

# Mechanical, Physical, and Morphological Characteristics of Concrete Incorporating Wastewater Treatment Plant Sludge as a Supplementary Cementitious Material

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## ABSTRACT

The production of wastewater treatment plant (WWTP) sludge is constantly increasing due to global population growth, posing significant environmental challenges related to its sustainable management. This study aims to present an innovative approach for reusing dried waste sludge (DSS) as a cementitious additive in concrete production, contributing to reducing waste generated by WWTPs and mitigating negative environmental impacts. DSS was incorporated into concrete mixtures by replacing cement at levels of 0%, 5%, 10%, and 15% by weight. The mechanical properties of the resulting concrete, including compressive, tensile, and flexural strengths, were evaluated after 7, 14, and 28 days of curing. Additionally, microstructural and compositional analyses were performed using XRD, XRF, and SEM techniques. The results showed that the incorporation of DSS affects the mechanical properties of concrete, with a strength reduction of up to 40% observed when 5% of cement was replaced by DSS. These results indicate the potential of DSS as a sustainable alternative to conventional cement, with further studies needed to improve mechanical performance and balance sustainability with structural efficiency.

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## INTRODUCTION

Concrete is the most widely used construction material globally, and demand for it is expected to continue growing due to urban expansion and the development of smart infrastructure (Kumar & Daniyal, 2025).

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However, the production of cement, the main component of concrete, contributes between 5% and 8% of total global carbon dioxide emissions, making it a major source of industrial pollution (Ethaib et al., 2020; Phougat & Nitu, 2025). In light of these environmental challenges, the need has emerged to develop sustainable concrete by partially replacing traditional concrete components with alternative materials with a lower environmental impact, known as supplementary cementitious materials (Dabbaghi et al., 2021; Hassan et al., 2020).

The increasing population on the planet leads to an increase in sludge production. For example, in China and the United States alone, it is estimated that about 10 million tons (dry matter) and 20 million tons of sludge respectively, are produced annually (Erabee & Ethaib, 2018b), leading to a greater need for waste disposal. The most prominent methods of final disposal of waste are disposal in soil, sanitary landfills, and incineration. However, these processes are not ideal solutions because they are likely to raise a number of technical and environmental problems, including odor emissions from these landfills, active diseases spread by these wastes, and contamination of soil and groundwater due to their components or uncontrolled leakage (Erabee & Ethaib, 2018b; Ethaib et al., 2015). Hence, these concerns have led researchers to look for different and feasible alternative methods for the final disposal of sludge that can be applied to allow some benefit without harm (Erabee & Ethaib, 2018a; Ethaib et al., 2015).

Among these alternatives, industrial sludge, particularly dried sludge from wastewater treatment plants (DSS), is one of the most promising materials that has received the attention of researchers in recent years (Xu et al., 2025). DSS contains oxides such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{Fe}_2\text{O}_3$ , which are major components of cement clinker, giving it pozzolanic and hydraulic properties that qualify it for use in concrete (Al-Obaidi et al., 2025; Fini et al., 2024; Lin et al., 2024).

Studies indicate that using DSS as a partial substitute for cement can contribute to reducing the consumption of natural resources, lowering production costs, reducing carbon emissions, and reducing the volume of solid waste generated by treatment plants (Al-Obaidi et al., 2025; Fini et al., 2024; Phougat & Nitu, 2025). DSS was tested in concrete mixes at different replacement ratios (5%, 10%, 15%), and mechanical tests such as compressive and flexural strength were conducted, along with compositional analyses using XRD, XRF, SEM, and TGA techniques (Al-Obaidi et al., 2025; Waghmare, 2020).

Environmentally, incorporating sludge into concrete is an innovative solution for recycling industrial waste, reducing reliance on landfills and reducing pollution from incineration or unsafe disposal of sludge (Fini et al., 2024). Using DSS in applications such as pavements, concrete blocks, and low-load buildings is a practical option for reducing environmental impact without significantly compromising structural performance (Al-Obaidi et al., 2025).

