

## Flexural Behavior of Tin Slag Polymer Concrete under Three-Point Bending: An Experimental Study

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### Abstract

This research aims to investigate the flexural properties of tin slag polymer concrete (TSPC) as a sustainable alternative construction material. The primary objective is to assess the flexural strength, strain behavior, and failure modes of TSPC using experimental methods. TSPC specimens were prepared by mixing 70% fine tin slag particles (<1 mm) with 30% polyester resin and Methyl Ethyl Ketone Peroxide (MEKP) catalyst, then cast into prismatic beams (25×25×100 mm) and tested under three-point bending in accordance with ASTM C78. The results show that TSPC-S1 achieved the highest flexural strength (48.97 MPa) and strain (0.0137), while TSPC-S3 had the lowest values (37.26 MPa, 0.0081). On average, TSPC exhibited flexural strength of 44.87 MPa, modulus of elasticity of 6.22 GPa, and a brittle failure mode with minimal plastic deformation. All specimens showed uniform fracture surfaces and consistent crack patterns, reflecting material homogeneity and low ductility. Compared to conventional concrete (4–6 MPa), TSPC demonstrates up to tenfold improvement in flexural performance. In conclusion, TSPC offers high flexural strength but limited ductility, suggesting the need for reinforcement to improve energy absorption. The study confirms the potential of tin slag as a beneficial additive for enhancing polymer concrete in structural applications.

**Key Words:** Tin Slag; Polymer Concrete; Flexural Strength; Three-Point Bending; Sustainable Materials; Brittle Failure

### 1.0 Introduction

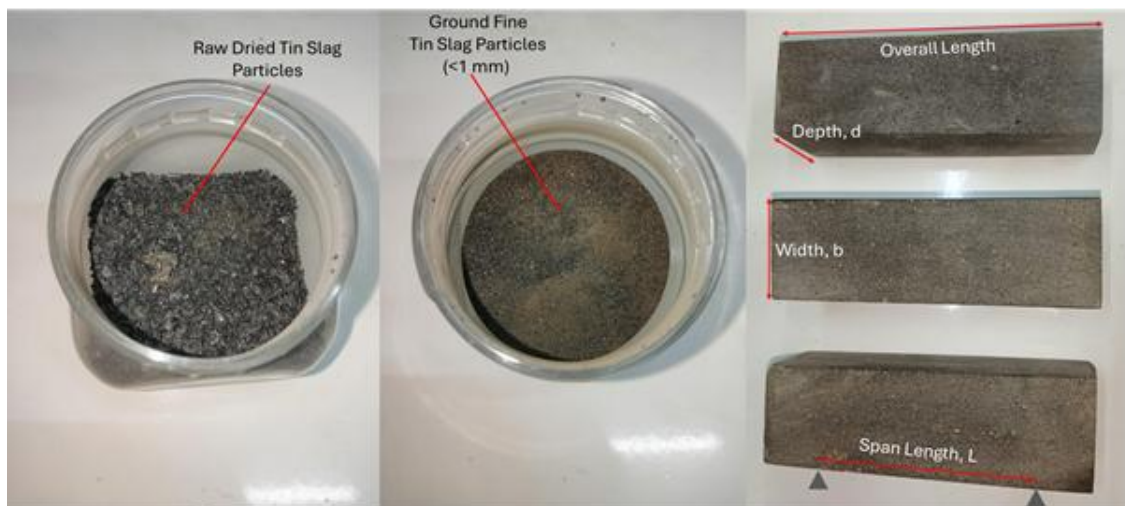
Polymer concrete has emerged as a sustainable alternative construction material owing to its enhanced mechanical properties and reduced environmental footprint compared to traditional cement-based concrete (Manda et al., 2023; Hassan et al., 2021; Shiravi et al., 2023). The usage of industrial by-products such as tin slag as a fine aggregate replacement is increasingly investigated to improve resource efficiency and material performance (Khoo et al., 2023; Olukotun et al., 2021). Tin slag (TS), a notable waste from the tin smelting industry, possesses unique physical and chemical characteristics that contribute positively to the concrete matrix, including improved bond strength and microstructural densification (Hassan et al., 2020). Previous studies reveal that compressive strength of tin slag polymer concrete (TSPC) has achieved 58.37 MPa (Manda et al., 2023) without any reinforcement and has been successfully enhanced to 156.88 MPa (Hassan et al., 2021) with fiber reinforced polymer (FRP) jacketing. In comparison to conventional cement concrete (10-50 MPa), Mebarkia & Vipulanandan (1990) has reported that polymer concrete strength was at least three times stronger as proven on TSPC. Beyond compressive strength, flexural properties are also critical for structural applications due to their ability to characterize tensile capacity and cracking resistance under bending loads (Sharma et al., 2023). Despite extensive research on compressive and tensile behaviors of tin slag polymer concrete (TSPC), notably by Manda et al. (2023), there remains a scarcity of detailed experimental studies investigating its flexural strength. Previous studies have reported that the flexural strength of common concrete beam was 4.53 MPa (Arora, 2015), 4.97 MPa (Ibrahim et al., 2015) and 5.39 MPa (Aminuddin et al., 2015), indicating that the flexural strength range for concrete was between 4.0 MPa to 6.0 MPa. Investigating flexural performance of TSPC and understanding flexural behavior is vital because failure under bending is a predominant mode in many structural components where tensile stresses are pronounced. Therefore, experimental validation coupled with an analysis of how tin slag replacement as polymer concrete's filler/

