Bond Strength of Self-Sensing Concrete (SSC) Incorporating Biomass-Activated Carbon

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Abstract

Self-sensing concrete (SSC) has emerged as a multifunctional smart material that combines structural performance with self-monitoring capabilities, offering significant potential for structural health monitoring. In this study, biomass-activated carbon (BAC) was incorporated into SSC as a supplementary cementitious material to investigate its impact on bond strength. While BAC is known to enhance electrical resistivity and compressive strength, its effect on interfacial bonding behaviour has not been comprehensively evaluated. Therefore, this study aims to assess the bond strength of SSC incorporating BAC (SSC-BAC). The mix design of SSC-BAC is based on C25/30, which consists of ordinary Portland cement (OPC), silica fume, BAC, sand, and water. Cube specimens were prepared for the compression test. Meanwhile, rectangular and prism specimens were prepared for the slant shear and three-point bending tests. Experimental tests revealed that the compressive strength decreases as BAC content increases. A similar trend was also observed in the bond strength. The threshold for the compressive strength is 31.54 MPa produced by 1% BAC. Meanwhile, 3% BAC has the lowest acceptable bond strength. The findings of this study suggest that SSC-BAC exhibits a strong bonding behaviour, which is suitable for application in structural health monitoring.

1. Introduction

In recent years, the demand for advanced and intelligent materials in civil engineering has increased significantly, primarily driven by the pursuit of structural durability and sustainable practices [1]. One promising solution is self-sensing concrete (SSC), a smart material that enables real-time monitoring. SSC offers more advantages over conventional approaches in structural health monitoring. Currently, structural health monitoring relies heavily on costly external sensors, such as accelerometers, fibre optic devices, and laser-based instruments, which limit sensitivity and coverage [1], [2]. In contrast, SSC integrates sensing capability directly into the concrete matrix, enabling real-time detection of strain, stress, and damage. thereby supporting proactive maintenance strategies and enhancing the service life of infrastructure [3]-[5]. SSC itself can be referred to as an internal sensor.

The self-sensing capability of SSC is commonly achieved through the inclusion of conductive additives that modify the electrical resistivity of concrete mixtures. Among many available conductive additives, biomass-activated carbon (BAC) has emerged as an eco-friendly and effective option. BAC derived from waste materials such as bamboo, coconut shells, palm oil kernels, wood sawdust, jute, and rubber leaves offers a high surface area and porosity, enhancing its mechanical and electrical properties [5], [6]. BAC may also be classified as one of the supplementary cementitious materials that can be utilised to support green construction [7]-[9].

Traditionally valued for its adsorption properties, BAC has found new utility in concrete mixtures. Its inclusion enhances electrical resistivity, which directly contributes to better sensing capability. As a result, SSC incorporating BAC (SSC-BAC) may function effectively as a smart sensing material. However, the underlying bonding mechanisms and performance characteristics of SSC-BAC remain underexplored. Until recently, there was limited literature about the bond strength of SSC-BAC with normal concrete or steel. This hinders the optimisation of SSC-BAC, especially in the application for overlays, embedded layers, and patch repairs [10].

Bond strength governs the viability of SSC-BAC, particularly in determining its compatibility and compositeness with existing structural components. The performance of SSC-BAC as an internal sensor depends heavily on its ability to form strong bonding behaviour with the substrate. While many supplementary cementitious materials, particularly fly ash and silica fume, have shown strong potential in enhancing bond strength through microstructural effects [11], [12], BAC lacks specific research on its bonding behaviour. Preliminary data suggest that BAC improves conductivity and certain mechanical properties, but adverse effects related to porosity may potentially compromise bond strength. It is well known that an increase in porosity reduces interfacial cohesion and subsequently has a negative influence on the bond strength.

Therefore, a systematic investigation evaluating both shear and flexural bonding characteristics is essential to prove the reliability of SSC-BAC, especially in structural health monitoring. Although significant progress has been made in the mechanical properties and electrical resistivity of SSC-BAC [13], its bond strength remains ambiguous. Without a comprehensive understanding of bonding behaviour, the application of SSC-BAC remains uncertain. Therefore, this study aims to investigate the bond strength of SSC-BAC through a series of experiments. Specifically, this study focuses on evaluating the bond strength using slant shear and three-point bending tests to observe the ultimate strength and failure mechanisms at the bond interface between SSC-BAC and normal concrete.

