 and thermal conductivities of 0.32–0.52 W/(m·K), which suit insulating rather than structural uses (Andreola et

al., 2024). In that work a hot-water wash at 80 °C removed extractives that otherwise delayed cement hydration. In wall composites, roughening the surface of crushed bamboo raised 28-day compressive strength by about 39–44% (Bakatovich et al., 2025).

Few studies have put bamboo in place of coarse aggregate in structural concrete. Park et al. (2019) replaced 10–30% of coarse aggregate by volume with 10 × 10 × 5 mm bamboo chips in a 31 MPa concrete, using chips that were oven-dried, waterproof-coated or soaked in water. At 10% replacement, the compressive strength retained ranged from 44% (dried) to 77% (soaked). The authors attributed the loss to the weak bond between chips and mortar and to the swelling of dry chips during curing. Pujianto and Tajuddin (2012) replaced 20–100% of coarse aggregate in a 27 MPa flowing concrete with superplasticizer and silica fume, and reported falling density and compressive strength. Tahara et al. (2021) replaced 5–15% by weight in a 20 MPa concrete and recommended 5% as the practical limit, while Vithiya and Sharminy (2024) found a substantial loss with 10% bamboo strips in C20 and C30 concrete. A review of this literature suggested 5–15% replacement and chips about 2–4 cm long, 1–2 cm wide and 1 cm thick, with epoxy coating as the most effective treatment (Idris et al., 2021). In Bangladesh, Mahzuz and Ahmed (2012) compared bamboo, rattan and wood as bio-aggregates for lightweight concrete.

This leaves three gaps. All comparable studies used normal-strength concrete (20–31 MPa), so nothing has been reported on bamboo chips in a stronger matrix, where the stiffness contrast between chip and paste is larger. The published work also stopped at compressive and, at most, splitting tensile strength. Flexural strength has not been measured, although it governs the design of slabs, pavements and other members in bending. Finally, design codes such as ACI 318 of the American Concrete Institute (ACI) estimate tensile and flexural strength from compressive strength through $\sqrt{f'_c}$ relations (ACI Committee 318, 2019), but whether these relations still hold once bamboo is added has not been checked. Replacement levels below 10%, where the strength is most likely to stay usable, have also had little attention.

The objectives of this study were to quantify the effect of 4–16% bamboo chips, in 4% steps, on the workability and on the compressive, splitting tensile and flexural strengths of an M40 concrete; to test whether flexural and splitting tensile strength remain proportional to $\sqrt{f'_c}$; and to place the results within the published data so that the main controlling factor can be identified.

2. Materials and methods

2.1 Materials

A commercial Portland composite cement was used; its properties are listed in Table 1. The fine aggregate was natural river sand passing the 4.75 mm sieve, with a specific gravity of 2.50, a bulk density of 1670 kg/m^3 and a fineness modulus of 2.90. The coarse aggregate was angular crushed stone with a rough surface texture and a maximum nominal size of 20 mm. Its specific gravity was 2.65, bulk density 1746 kg/m^3, fineness modulus 7.3, absorption capacity 0.85% and moisture content 0.4%. Potable water was used for mixing and curing.

Locally available, seasoned bamboo was cut by hand into chips 20–50 mm long and 10–30 mm wide, the thickness being that of the culm wall. The chips were used without chemical or physical treatment. The density of the bamboo was taken as 650 kg/m^3 for batching; the density and water absorption of the chips were not measured.

Table 1 Properties of the Portland composite cement

Property	Result	Requirement
Fineness (% passing)	96.5	> 95
Specific gravity	3.15	–
Normal consistency (%)	29	–
Initial setting time (min)	68	> 45
Final setting time (min)	195	< 420

2.2 Mix proportions

The control mix was proportioned for a target strength of 40 MPa following ACI 211.1 (ACI Committee 211, 1991), with a water–cement ratio of 0.40 and no chemical admixture. The batch masses correspond to a cement: sand: stone mass ratio of 1: 0.99: 1.80. Bamboo chips replaced 4, 8, 12 and 16% of the coarse-aggregate volume; all other constituents were kept constant. Table 2 gives the proportions per cubic meter, calculated from this ratio by the absolute-volume method with 2% entrapped air.

Table 2 Mix proportions per m^3 (calculated from the batch mass ratio; see text)

Mix	Bamboo (% vol. of CA)	Cement (kg)	Sand (kg)	Stone (kg)	Bamboo (kg)	Water (kg)
B0	0	547	541	984	0	219
B4	4	547	541	945	9.7	219
B8	8	547	541	905	19.3	219
B12	12	547	541	866	29.0	219
B16	16	547	541	827	38.6	219

CA = coarse aggregate. Bamboo mass based on an assumed density of 650 kg/m^3.

