

Investigation of Concrete Tensile Strength with Partial Replacement of Cement with Bamboo Stem Ash (BSA) in Concrete Structures

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ABSTRACT

The research study is an investigation of concrete tensile strength with bamboo stem ash (BSA) partial replacement of cement and involves evaluation of split tensile strength of BSA concrete under certain curing conditions for optimum replacement level of BSA. Cement paste is solely responsible for the formation of intermolecular bonds in solid concrete which directly affects tensile strength. The research procedure involves casting concrete cylindrical elements (150 x 300 mm long) using a mix proportion of 1:1.5:3 and a constant water cement ratio of 0.5. Concrete was partially replaced with bamboo stem ash at 5%, 7.5%, and 10% by weight of cement. Workability test was performed using slump test and two curing conditions were employed, ie, air and water, also splitting tensile test experiment were conducted at 3, 7, 14, 21, 28 and 42 days. Split tensile strength is calculated from observed failure load due to tension, and equivalent to loss of intermolecular force of attraction (ie, debonding) between concrete molecules. The observed results indicated that for air cured specimen, control concrete exhibited substantial increase in tensile strength between 3 and 14 days with maximum of 2.15 N/mm² at 14 days, similarly 5% BSA concrete demonstrated considerable improvement during this period, with increase from 1.43 N/mm² to 1.75 N/mm² at 14 days, while replacement levels of 7.5% and 10% resulted in progressive reduction in tensile strength due to effect of BSA contribution to cementitious-paste matrix bond strength. Water cured specimen produces stable strength development throughout the curing period and at 3 days, 5% BSA concrete presented highest splitting tensile strength of 8.66N/mm² at 14 days while the control concrete specimen strength equals 8.00 N/mm² at 14 days. In conclusion, 5% BSA replacement level consistently produced highest tensile strength performance and beneficial effect at this replacement level effectively compensated for reduction in cement content

Keywords: Concrete, Cement, BSA, Tensile strength, Intermolecular forces

INTRODUCTION

Concrete is a structural and civil engineering construction material that has low and insignificant tensile strength compared to its compressive strength, with corresponding low performance during tensile load application. Understanding the behaviour structural response becomes importance as it is required in estimating the stress level at which initiation and development of cracks in concrete occurs (Dabbagh et al, 2017). Tensile properties of concrete is mainly influenced by the followings, water to cement ratio, characteristics and quality of fine and coarse aggregates, concrete age, nature of applied load, loading rate, addition of additives etc (Rashid et al, 2012), also measured by direct or splitting tension, or flexural strength tests. Concrete is a brittle material with bi-modulus characteristics (young modulus in tension is not the same as that of compression), It comprise of fine aggregate (sand), coarse aggregate (eg, granite) and cementitious paste as binder matrix (ie, cement + BSA), which produce a weak intermolecular bonds in the solid concrete. When concrete is subjected to tension, stress concentrates and the weak bond of “aggregates and binder matrix can easily be subjected to brittle failure (Yan et al, 2013), due to low intermolecular bond and dissociation energy. Microscopic forces in concrete include hydrogen bonds, van der waals/dispersion forces and cement cohesion forces. Hydrogen bonds form between calcium-silicate-hydrate (C-S-H) gel structures and trapped or the structural water molecules heavily influence the elasticity and toughness of cement matrix (Beanguer

et al, 2021). Van der Waals/Dispersion forces cause microscopic cement particles to attract and clump together when first mixed with water, affecting the overall flow and workability of wet concrete (Flatt, 2004).

Adhesion between cementitious binder and substrate (ie, aggregates) can occur either by mechanical means or by chemical mechanism and the strength of adhesion depends on several factors including bonding mechanism, interfacial tension, surface roughness and wettability, curing process etc. (Windisch, 2020), also the adhesive energy is energy required to separate (or, bind) two materials (or, material constituents). Cement cohesion is the internal binding force that makes wet cement paste turn into a hard, solid rock. The strength comes from C-S-H gel, where water and charged ions get trapped in tiny spaces and lock tightly together through strong electrostatic forces. Atomic force microscopy (AFM) is used to measure the nanoscale forces between calcium -silicate-hydrate nanoparticles in cement (Israelacchvili, 2011 and Samuel et al 2001). Research using AFM reveals that cement cohesion is primarily driven by ionic correlation forces mediated by confined water and divalent calcium ions within the interstitial solution rather than standard electrostatic repulsion. Concrete curing is controlled process after setting of fresh concrete that enables transition to hardened state with adequate structural strength at about 28 days of casting, it involves change from plastic bonding of fresh concrete to solid molecular bonds of solid concrete (Afolabi and Salako, 2025).. Objective of the study is the evaluation of workability characteristics and splitting tensile strength of BSA-blended concrete and determining an optimal replacement level of bamboo stem ash, by substituting BSA at 0%, 7.5% and 10% replacement level by-weight of cement in concrete, cured in air and water before performing the tensile test