2. Methodology

This study aims to evaluate the bond strength of SSC-BAC, where BAC is used as a supplementary cementitious material. The study consists of three main stages: (i) materials preparation, (ii) specimen preparation, and (iii) experimental testing.
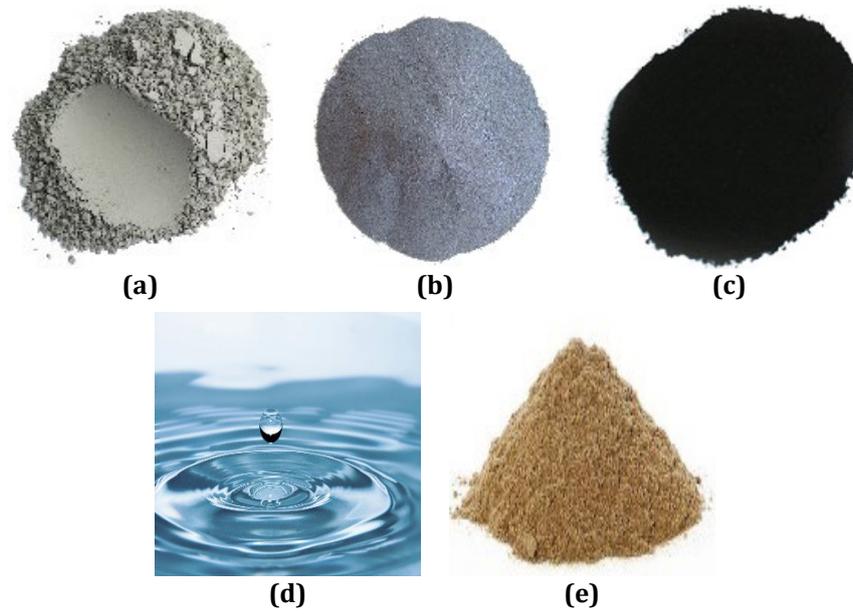
2.1 Materials Preparation

The raw materials used in producing SSC-BAC include ordinary Portland cement (OPC), silica fume, BAC, sand, and water. OPC functions as the primary binder in the concrete mixtures, while silica fume was used as a 10% partial cement replacement to enhance the microstructure and reduce porosity. The quality of silica fume is 10% of the cement weight. Meanwhile, BAC was added into the concrete mixtures at 1%, 3%, and 5% of the cement weight. BAC was obtained from a pyrolysis of agricultural waste. Clean and dry river sand serves as the fine aggregate, and potable water was used for the hydration process and to provide the necessary plasticity and workability. A control mix without BAC was also prepared for a comparison.

The mix design of SSC-BAC was formulated to achieve a targeted strength of C25/30. The mix design is 0.5 for a cement-to-sand ratio (C/S) and 0.5 for a water-to-cement ratio (W/C). All raw materials were mixed to ensure uniform dispersion of the constituents. OPC, silica fume, BAC and sand were blended first, followed by the gradual addition of water to create a consistent and workable concrete paste. The prepared mix was then used to cast the designed specimens. Fig. 1 shows the raw materials used in the production of SSC-BAC.
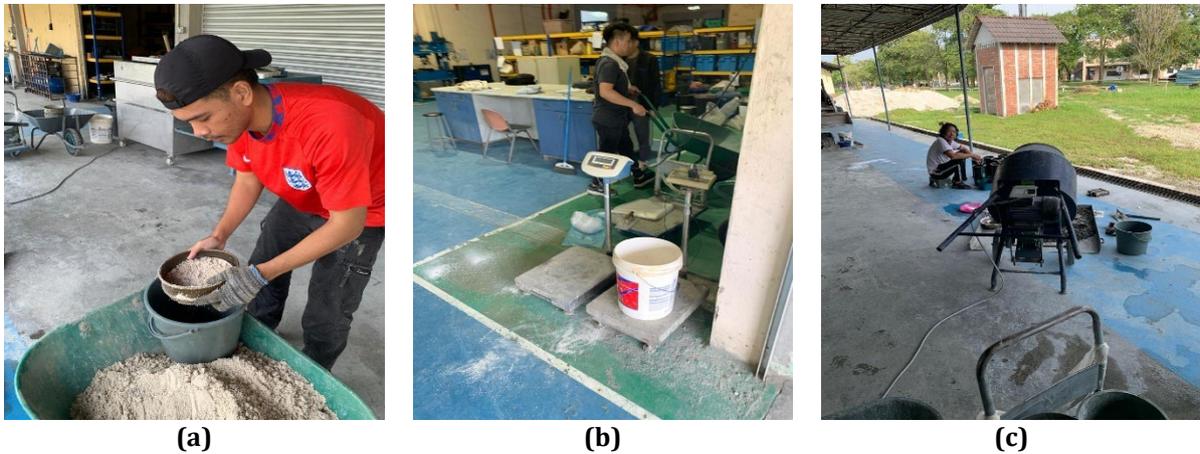
2.2 Specimens Preparation