2.3 Specimen preparation

Mixing was done by hand on a watertight platform. Cement and sand were first mixed dry to a uniform color, the stone and bamboo chips were then added and mixed, and finally the water was added. The concrete was placed in three layers and compacted with a tamping rod. For each mix, six cylinders (102.5 mm diameter × 200 mm) and two beams (150 × 150 × 750 mm) were cast, giving 30 cylinders and 10 beams in total. Specimens were demolded after 24 h, cured in water for 28 days, and air-dried before testing.

2.4 Test methods

All tests followed the standard methods of ASTM International. Slump was measured immediately after mixing (ASTM C143). Compressive strength was determined on three cylinders per mix (ASTM C39); machine readings were converted with the calibration equation $P = 5.995\ P_{obs} - 19.123$ (kN), and the strength was calculated as

$$f'_c = \frac{P}{A} \tag{1}$$

where P is the maximum load and A the cross-sectional area of the cylinder. Splitting tensile strength was determined on three cylinders per mix (ASTM C496) as

$$f_{sp} = \frac{2P}{\pi l d} \quad (2)$$

where l and d are the length and diameter of the cylinder. Flexural strength (modulus of rupture) was determined on two beams per mix under third-point loading (ASTM C78) as

$$f_r = \frac{PL}{bd^2} \quad (3)$$

where L = 450 mm is the span between supports (beam length 750 mm), and b and d are the width and depth of the beam.

2.5 Statistical analysis

Results are reported as mean ± standard deviation (SD) with the coefficient of variation (COV). For each property, the effect of bamboo content was tested by one-way analysis of variance (ANOVA) with bamboo content as the single factor at five levels; the effect size is reported as $\eta^2 = SS_{between}/SS_{total}$. Homogeneity of variances was checked with Levene's test (median-centered) and normality of the residuals with the Shapiro–Wilk test. Where ANOVA was significant, all ten pairs of mixes were compared with Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$, and mixes that did not differ were assigned the same grouping letter. Linear regressions of strength on bamboo content were fitted to individual specimen results. The dependence of flexural and splitting tensile strength on compressive strength was described by power laws of the form

$$f = a(f'_c)^b \quad (4)$$

fitted by least squares on log-transformed mix means, where f is the flexural or splitting tensile strength and a and b are fitted constants. Statistical analyses were performed with SciPy, and figures were produced with Matplotlib, both in Python.

2.6 Use of artificial intelligence tools

During the preparation of this manuscript, the authors used Claude (Anthropic), a large language model, to assist with comparing the results with the published literature, writing the Python code for the statistical analysis and figures, and drafting and editing the text. The experimental data were produced by the authors. The authors checked all data, calculations and citations against the original sources, revised the text, and take full responsibility for the content of the publication.

3. Results

3.1 Workability

Slump decreased slightly with bamboo content, from 58.0 mm for the control to 55.5, 55.5, 55.0 and 54.5 mm at 4, 8, 12 and 16% bamboo. A total drop of 3.5 mm (6%) is small, so at these volumes the chips do not materially affect workability. The slight loss is consistent with the chips absorbing some of the mixing water. Larger reductions have been reported at higher volumes: slump fell from 180 mm to 140 mm at 20% replacement and to 10 mm at 100% (Pujianto & Tajuddin, 2012), and slump also decreased progressively from 5% to 15% Beting

bamboo (Tahara et al., 2021). At 10%, bamboo strips also gave lower workability than coconut shell at the same content (Vithiya & Sharminy, 2024).

Table 3 Twenty-eight-day strengths (mean ± SD, with COV, strength retained relative to the control, and Tukey HSD groups)

Bamboo (%)	Compressive (MPa)	Ret.	Splitting tensile (MPa)	Ret.	Flexural (MPa)	Ret.
0	44.19 ± 0.31 (0.7%) A	100%	3.07 ± 0.05 (1.7%) A	100%	4.64 ± 0.05 (1.1%) A	100%
4	35.79 ± 0.73 (2.0%) B	81%	2.39 ± 0.05 (2.2%) B	78%	3.90 ± 0.04 (1.0%) B	84%
8	29.32 ± 0.75 (2.6%) C	66%	2.18 ± 0.10 (4.4%) C	71%	3.47 ± 0.00 (0.0%) C	75%
12	21.74 ± 0.55 (2.5%) D	49%	2.05 ± 0.05 (2.5%) C	67%	3.04 ± 0.05 (1.7%) D	66%
16	15.36 ± 0.36 (2.3%) E	35%	1.81 ± 0.10 (5.3%) D	59%	2.51 ± 0.05 (1.9%) E	54%

n = 3 cylinders (compression, splitting) and n = 2 beams (flexure, 450 mm span) per mix. Ret. = strength retained relative to the control. Within a column, means sharing a letter (A–E) do not differ significantly (Tukey HSD, $\alpha = 0.05$).