reinforcement influences flexural properties is necessary for paving the way toward practical applications. The key objective of this study is to investigate the flexural strength of TSPC with several prismatic specimens for consistent measures in mechanical properties, failure pattern and fracture surface through experimental.

## 2.0 Materials and Method

### 2.1 Materials

The binder system that has been applied was polyester resin with 2 % of Methyl Ethyl Ketone Peroxide (MEKP) as catalyst, which offers good adhesion and compatibility with the aggregates, as reported by Hassan et al. (2020; 2023) and Manda et al. (2022). Tin slag sourced from the final processing stage of tin production is dried for 2 hours with 200°C temperature in a drying oven and ground to a fine size (passing <1 mm sieve), making it appropriate for use as fine aggregate replacement (Abu Hassan et al., 2020; Olukotun et al., 2021). Uniform grading was chosen based on previous aggregate gradation and replacement percentages study as documented by Khoo et al. (2023) and Hassan et al. (2021). The wet mixture with pre-determined ratio of matrix binder and aggregates (30:70) was cast into PVC mould of prismatic specimens (Manda et al., 2022). Figure 1 shows raw materials, ground TS particles and geometry of the TSPC specimen.



**Figure 1:** Materials and geometry of the TSPC specimen

### 2.2 Sample Preparation

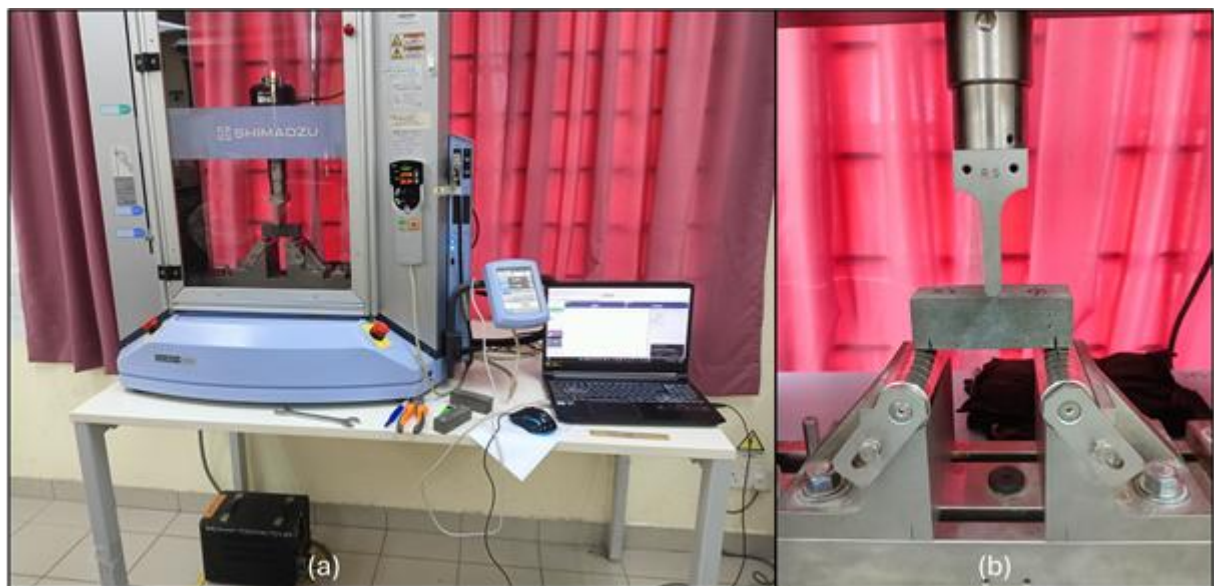
The polymer concrete mix designs are tailored to produce three prismatic (25 x 25 x 100 mm) specimens of TSPC-S1, TSPC-S2 and TSPC-S3, maintaining consistent binder to aggregate ratios 30:70 (Olukotun et al., 2021; Khoo et al., 2023). The specimen preparation is based on (ASTM C192/470) standard specifications for making and curing concrete test specimens. Then the specimens are moulded into beam shapes conforming with recognized testing standards (ASTM C78) and cured under room temperature conditions for 7 days to achieve full polymerization and representative properties (Manda et al., 2023). Table 1 classified TSPC test sample listing composition and final geometry of each specimen after final trimming.