LITERATURE REVIEW

Total interaction energy is the change in energy required for two or more molecules, atoms or objects to interact together leading to formation of permanent association (ie,)chemical bonds. Intermolecular distance is the empty space between separate molecules or particles, which depends on the state of matters (ie, ie, solid, liquid or gas). Columb's law of attraction states that opposite electric charges pull toward each other. Strength of this pull grows when the charges are large and gets weaker when the distance between them increases (Ahmed, 2025), that is, an inverse relationship between the bond length and bond strength (or, dissociation energy)

$$\text{ie, } F = \frac{k q_1 q_2}{r^2}$$

where

F = electric pull force

. k = Column's constant ($8.99 \times 10^9 \text{ N.m}^2/\text{C}^2$)

. q_1 and q_2 = size of each charge in Columb C

. r = microscopic distance (ie, bond length) between interacting molecules

Action of tensile force on structural component directly affect stability of weak interactive forces and bond energy in concrete with tendency to separation and cracks (Windisch, 2020). Hence if dissociation energy is low the materials will yield easily in response to the applied force and produce tension cracks and fracture on little application of tensile force. Bond mechanism between aggregate and binder matrix in concrete relies on chemical adhesion, physical friction and mechanical interlock within the interfacial transition (or contact) zone, that hold aggregate particles and hardened cement paste together to give the composite material's strength (Deraf, 2016). Shen et al 2020, investigated tensile splitting strength, crack initiation load, and damage characteristics and analyzed based on experimental data and fracture surface of samples and concluded that tensile splitting strength and crack initiation have the descending order as HT (high strength concrete) > LT (low strength concrete) > FT (interface reinforced by steel fiber) > OT (interface not reinforced). Tensile splitting strength is related not only to the roughness of fracture surface but also to the percentage of

fractured aggregates. Le 2021, investigated the splitting tensile strength of ultra-high-performance concrete (UHPC) and aimed at presenting experimental and statistical evaluation of splitting tensile strength of UHPC. Tests were conducted on cylindrical specimens of 100 x 200 mm size, reinforced with macro steel fibres by volumetric percentages of 0, 1 and 2%. The values of splitting tensile strength of UHPC with and without fibres in previous studies were reviewed and subsequently verified with the predictions of the splitting tensile strength obtained from existing models. Magsalansan et al 2025, in their study on effectiveness of using chopped carbon fibre reinforced polymer (CCFRP) on mechanical properties of self compacting concrete. A total of 126 cylindrical concrete specimen, divided into three design mixes (M20, M30 and M40) with varying percentages of CCFRP (0%, 0.05%, 0.10%, 0.125%, 0.15%, 0.175% and 0.20%) were tested for compressive and split tensile strength. The result show that its effect on split tensile strength varied based on design mix. For M20 and M30, there was no significant effect on split tensile strength, whereas for M40 the CCFRP had a significant impact.

MATERIALS AND METHODOLOGY

Concrete constituent materials used are cement, BSA, sand (fine aggregate) and granite (coarse aggregate), which were proportioned and mixed before casting in cylindrical moulds for splitting tensile tests The bamboo stems were collected from locally available sources and prepared for processing by removing surface dirt and foreign materials and then air-dried under ambient laboratory conditions to reduce moisture content. The prepared bamboo material was subjected to controlled combustion to produce raw ash, which was then calcined in a muffle furnace at a temperature of 600°C for 1.5 hours. This temperature range was selected based on literature recommendations to promote the formation of amorphous silica while minimizing the formation of crystalline phases and unburnt carbon, that can adversely affect pozzolanic activity. After calcination, the ash was allowed to cool gradually to room temperature under controlled conditions to avoid thermal shock and structural alteration. The cooled ash was then ground manually/mechanically to achieve a fine powder suitable for use in concrete.