3.2 Statistical significance

Table 3 lists the mean 28-day strengths, their variability and the Tukey groups. One-way ANOVA (Table 4) showed a highly significant effect of bamboo content on all three properties. The factor explained 99.8% of the total variation in compressive and flexural strength and 98.1% in splitting tensile strength (η^2), so differences between mixes far outweigh the scatter between specimens. For compressive and splitting tensile strength, the variances were homogeneous (Levene, $p = 0.87$ and 0.84) and the residuals were consistent with normality (Shapiro–Wilk, $p = 0.29$ and 0.41). With only two beams per mix, these checks mean little for flexure, so the flexural ANOVA should be taken as indicative, even though its F value is very large ($F = 750$).

Table 4 One-way ANOVA of the effect of bamboo content on 28-day strength

Property	Source	SS	df	MS	F	p	η^2
Compressive	Between mixes	1546.351	4	386.588	1189.9	2.4×10^{-13}	0.998
	Within mixes (error)	3.249	10	0.325			
	Total	1549.600	14				
Splitting tensile	Between mixes	2.7662	4	0.6916	132.1	1.3×10^{-8}	0.981
	Within mixes (error)	0.0523	10	0.0052			
	Total	2.8186	14				
Flexural	Between mixes	5.2902	4	1.3225	749.7	3.9×10^{-7}	0.998
	Within mixes (error)	0.0088	5	0.0018			
	Total	5.2990	9				

SS = sum of squares; df = degrees of freedom; MS = mean square; $\eta^2 = SS_{between}/SS_{total}$.

Tukey's HSD test (Table 5) showed that every bamboo mix differed from the control for all three properties ($p < 0.001$). For compressive and flexural strength, every pair of mixes differed, giving five distinct groups. For

splitting tensile strength, all pairs differed except 8% and 12% (mean difference 0.13 MPa, 95% CI −0.07 to 0.32 MPa, p = 0.27), which form one group.

Table 5 Tukey HSD pairwise comparisons: mean difference (MPa) with 95% confidence interval and adjusted p value

Pair (% bamboo)	Compressive	p	Splitting tensile	p	Flexural	p
0 vs 4	8.40 (6.87, 9.93)	<0.001	0.68 (0.49, 0.87)	<0.001	0.74 (0.57, 0.90)	<0.001
0 vs 8	14.88 (13.35, 16.41)	<0.001	0.89 (0.70, 1.09)	<0.001	1.16 (1.00, 1.33)	<0.001
0 vs 12	22.45 (20.92, 23.99)	<0.001	1.02 (0.83, 1.21)	<0.001	1.60 (1.43, 1.76)	<0.001
0 vs 16	28.83 (27.30, 30.37)	<0.001	1.26 (1.07, 1.46)	<0.001	2.13 (1.96, 2.30)	<0.001
4 vs 8	6.48 (4.95, 8.01)	<0.001	0.21 (0.02, 0.41)	0.030	0.43 (0.26, 0.60)	<0.001
4 vs 12	14.05 (12.52, 15.59)	<0.001	0.34 (0.15, 0.53)	0.001	0.86 (0.69, 1.03)	<0.001
4 vs 16	20.43 (18.90, 21.97)	<0.001	0.58 (0.39, 0.78)	<0.001	1.39 (1.22, 1.56)	<0.001
8 vs 12	7.58 (6.05, 9.11)	<0.001	0.13 (−0.07, 0.32)	0.27 (n.s.)	0.43 (0.26, 0.60)	<0.001
8 vs 16	13.96 (12.43, 15.49)	<0.001	0.37 (0.18, 0.56)	<0.001	0.96 (0.80, 1.13)	<0.001
12 vs 16	6.38 (4.85, 7.91)	<0.001	0.24 (0.05, 0.44)	0.014	0.53 (0.36, 0.70)	<0.001

Mean difference = lower-bamboo mix minus higher-bamboo mix. n.s. = not significant at α = 0.05.

3.3 Compressive strength

Compressive strength fell steadily as the bamboo content rose (Table 3, Fig. 1), from 44.19 MPa for the control to 35.79, 29.32, 21.74 and 15.36 MPa at 4, 8, 12 and 16%. These values correspond to 81, 66, 49 and 35% of the control strength. The decline is closely linear:

$$f'_c = 43.63 - 1.793p \quad (5)$$

where p is the bamboo content in percent ($R^2 = 0.996$, n = 15) and the standard error of the slope is 0.032 MPa per percent. Each 4% step removed a similar absolute amount of strength (8.40, 6.48, 7.58 and 6.38 MPa), but because the base strength kept falling, the relative loss per step grew from 19% and 18% for the first two steps to 26% and 29% for the last two. In relative terms, each added increment of chips costs more strength at high contents than at low ones. Scatter within each mix was low (COV 0.7–2.6%), which suggests the chips were spread evenly despite hand mixing. Every mix formed its own Tukey group (Table 3).