**Table 1:** Composition and final geometry of each specimen

| <i>Specimen</i> | <i>Composition</i>                  | <i>Depth,<br/>d (mm)</i> | <i>Width,<br/>b (mm)</i> | <i>Overall<br/>Length<br/>(mm)</i> | <i>Span<br/>Length,<br/>L (mm)</i> | <i>Weight<br/>(g)</i> |
|-----------------|-------------------------------------|--------------------------|--------------------------|------------------------------------|------------------------------------|-----------------------|
| <i>TSPC-S1</i>  | 70 % Fine<br>Tin Slag<br>Particles  | 30                       | 30                       | 100                                | 80                                 | 200                   |
| <i>TSPC-S2</i>  | (<1mm) +<br>30 %                    | 28                       | 28                       | 100                                | 80                                 | 165                   |
| <i>TSPC-S3</i>  | Polyester<br>Resin with 2<br>% MEKP | 25                       | 25                       | 100                                | 80                                 | 100                   |

### 2.3 Experimental Setup

Flexural testing is performed using three-point loading setups (ASTM C78) to measure bending strength, employing displacement sensors to monitor deformation and cracking behaviour accurately (Sharma et al., 2023; Shiravi et al., 2023). The set-up was referred to previous testing on other TSPC sample as reports by Manda et al. (2023). Main testing machine employed is 50kN Shimadzu universal testing machine (UTM) with three-point test jig and fixture incorporating both bottom support and top loading apparatus. The loading rate was set at 0.30 mm/min strain rate according to standard (ASTM C78), to achieve optimum steady loading action. Specimen geometry, testing parameter setting, test expected output parameters and results are performed using Trapezium software. Figure 2 describes the testing machine, software integration and specimen placement on test jig.



**Figure 2:** Experimental setup. (a) Testing machine and software integration. (b) Specimen placement on testing jig and fixture.

### 2.4 Data Analysis

The entire study involves both quantitative and qualitative analysis where mechanical properties measured from experimental test, results in primary data for loading and displacement. Then, the secondary data derived from experimental data and specimen geometry producing the flexural strength, strain and Young's modulus (modulus of elasticity) based on equation (1), (2) and (3).

$$\sigma = \frac{3FL}{2bd^2} \quad (1)$$

$$\varepsilon = \frac{\Delta L}{L} \quad (2)$$

$$E = \frac{\sigma}{\varepsilon} \quad (3)$$

Where,  $\sigma$  = flexural strength (MPa),  $F$  = bending load (N),  $L$  = span length (mm),  $b$  = width (mm),  $d$  = depth (mm),  $\varepsilon$  = flexural strain,  $\Delta L$  = bending displacement (mm), and  $E$  = Young's modulus/ elastic modulus (GPa). Other than that, fractured patterns and fractured surface of all specimens were also analyzed to describe failure modes of TSPC bar under flexural loading.