A total of 48 specimens were prepared for the experiments. These consist of 24 cube specimens for the compression test, 12 rectangular specimens for the slant shear test, and 12 prism specimens for the three-point bending test. The cube specimens are 100 mm × 100 mm × 100 mm in size, while the rectangular specimens have a constant surface of 100 mm square and a height of 400 mm. On the other hand, the size of prim specimens is 160 mm × 40 mm × 40 mm. All specimens were cast using standard steel moulds and were cured under controlled laboratory conditions for 7 and 28 days.

The mixing process began with a control batch made of concrete mixtures without BAC, followed by concrete mixtures of 1%, 3%, and 5% BAC. The process of specimens preparation is presented in Fig. 2. After mixing, a slump test was conducted for each batch to evaluate the workability of the fresh concrete prior to casting. Fig. 3 shows the measurement of slump height. The lowest slump height was measured at 31 mm for 5% BAC, indicating a low-workability mix. According to BS EN 12350-2 [14], this corresponds to a stiff consistency, typically associated with lower water content and the presence of fine granular. Despite the reduced slump, all concrete mixtures remained workable with adequate compaction, and no segregation or bleeding was observed.

Fig. 1 *Raw materials for SSC-BAC - (a) Cement; (b) Silica fume; (c) BAC; (d) Water; and (e) Sand*

Fig. 2 *The process of specimens preparation - (a) Sieving; (b) Weighing; and (c) Mixing*

Fig. 3 *Measurement of slump height*

While the preparation of cube specimens was straightforward, the casting of rectangular and prism specimens required special procedures. For the rectangular specimens, the interface between the SSC-BAC and normal concrete was cast at a 45° angle, as recommended by Haber et al. [15] and Diab et al. [16]. In preparing the

rectangular specimens, the normal concrete was poured first and allowed to settle for approximately one hour before SSC-BAC was added. For prism specimens, the mould was divided longitudinally, with one half filled with SSC-BAC and the other half with normal concrete. The schematic details of rectangular and prism specimens are illustrated in Fig. 4.
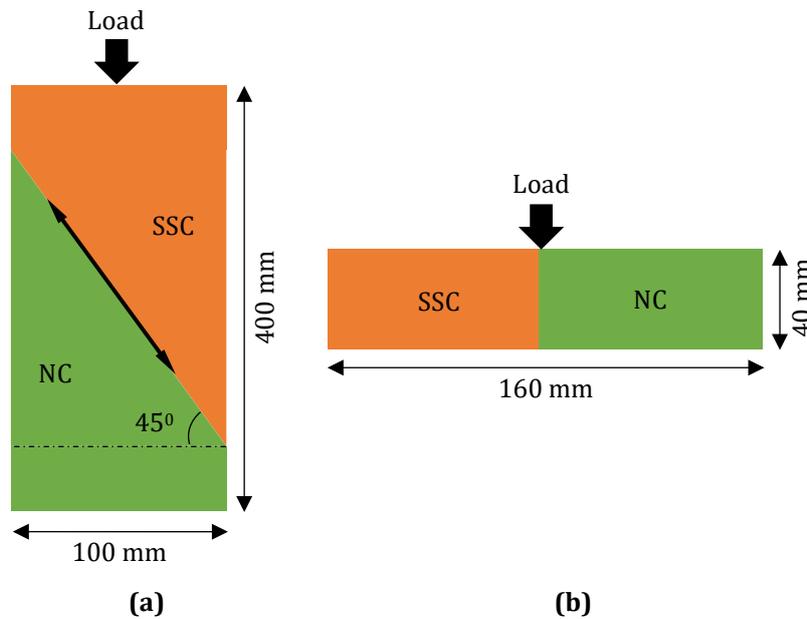

Fig. 4 *Schematic details - (a) Rectangular specimens; and (b) Prism specimens*

2.3 Experimental Tests

Three experimental tests were conducted to assess the bond strength and failure mechanism. After 7 and 28 days of curing, compression tests were performed on cube specimens using a Universal Testing Machine (UTM) in accordance with BS EN 12390-3 [17]. Meanwhile, the slant shear and three-point bending tests were conducted on the rectangular and prism specimens at 28 days of curing. The slant shear test is based on BS EN 12615 [18], where the gradually increasing load at a rate of approximately 0.14 MPa/min to 0.34 MPa/min was imposed until the rectangular specimens experienced failure. This ensures uniform stress distribution and reduces the likelihood of sudden failure as per standard guidelines. During the test, a vertical compression load was applied to generate stress along the interface, inducing failure in the form of cohesive, adhesive, and mixed-mode failure. A cohesive or mixed-mode failure generally indicated strong bonding, while adhesive failure suggested weaker interface performance.