In absolute terms, 4% bamboo still gave 35.8 MPa and 8% gave 29.3 MPa, both above the 25–30 MPa commonly specified for ordinary reinforced concrete, while 12% (21.7 MPa) and 16% (15.4 MPa) fall below normal structural grades. The fitted line predicts 25.7 MPa (58% of the control) at 10% bamboo, which can be set against the published 10% results in Table 6. It lies between those of Park et al. (2019) for oven-dried chips (44%), waterproof-coated chips (49%) and water-soaked chips (77%). It is also below the 72% retained with 10% bamboo strips in C30 concrete, but far above the 14% reported for the same strips in C20 concrete (Vithiya & Sharminy, 2024). Tahara et al. (2021) obtained about 54% of the control strength at 5% replacement, but their replacement was by weight. Because bamboo is roughly one-quarter as dense as stone, 5% by weight corresponds to a much larger volume (about 18% by volume, if the densities are similar to those assumed here), so their result is consistent

with a severe loss at high volume fractions. Losses are much smaller when bamboo replaces sand: 5% bamboo fiber as fine aggregate retained 92% of the control strength (Noh et al., 2021). They can even turn to small gains when chips are added at 1% of the cement mass (+4.9%; Dary et al., 2024), because in that case no stone is removed.

Table 6 Twenty-eight-day compressive strength of concrete containing bamboo in this and published studies (data from Park et al., 2019; Pujianto & Tajuddin, 2012; Tahara et al., 2021; Vithiya & Sharminy, 2024; Noh et al., 2021; Dary et al., 2024)

Study	Bamboo form and treatment	Replacement	Control (MPa)	With bamboo (MPa)	Retained
This study	Chips 20–50 mm, seasoned, untreated	4 / 8 / 16% vol. CA	44.19	35.79 / 29.32 / 15.36	81 / 66 / 35%
Park et al. (2019)	Chips 10 × 10 × 5 mm, oven-dried	10 / 20 / 30% vol. CA	30.77	13.55 / 5.76 / 3.13	44 / 19 / 10%
Park et al. (2019)	Same, waterproof-coated	10 / 20 / 30% vol. CA	30.77	15.01 / 14.15 / 8.99	49 / 46 / 29%
Park et al. (2019)	Same, soaked 24 h	10 / 20 / 30% vol. CA	30.77	23.73 / 19.04 / 17.75	77 / 62 / 58%
Pujianto & Tajuddin (2012)	Pieces; superplasticizer + silica fume	20 / 40% CA	26.97	18.65 / 13.37	69 / 50%
Tahara et al. (2021)	Beting bamboo chips, untreated	5 / 10 / 15% wt. CA	≈ 39	≈ 21 / 15 / 13	≈ 54 / 38 / 33%
Vithiya & Sharminy (2024)	Strips 4.75–10 mm, C20 / C30	10% CA	19.27 / 27.60	2.72 / 19.82	14 / 72%
Noh et al. (2021)	Fiber replacing sand	5% FA	30.15	27.77	92%
Dary et al. (2024)	Chips added (2–3 cm)	1% of cement mass	30.04	31.51	105%

CA = coarse aggregate; FA = fine aggregate. Tahara et al. values are approximate, read from their Fig. 7. Vithiya & Sharminy tested cubes; all others cylinders.

3.4 Splitting tensile strength

Splitting tensile strength fell from 3.07 MPa to 2.39, 2.18, 2.05 and 1.81 MPa (78, 71, 67 and 59% of the control). Unlike compression, the loss was concentrated at the first step: the change from 0% to 4% removed 0.68 MPa (22%), whereas the next three steps removed only 0.21, 0.13 and 0.24 MPa (9%, 6% and 12% of the preceding value). The linear fit is therefore weaker than for compression (slope −0.072 MPa per percent, $R^2 = 0.875$), and Tukey's test could not separate 8% from 12% (Table 5). The sharp initial drop suggests that the first chips introduce weak, debonded interfaces in the plane of splitting. Further chips add to these flaws but do not change the failure mode. COV values ranged from 1.7 to 5.3%, slightly higher than in compression, as is typical of the splitting test.