### 3.0 Results and Discussion

#### 3.1 Flexural Properties

Table 2 presents the flexural properties data for all TSPC specimens; TSPC-S1, TSPC-S2, and TSPC-S3, tested under 3-point flexural loading conditions. TSPC-S1 recorded the highest maximum load (11.02 kN) and strength (48.97 MPa), along with the greatest displacement (1.098 mm) and strain (0.0137), indicating superior load-bearing capacity and moderate ductility. TSPC-S2 showed a slightly lower strength (48.39 MPa) but had the highest modulus of elasticity (7.43 GPa), suggesting it was the stiffest material among the three. In contrast, TSPC-S3 demonstrated the lowest values across most parameters, with a maximum strength of 37.26 MPa and strain of 0.0081, reflecting the least mechanical performance and highest brittleness. On average, the TSPC samples exhibited a flexural strength of 44.87 MPa, a strain capacity of 0.0106, and a modulus of elasticity of 6.22 GPa, highlighting that while TSPC has good strength and stiffness, its brittle nature limits its deformation capacity. However, in comparison with cement concrete (4-6 MPa), the flexural strength of TSPC beam (30-50 MPa) has attained more strength than expected which has reached almost 10 times stronger without any reinforcement application.

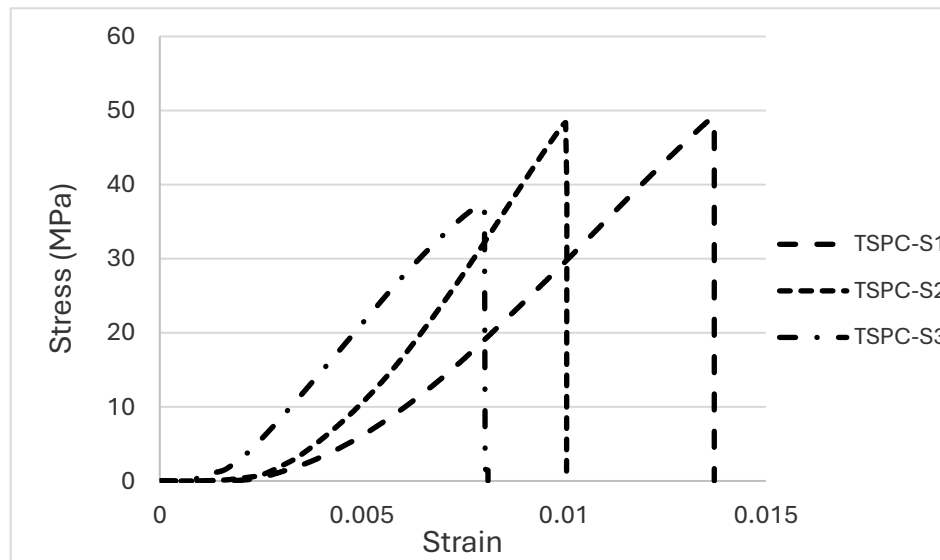
**Table 2:** Flexural properties data for TSPC-S1, TSPC-S2, TSPC-S3 AND average value.

| Specimen | Max. Load (kN) | Max. Displacement (mm) | Max. Strength (MPa) | Max. Strain | Modulus of Elasticity (GPa) |
|----------|----------------|------------------------|---------------------|-------------|-----------------------------|
| TSPC-S1  | 11.02          | 1.098                  | 48.97               | 0.0137      | 5.27                        |
| TSPC-S2  | 8.85           | 0.806                  | 48.39               | 0.0101      | 7.43                        |
| TSPC-S3  | 4.85           | 0.869                  | 37.26               | 0.0081      | 5.96                        |
| Average  | 8.24           | 0.924                  | 44.87               | 0.0106      | 6.22                        |

#### 3.2 Stress Versus Strain Curve

The stress versus strain curve in Figure 3 illustrates the flexural behavior of all test specimens; TSPC-S1, TSPC-S2, and TSPC-S3. All specimens display an initial linear region indicating elastic behavior, followed by a sharp drop in strength after reaching peak load, signifying brittle failure. TSPC-S1 exhibits the highest flexural strength (48.97 MPa) and stiffness but fails shortly, indicating low ductility. TSPC-S3 shows the lowest flexural strength (37.26 MPa) and a little strain capacity (0.0081), making it the most brittle and