Preliminary tests were conducted on concrete constituents for quality assurance of the concrete produced according to standard specifications (BS 812 series and BS EN 197-1)

Chemical composition of bamboo stem ash is the following table (Source: Leksikowati and Rachmawali, 2024)

Table 3.1. Chemical composition of Bamboo Stem Ash

S/No	Composition	%
1	Silicon dioxide (SiO ₂)	24.0 – 68.8%
2	Potassium oxide (K ₂ O)	2.7 – 34.2%
3	Calcium oxide (CaO)	1.0 – 11.9%
4	Magnesium oxide (MgO)	5.8 - 6.7%
5	Sulphur trioxide (SO ₃)	0.4 – 14.1%
6	Aluminium oxide (Al ₂ O ₃)	0.1 – 0.5%
7	Iron oxide (Fe ₂ O ₃)	0.1 – 0.8%

The Split tensile strength of concrete is an indirect test method used to determine resistance to pulling forces and cracking. absence of cracking is important in maintaining the continuity of a concrete structure for diminishing the corrosion of reinforcement, the liquid retaining structures, for aesthetics, etc.

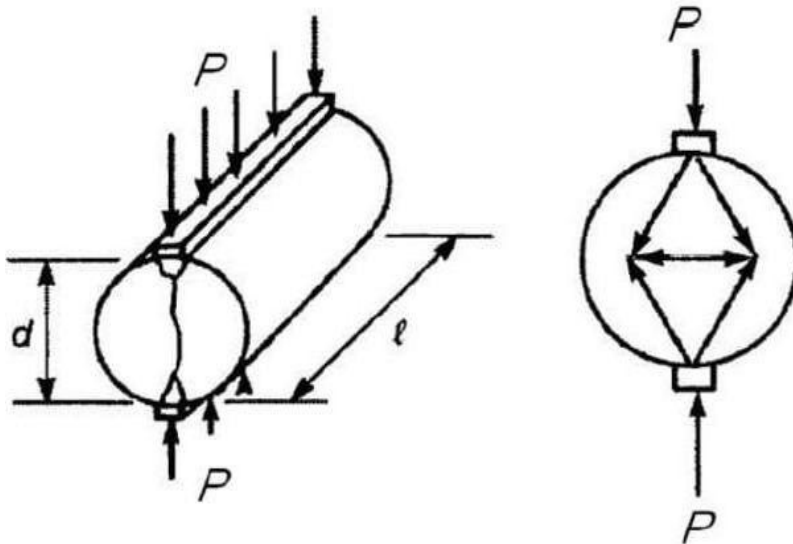


Figure 3.1. Splitting tensile tests experiment

The experiments were implemented according to ASTM C496 and BS EN 12390-6, which involve placing horizontally a standard cylinder of concrete specimen between the loading surfaces of Compression testing machine, then applying a compression load along diametrical axis (figure 3.1) of the cylinder until failure on the vertical plane. To allow for uniform distribution of this applied load a strip of plywood is placed between the specimen and loading platens of the testing machine. Concrete cylinder split into two halves along the vertical plane due to indirect tensile stress generated by poisons effect.

Assuming concrete specimen behaves as an elastic body, a uniform lateral tensile stress acting along the vertical plane can be calculated from the following formula:

$$f_{ct} = \frac{2P}{\pi LD}$$

where, f_{ct} is the split tensile strength, P is maximum load at failure, L is the length of the cylinder, and D is the diameter of the cylinder.

The splitting cylinder test gives values of about 1.05-1.15 times those obtained from direct tension test.

DISCUSSION OF RESULTS

Concrete mixtures containing 0%, 5%, 7.5%, and 10% bamboo stem ash were investigated for split tensile strength with both air-curing and water-curing conditions

Workability of fresh concrete mixtures:

The property of hardened concrete directly depends on property and quality of fresh concrete produced, because the production process involve transition from the plastic state through curing to hardened (solid) concrete (Afolabi and Edidi, 2025). The workability test is determined by performing slump test according to standard specifications (BS EN 12350-2).

Table 4.1. Slump values of BSA-Cement Concrete

Test No	BSA percent	Slump value	Comment
1	0 %	150 mm	High workability
2	5 %	50 mm	Low-Medium workability

3	7.5 %	40 mm	Low workability
4	10 %	60 mm	Medium workability

The workability results in table 4.1 indicated that inclusion of BSA improves stability of BSA-Cement concrete with decrease in slump values between 40mm and 60mm, thus defining a workable fresh concrete mixture (BS EN 12350-2:2019)

Split tensile strength of BSA-Cement concrete

Split tensile strength test provides valuable information regarding the cracking resistance, bond characteristics, and overall structural integrity of concrete. Split tensile strength test offers a simpler and more reliable means of evaluating the tensile behaviour of concrete and therefore considered adequate method in both research and engineering practice. In the present study the split tensile strengths of cylindrical concrete specimens (150 mm × 300 mm) containing varying proportions of bamboo stem ash (BSA) cured in air and water were evaluated.