The same pattern appears in the data of Park et al. (2019). With 10% chips, splitting tensile strength fell from 2.38 MPa to 1.59 MPa for oven-dried chips (67%), 1.74 MPa for coated chips (73%) and 2.21 MPa for soaked chips (93%). At 30%, it fell to 0.38, 0.84 and 1.61 MPa (16, 35 and 68%). The present 8% mix retained 71%, close to

Park's dried and coated chips at 10%, which again places the seasoned chips used here between the dry and saturated conditions. Bamboo fibers added in small amounts behave quite differently. Splitting tensile strength peaked at about 1% fiber in stone-chip concrete (Sarker et al., 2017). It rose by about 10% with 0.75% bamboo fiber combined with 5% waste marble and glass powder as cement replacement (Gelanew & Demiss, 2023), and by 15.5% (2.51 to 2.90 MPa) with 0.5% bamboo fiber combined with 4% calcined kaolin (Asrat & Songa, 2025). Slender fibers can bridge cracks, whereas chips 10–30 mm wide behave as weak inclusions.

3.5 Flexural strength

Flexural strength fell from 4.64 MPa to 3.90, 3.47, 3.04 and 2.51 MPa (84, 75, 66 and 54% of the control), at a nearly constant rate of 0.128 MPa per percent of bamboo (R^2 = 0.988). The four 4% steps removed 0.74, 0.43, 0.43 and 0.53 MPa (16, 11, 12 and 17% of the preceding value). Flexure was the property least affected at 4% (84% retained) and was intermediate at 16% (54%), between splitting tension (59%) and compression (35%). Every pair of mixes differed (Tukey, $p \leq 0.001$), and the COV with two beams per mix was at most 1.9%.

The ratio of flexural to compressive strength rose from 0.105 for the control to 0.163 at 16% (Table 7). At every level, the measured strength was higher than the modulus of rupture given by ACI 318, $0.62\sqrt{f'_c}$ (ACI Committee 318, 2019): 4.64 against 4.12 MPa for the control (+13%), and 3.90, 3.47, 3.04 and 2.51 MPa against 3.71, 3.36, 2.89 and 2.43 MPa for the bamboo mixes (+3 to +5%). The margin narrows once bamboo is present but does not disappear. To the authors' knowledge, no flexural data have been published for concrete in which bamboo replaces part of the coarse aggregate. Published flexural results for bamboo deal either with added fibers, which increased flexural strength by about 23% at 0.5% fiber with 4% calcined kaolin (Asrat & Songa, 2025), or with bamboo used as reinforcing bars, where the low modulus of bamboo allowed flexural cracks to form at service loads (Rahman et al., 2011; Ding, 2015).

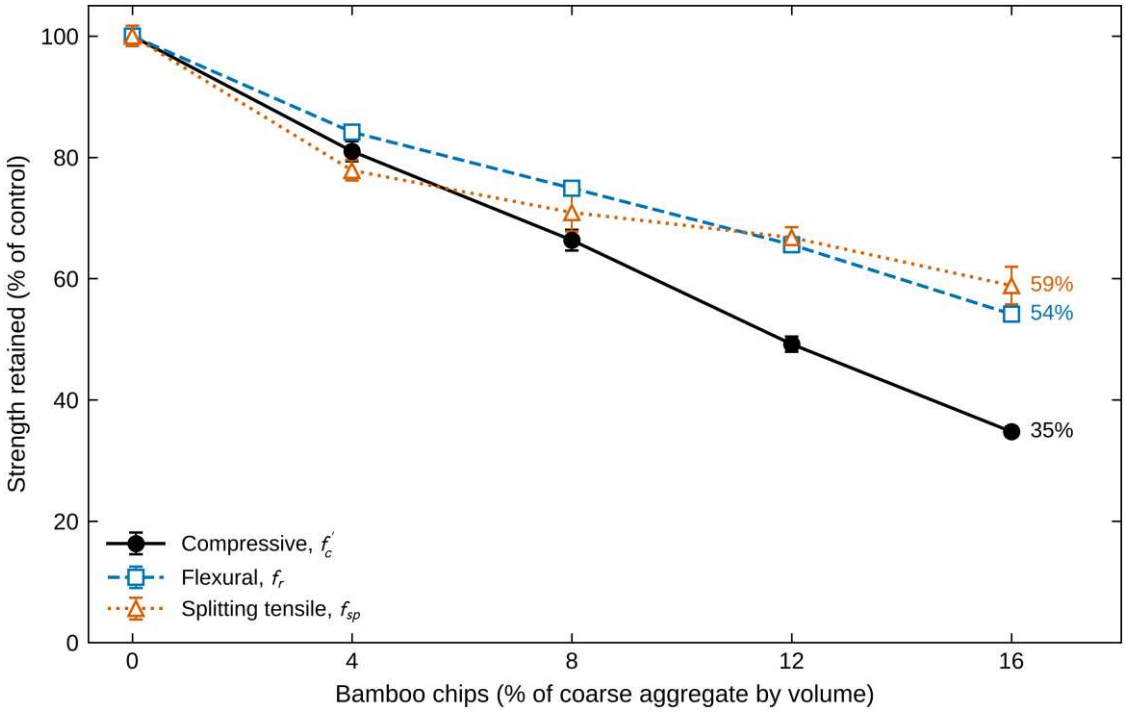


Fig. 1 Strength retained at 28 days as a function of bamboo content. Error bars show ± 1 SD relative to the control mean