The three-point bending test was conducted on prism specimens to evaluate flexural strength and failure mechanism in accordance with BS EN 12390-5 [19]. The prism specimens were loaded steadily at a rate of 0.55 MPa/min until fracture. The flexural strength of prism specimens was calculated using Eq. (1), while the deflection at the mid-span was directly measured using a linear variable differential transformer (LVDT). All tests involved in this study are shown in Fig. 5.
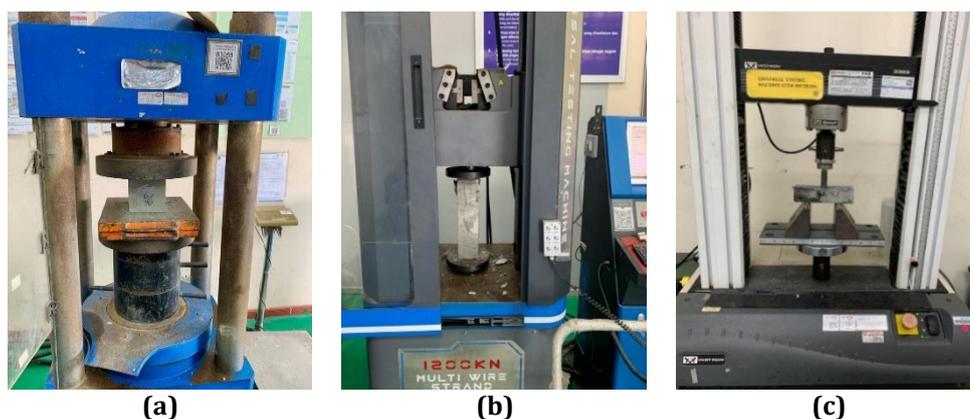

Fig. 5 *Experimental tests - (a) Compression test; (b) Slant shear test; and (c) Three-point bending test*

3. Results and Discussion

Results obtained from the experimental tests provide a clear understanding of the strength characteristics, bonding behaviour and failure mode of SSC-BAC. The compressive strength from the compression test shows the achievement of compressive strength of SSC-BAC at 7 and 28 days, corresponding to BAC contents (1%, 3% and 5%). Meanwhile, the results of bond strength from shear slant and three-point tests indicate the bond performance between SSC-BAC and normal concrete.

3.1 Compressive Strength

The compressive strength of SSC-BAC at 7 and 28 days is shown in Fig. 6. By adding BAC in concrete mixtures, the compressive strength gradually decreases from 35.16 MPa for 0% BAC to 22.91 MPa for 5% BAC. This trend suggests that BAC contribute to the negative effects on the strength characteristics due to the physical characteristics that interfere with the hydration process and the microstructure of hardened concrete. The presence of BAC introduces additional voids, making concrete less dense, which directly lowers its compressive strength. In addition, BAC was found to have poor particle packing, which does not pack efficiently with fine aggregate and causing higher interparticle voids. During the mixing process, it was observed that BAC observes a large amount of water, which leads to the formation of a weaker C-S-H gel. The decreases in C-S-H gel may also be due to the dilution effects, where BAC does not contribute to cementitious reactions. Considering the targeted strength of SSC-BAC is C25/30, only 1% BAC is suitable for producing SSC-BAC. However, the utilisation of 3% BAC is still adequate for the load-bearing structures.
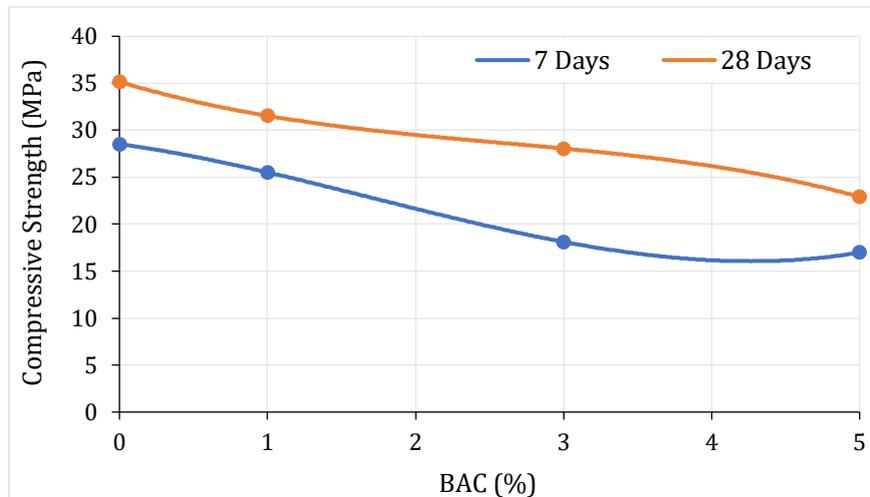