Table 4.2. Result of Split tensile strength test of air cured BSA-Cement concrete

BSA Percent	3 days (N/mm ²)	7 days (N/mm ²)	14 days (N/mm ²)	21 days (N/mm ²)	28 days (N/mm ²)	42 days (N/mm ²)
0%	1.74	1.45	2.16	1.70	1.42	1.60
5%	1.42	1.84	1.75	1.68	1.78	1.73
7.5%	0.86	1.06	0.92	1.08	1.14	1.26
10%	1.00	1.10	1.02	1.22	1.23	1.30

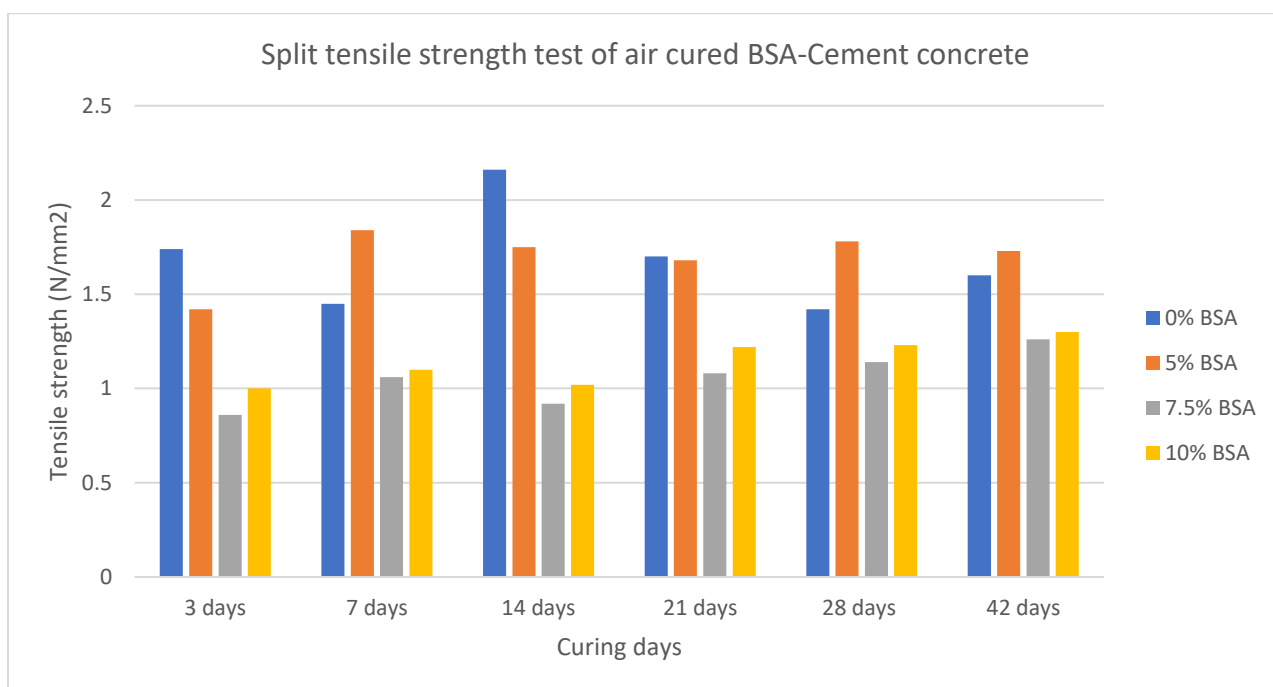


Figure 4.1. Split tensile Strength of air cured BSA-cement concrete

Table 4.2 and Figure 4.1 are the laboratory results of split tensile strength of concrete cured in air with 5% replacement level having comparative behaviour as the control (0% BSA), with maximum tensile strength of 1.78 N/mm² occurring at 28 days which is slightly higher than 0% BSA of 1.60 N/mm² at the same curing period, though the overall maximum was unexpectedly 2.16 N/mm² at 14 days for the control concrete mix.