4. Discussion

4.1 Strength-scaling relations

Compressive strength declined faster than the other two properties: at 16% bamboo it retained 35%, against 54% for flexure and 59% for splitting tension. As a result, the ratio of splitting tensile to compressive strength rose from 0.069 to 0.118 (Table 7). Such a rise could be read as evidence that the fibrous chips bridge cracks. But it is also what the usual non-linear relation between tensile and compressive strength predicts: when f'_c falls, $\sqrt{f'_c}$ falls proportionally less.

To tell the two explanations apart, flexural and splitting tensile strength were regressed on compressive strength in logarithmic form (Fig. 2). The fitted relations are $f_r = 0.539\ f'_c{}^{0.56}$ ($R^2 = 0.989$) and $f_{sp} = 0.512\ f'_c{}^{0.45}$ ($R^2 = 0.883$). The 95% confidence intervals of the exponents, 0.45–0.67 and 0.15–0.75, both include 0.5, the exponent used in ACI 318. In line with this, the normalized coefficients $k = f/\sqrt{f'_c}$ were nearly constant across all five mixes: 0.66 ± 0.02 for flexure (COV 3.6%) and 0.43 ± 0.03 for splitting tension (COV 7.1%). The flexural coefficient lies just above the 0.62 used for the modulus of rupture in ACI 318 (ACI Committee 318, 2019): measured flexural strengths exceeded $0.62\sqrt{f'_c}$ by 13% for the control and by 3–5% for every bamboo mix (Fig. 2).

In practice, bamboo chips lower the strength of the concrete but leave the relationship between its properties unchanged. Designers can therefore treat bamboo-chip concrete as a lower-strength concrete and estimate its tensile and flexural capacity from a compressive test with the usual $\sqrt{f'_c}$ expressions; for flexure, the ACI 318 expression remained conservative at every replacement level tested. No additional toughening by crack bridging needs to be assumed, and none should be claimed without load–deflection data. The same rise in the tension-to-compression ratio is visible in the data of Park et al. (2019), where it increased from 0.077 for plain concrete to 0.117 at 10% dried chips.

Table 7 Ratios of tensile and flexural strength to compressive strength

Bamboo (%)	f_{sp} / f'_c	f_r / f'_c	$f_{sp} / \sqrt{f'_c}$	$f_r / \sqrt{f'_c}$
0	0.069	0.105	0.46	0.70
4	0.067	0.109	0.40	0.65
8	0.074	0.118	0.40	0.64
12	0.094	0.140	0.44	0.65
16	0.118	0.163	0.46	0.64