Fig. 6 *Compressive strength of SSC-BAC*

3.2 Bond Strength

The slant shear test yields the results of shear bond strength, which signify the maximum shear stress a bonded interface can resist before failure. Shear bond strength indicates the ability of SSC-BAC to resist the shear force that acts parallel to the interface. The value is directly obtained from the slant shear test, which is represented by the peak strength. Meanwhile, the three-point bending test yields the ultimate strength. This value is vital in the calculation of the flexural bond strength, as in the following equation:

$$f = \frac{3PL}{2bd^2} \tag{1}$$

where f is the flexural bond strength, and P is the ultimate strength retained by the prism specimens. Meanwhile, L, b and d represent the length and cross-section dimension of the prism specimens. The three-point bending test is used to determine the flexural bond strength by applying a concentrated load at the mid-span of prism specimens. This setup induced bending stress, allowing the evaluation of the material's resistance to flexural failure. Fig. 7 shows the bond strength of SSC-BAC from the slant shear and three-point bending tests.

It can be clearly observed that the bond strength has a declining trend when the BAC content increases from 0% to 5%. This trend is similar to the compressive strength, indicating that the bond strength is likely governed by the compressive strength. Typical design bond stresses for normal concrete (C25/30 to C40/50) fall roughly in the range of 1.5 MPa to 3.0 MPa. In this study, the design bond stresses were identified as 4.13 MPa for 0% BAC, 3.43 MPa for 1% BAC, 2.37 MPa for 3% BAC, and 1.03 MPa for 5% BAC. Therefore, the use of 3% BAC is acceptable

in concrete mixtures. The range of design bond stresses may prevent slip, delamination, premature failure and reduced load-carrying capacity.
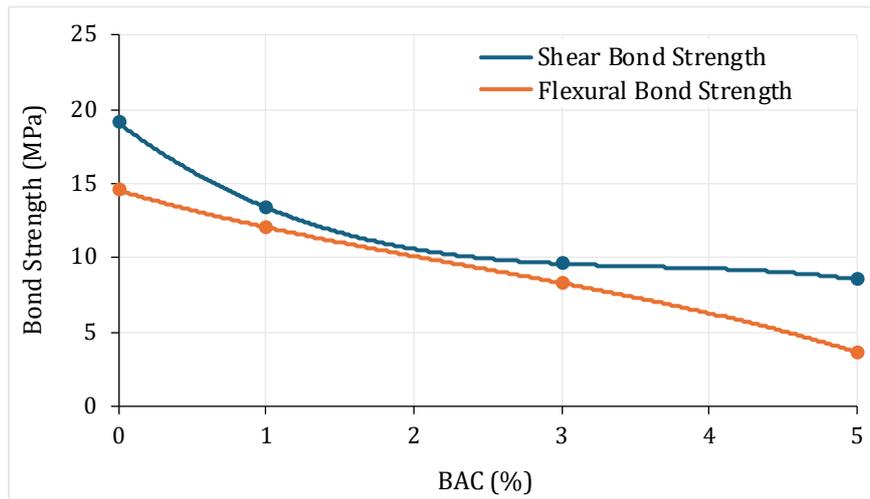