Table 4.3. Results of Split tensile strength test of water cured BSA-Cement concrete

BSA Percent	3 days (N/mm ²)	7 days (N/mm ²)	14 days (N/mm ²)	21 days (N/mm ²)	28 days (N/mm ²)	42 days (N/mm ²)
0%	6.5	6.7	8.1	7.5	7.5	6.2
5%	5.6	6.2	8.7	8.0	8.4	8.9
7.5%	3.6	5.0	6.5	6.1	6.3	6.7
10%	3.4	4.0	5.4	4.9	5.6	5.4

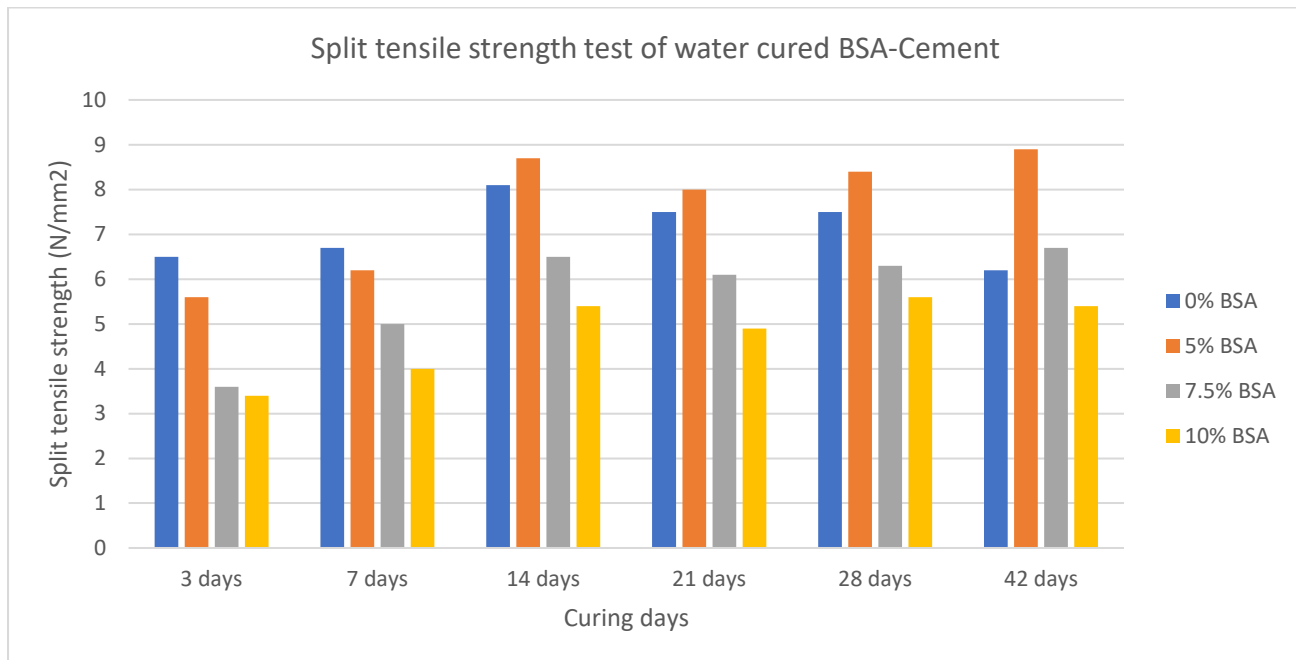


Figure 4.2. Split tensile Strength of water cured BSA-cement concrete specimen

Table 4.3 and Figure 4.2 are laboratory results of split tensile strength of concrete cured in water, with 5% BSA level tensile strength behaviour having close comparison with the control (0 % BSA), Also maximum splitting tensile strength of 8.7 N/mm² occurred at 14 days curing at 5 % BSA replacement level, and the control strength was 8.1 N/mm² . Split tensile strength at 28 days was 7.5 N/mm² and 8.4 N/mm² for the control and 5% BSA respectively

CONCLUSION

The workability results indicated that inclusion of BSA improves stability of BSA-Cement concrete with decrease in slump values between 40mm and 60mm, thus defining a workable fresh concrete mixture

Water curing BSA-Cement concrete consistently produced higher mechanical strengths than air curing because continuous moisture availability promoted more complete cement hydration and enhanced the pozzolanic reaction of bamboo stem ash

Splitting tensile strength increased progressively with curing age for all BSA-Cement concrete mixtures, indicating continuous hydration and gradual development of the cementitious microstructure, with increase in intermolecular bonds of the cementitious binder matrix

The 5% bamboo stem ash replacement level consistently produced the highest mechanical performance among the modified concretes. At this replacement level, the beneficial filler effect and secondary pozzolanic reactions effectively compensated for the reduction in cement content.

Bamboo stem ash can therefore be recommended as a sustainable supplementary cementitious material capable of reducing Portland cement consumption while maintaining satisfactory structural performance at moderate replacement levels.

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