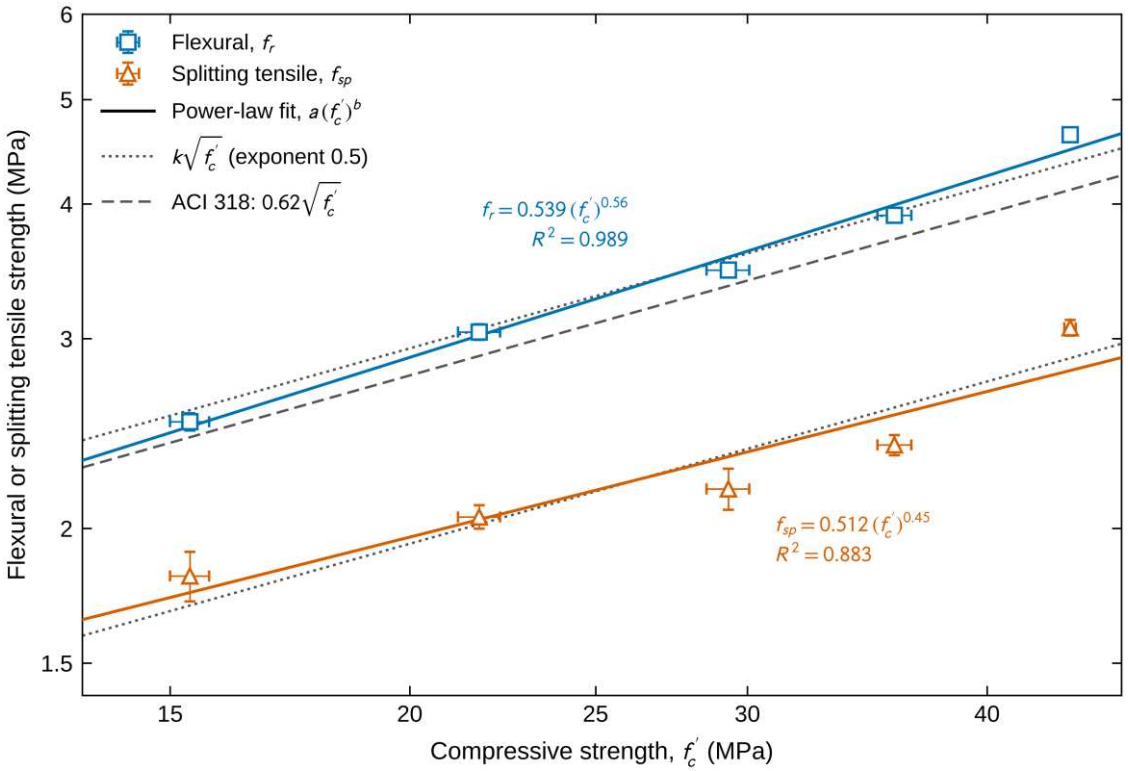


Fig. 2 Flexural and splitting tensile strength against compressive strength (log–log scale). Solid lines are power-law fits; dotted lines show k√f′c with k equal to the mean ratio; the dashed line is the ACI 318 modulus of rupture, 0.62√f′c. Error bars show ± 1 SD on both axes

4.2 Comparison with published data

Fig. 3 compares the compressive strength retained in this study with the results of Park et al. (2019) and Pujianto and Tajuddin (2012) (see also Table 6). Expressed per percent of replacement, the present study lost about 4.1 percentage points of strength per 1% of bamboo. Park et al. reported a loss of 5.6 points per 1% for oven-dried chips and 2.3 points for water-soaked chips over the first 10%. Pujianto and Tajuddin, whose flowing mix contained superplasticizer and silica fume, reported 1.5 points per 1% over the first 20%. The present results thus lie between those for dried and soaked chips, which is consistent with the seasoned, air-dry condition of the chips used here.

The ranking suggests that the moisture condition of the chips, and not only their volume, controls the strength loss. Dry bamboo absorbs water rapidly: Park et al. (2019) measured an absorption of 55.9%, and Bakatovich et al. (2025) measured 43–45% within 24 h. Chips that take up mixing water swell during curing and shrink when the concrete dries, loosening the interfacial zone and initiating microcracks (Park et al., 2019). Two other mechanisms add to this. First, bamboo is far less stiff than stone and its compressive strength is low, reported between 12 and 42.5 MPa (Park et al., 2019; Rahman et al., 2025), so the chips act as soft, weak inclusions that concentrate stress. Second, soluble extractives can retard hydration of the paste next to the chips (Andreola et al., 2024). The present data cannot separate the influence of the stronger matrix from that of chip moisture, because the chip condition was not varied.