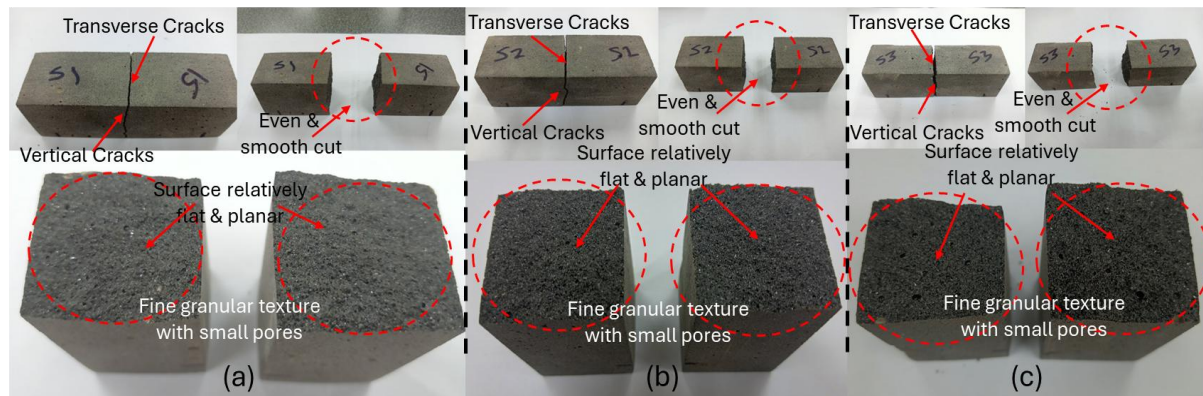
least resistant to flexural loads. In contrast, TSPC-S3, with slightly lower strength than TSPC-S1, demonstrates the highest strain at failure, suggesting improved ductility and energy absorption capacity. Overall, TSPC-S1 is the strongest, TSPC-S2 is the most ductile, and TSPC-S3 performs weakest in both aspects (stress and strain). However, from the stress versus strain curve of its flexural behaviour, TSPC can be described as a material which exhibits linear elastic response followed by a sudden brittle failure, indicating high stiffness with limited ductility.



**Figure 3:** Flexural behaviour of all test specimens; TSPC-S1, TSPC-S2, and TSPC-S3

### 3.3 Failure Modes

Figure 4 shows the failure modes of all test specimens, TSPC-S1, TSPC-S2 and TSPC-S2. The crack pattern for all specimens consistently indicates transverse crack on top side and vertical crack on front side. This crack pattern describes that the failure occurred due to tensile effect from the bending load without any shearing effect. This condition occurs because the aggregates was uniformly graded with 100% fine tin slag particles, resulting in unidirectional resistance towards bending load, thus break with smooth and even cut. This explanation was reflected towards common diagonal crack pattern in concrete beam with gaps or well graded aggregates of coarse, medium and fine size particle mixtures where the failure was due to shearing effect. The shearing occurs because the resistance toward bending load was distributed and spread in many directions. Then, all the test specimens were split into two even and symmetrical parts without any scattered fragments or chips, which confirm the uniform mixture of aggregates and binders throughout the specimen. Finally, evaluation on fractured surface reveals higher level of consistency where for all specimens, the fracture surface is relatively flat and planar, indicating a sudden and brittle crack propagation with minimal plastic deformation. The fine granular texture and the presence of small pores across the surface suggest some degree of porosity, likely due to entrapped air or incomplete compaction during casting. The fracture path appears straight with no significant deviation, reflecting low fracture toughness and a homogeneous distribution of materials. Overall, the fractured surface reveals that the TSPC bar has limited energy absorption capacity under flexural stress, which is typical of rigid and brittle composite materials and actual application would require reinforcement to enhanced ductility as well as overcoming brittle and sudden failure.



**Figure 4:** Failure modes for all test Specimens (a) specimen TSPC-S1 (b) Specimen TSPC-S2 (c) Specimen TSPC-S3

#### 4.0 Conclusion

This study demonstrates that Tin Slag Polymer Concrete (TSPC), formulated with 70% finely ground tin slag and 30% polyester resin, exhibits impressive flexural strength with average of 44.87 MPa surpassing the performance of conventional concrete. The experimental results also reveal the flexural behaviour of TSPC as a material with high stiffness and strength, though inherently brittle, as indicated by its clean and uniform fracture patterns. These findings not only highlight structural potential of TSPC but also reinforce its value as a sustainable construction material by effectively utilizing industrial waste. However, its limited ductility suggests the need for reinforcement strategies to ensure resilience under real-world conditions. Moving forward, further research should explore long-term durability, reinforcement integration, and advanced modeling techniques to fully realize the practical application of TSPC in modern infrastructure.

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