Fig. 7 *Bond strength of SSC-BAC*

The correlation between flexural bond strength and shear bond strength, as shown in Fig. 8, can be fitted as the following equation:

$$f_{b,y} = -0.1241f_{b,v}^2 + 4.3613f_{b,v} - 23.563 \tag{2}$$

where $f_{b,y}$ is the flexural bond strength and $f_{b,v}$ is the shear bond strength. This correlation highlights the potential to predict the bond strength based on either the results of the slant shear test or the three-point bending test, providing a practical approach for evaluating the bond strength of SSC-BAC.
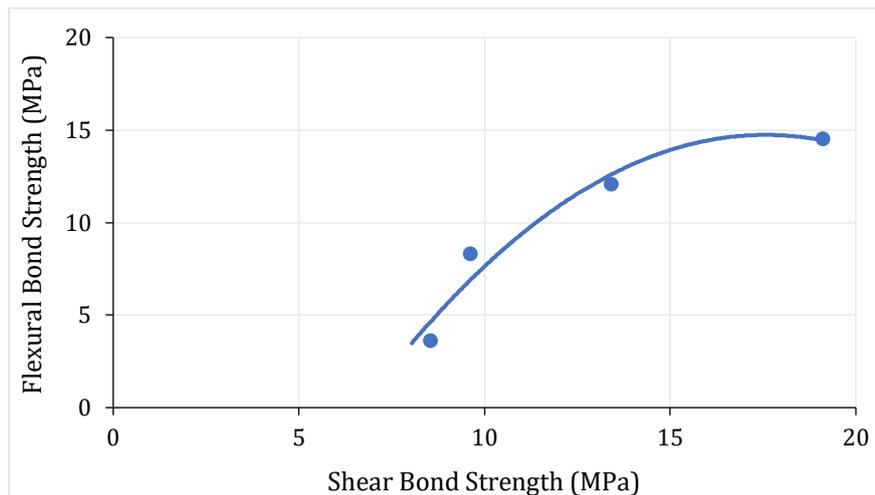

Fig. 8 *Correlation between flexural bond strength and shear bond strength*

3.3 Failure Mode

Fig. 9 illustrates the failure modes of prism specimens under slant shear and three-point bending tests. A typical failure mode was observed for BAC content of 0% to 5%. When subjected to the slant shear test, all prism specimens suffer cohesive or mixed-mode failure. This shows that SSC-BAC have strong bonding behaviour. However, prism specimens with higher BAC content, especially those with 5% BAC, showed severe adhesion failure, indicating weaker interface performance. In the three-point bending test, flexural failure developed from the vertical crack propagation. These cracks are expected to develop within the interface of SSC-BAC and normal concrete. As concrete is weak in tension, the cracks initiate at the bottom side of the mid-span of the prism specimens. This region experiences flexural bond stresses and a concentration of bond demand near cracks. As the load increases, the flexural bond strength eventually becomes low. This leads to the cracks widening

excessively, and their length becomes more apparent, causing a complete split between SSC-BAC and normal concrete.

(a)   **(b)**
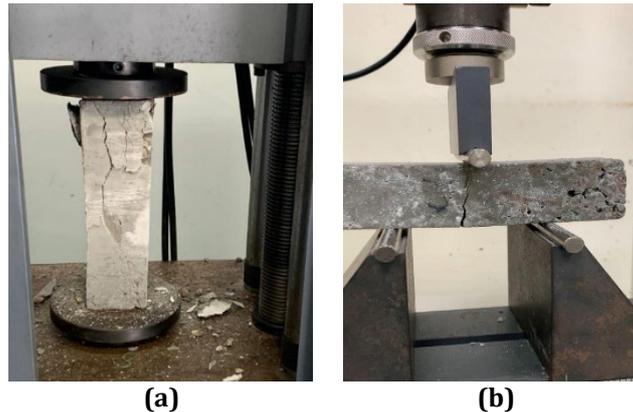
Fig. 9 *Failure mode of SSC-BAC - (a) Under slant shear test; and (b) Under three-point bending test*

4. Conclusion

This study investigates the bond strength of SSC-BAC, where the BAC content ranges from 0% to 5%. The compression test was conducted to determine the compressive strength. It was found that the compressive strength reduced in corresponding to the BAC content. A similar trend also occurred in the bond strength. The flexural and shear bond strengths decrease as the BAC content increases. Despite the declining trend in compressive and bond strengths, SSC-BAC retains a good performance at 3% BAC. Higher BAC content is attributed to the higher porosity of the concrete mixtures. Therefore, the hardened concrete becomes less dense, and consequently, its strength characteristics decrease. At 1% and 3% BAC, the design bond stresses of SSC-BAC were in the range of normal concrete. This indicates that SSC-BAC has a strong bond strength, preventing slip, delamination, premature failure, and reduced load-carrying capacity. However, further investigation is needed to understand the correlation between bond strength and electrical resistivity.

Acknowledgement

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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