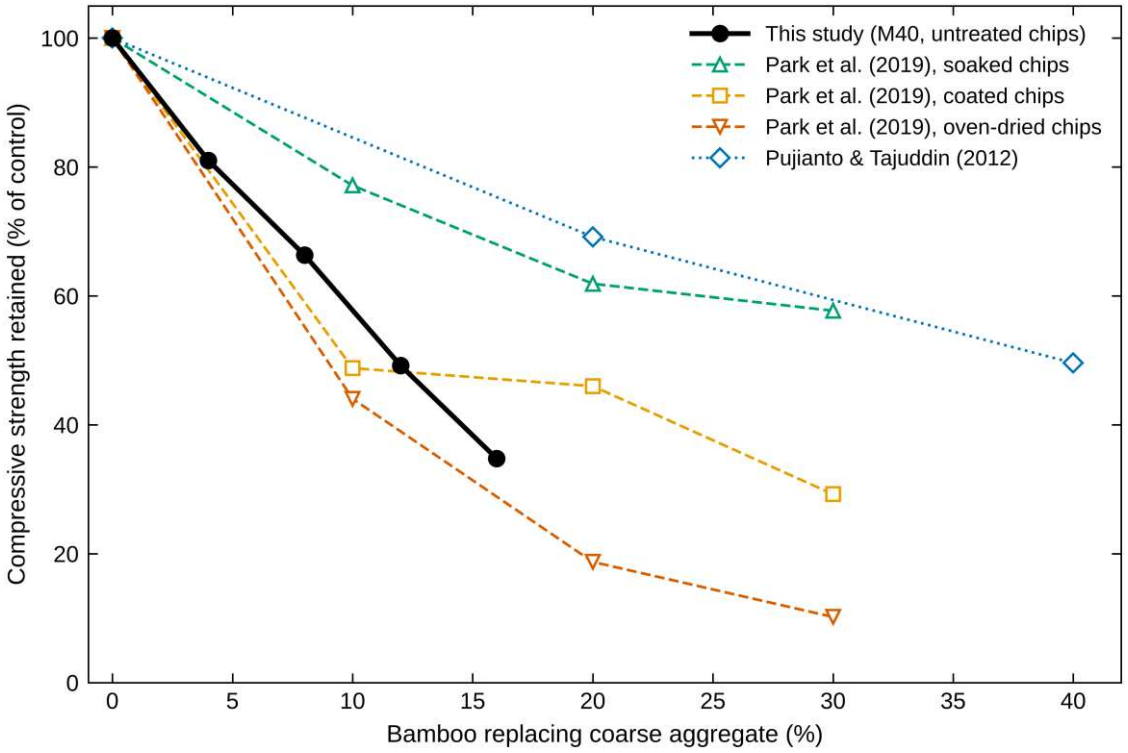


Fig. 3 Compressive strength retained versus bamboo replacement level: present study compared with Park et al. (2019, Table 4) and Pujianto and Tajuddin (2012, Table 5). Each series is normalized to its own control

4.3 Practical implications

At 4% and 8% bamboo the concrete retained 35.8 and 29.3 MPa, so a 40 MPa design mix with up to 8% bamboo still meets ordinary structural grades of about 25–30 MPa. At 12–16%, strengths of 15–22 MPa limit the material to lightly loaded or non-structural elements such as partition blocks, lean concrete and site works. Per cubic meter, replacing 4–16% of the coarse aggregate saves 39–157 kg of stone and reduces the theoretical density by 1.3–5.2% (calculated from Table 2; density was not measured). These savings have to be set against the extra cement needed to recover the lost strength, and the trade-off is likely to pay off only at low replacement levels or with treated chips.

5. Limitations and future work

The study has several limitations. The chips were untreated, and their species, age, density and water absorption were not recorded, so the effective water–cement ratio is uncertain. The longest chips (up to 50 mm) exceed one-third of the cylinder diameter, which may have exaggerated the strength loss in cylinder tests. The sample sizes were small (three cylinders and two beams per mix), and only 28-day properties were measured. Specimens were air-dried before testing rather than tested in a moist condition, and mixing and compaction were done by hand. Durability was not studied.

Future work should test cheap chip treatments that can be done locally: pre-soaking to a saturated surface-dry condition, hot-water washing and surface roughening. It should also use chips no larger than 20 mm, measure density, absorption and load–deflection behavior, and extend testing to 90 days and to wet–dry and biological durability.

6. Conclusions

(1) Replacing 4–16% of the coarse aggregate in an M40 concrete with untreated bamboo chips changed slump by only 3.5 mm, so workability was not materially affected.

(2) Compressive strength decreased linearly by 1.79 MPa per 1% of bamboo ($R^2 = 0.996$), from 44.2 MPa to 15.4 MPa at 16% (−65%).

(3) Flexural and splitting tensile strengths decreased less, by 46% and 41% at 16%. The flexural loss was linear (0.128 MPa per 1%), whereas splitting tensile strength dropped most at the first 4% step.

(4) Flexural and splitting tensile strengths scaled with compressive strength to the powers 0.56 and 0.45, statistically consistent with 0.5. The usual $\sqrt{f'_c}$ relations therefore remain valid for bamboo-chip concrete, and the rising tension-to-compression ratio reflects this scaling rather than toughening by the chips. Measured flexural strengths (2.51–4.64 MPa) exceeded the ACI 318 modulus of rupture at all replacement levels.

(5) The strength losses lie between those published for oven-dried and water-soaked chips, indicating that chip moisture condition is the main controllable factor.

(6) Up to 8% bamboo retained 66–81% of the control compressive strength (29–36 MPa) and is suitable for ordinary structural grades. Higher contents should be limited to non-structural uses unless the chips are pre-treated.

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Statements and Declarations

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests, the authors have no relevant financial or non-financial interests to disclose.

Author Contributions Md. Ariful Islam carried out the experimental work, data collection, statistical analysis and visualization, and wrote the first draft of the manuscript. Md. Saiful Islam conceived and supervised the study, provided the laboratory resources, and reviewed and edited the manuscript. All authors read and approved the final manuscript.

Data Availability All data generated or analyzed during this study are included in this published article (Table 3). The Python scripts used for the statistical analysis and figures are available from the corresponding author on reasonable request.

Ethics Approval Not applicable. This study did not involve human participants or animals.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- bamboodata.py
- statisticalanalysis.py
- makefigures.py