Despite significant progress in the use of DSS as a partial cement replacement in concrete, scientific literature still suffers from significant research gaps that limit the potential for widespread industrial application of this technology. Most current studies focus on one aspect of sludge use, without providing a comprehensive and integrated view linking treatment, formulation, performance, and environmental applications. One of the most notable gaps is the lack of systematic reviews comparing the effects of different sludge treatment methods, such as thermal drying versus incineration, on the physical and chemical properties of the sludge and, consequently, its performance as a cement replacement. The chemical properties of DSS and sewage sludge ash (SSA) have revealed the concentration of important oxides, including  $\text{Fe}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{CaO}$ , and  $\text{Al}_2\text{O}_3$ . The treatment method directly affects the content of active oxides such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ , which are essential for the pozzolan reaction in concrete (Fini et al., 2024). However, most studies are still limited to the use of a single treatment type without a comparative analysis of the impact of each method on the performance of the resulting concrete. Ethaib et al. (2020) indicated that sludge properties vary significantly depending on the treatment method, calling for systematic comparative studies to determine the optimal method. Most studies focus on short curing periods, without examining concrete behavior under realistic service conditions such as exposure to moisture, thermal changes, or aggressive environments. This represents a critical gap, especially if this concrete is to be used

in construction or environmental applications that require long-term performance. Numerous studies have addressed the preparation of cement substitutes using industrial sludge, focusing on collection and processing methods, as well as on the properties of the resulting materials, such as density, flexural strength, compression, and microscopic analysis (Shi et al., 2025; Zdeb et al., 2022). Advanced analytical techniques such as SEM, XRD, and XRF were also used to determine the mineral and chemical composition of the materials (Shi et al., 2025). Phougat & Nitu (2025) noted that concrete modified with secondary materials may exhibit gradual deterioration in harsh environments, necessitating extensive durability tests that include abrasion, permeability, and freeze-thaw resistance. Finally, there are currently no clear standards or guidelines defining the optimal ratios for cement replacement with sludge, which balance structural performance with environmental sustainability (Mojapelo et al., 2025). Suggested ratios vary widely between studies, typically ranging from 5% to 20%, with no scientific consensus on the optimal ratio that ensures the preservation of the concrete's basic mechanical properties (Mandlik & Karale, 2018). Feitosa et al. (2023) and Kumar & Daniyal (2025) discussed the importance of developing design criteria that take into account the type of sludge, its curing method, and the concrete's end-use conditions. Addressing these research gaps is essential to enhance the reliability of DSS use in concrete and to open the way for broader, more sustainable applications in the construction sector, especially in light of the global trend toward a circular economy and reducing the carbon footprint of construction materials.

Accordingly, this study aims to fill some of these gaps through a comprehensive evaluation of the impact of replacing cement with different proportions of DSS derived from wastewater treatment plants (WWTPS) on the mechanical and structural properties of concrete, with a focus on potential environmental applications and its role in supporting the circular economy in the construction sector.

## METHODOLOGY

### Materials preparations

Ordinary Portland cement of the first type (compliant with Iraqi Specification No. 5 of 2019) was used in all concrete mixes. The coarse aggregate was made from local river gravel, crushed and graded to a maximum size of 14 mm, in accordance with Iraqi Specification No. 45-1984 [IQS No.45-1984]. The fine aggregate was made from river sand taken from the Samarra region (Tigris River), in accordance with Iraqi/Region III Specification No. 45/1984. Tap water was used for mixing and processing, ensuring that the concentration of dissolved salts was less than 1000 ppm.

### Collection and preparation of industrial sludge

Dried sludge was collected from the Baghdad wastewater treatment plant, where it was stored and transported in sealed containers at temperatures below 40 °C to prevent bacterial growth. The sludge underwent cleaning processes to remove impurities and was then oven-dried at temperatures between 100 and 300 °C for 24 hours to reduce moisture. Selecting this temperature range achieves a balance between moisture removal (Feitosa et al., 2023), inhibition of biological activity, and preservation of the chemical and physical properties of the sludge (Fini et al., 2024), making it the ideal choice for preparing sludge for use in concrete (Al-Obaidi et al., 2025). The dried sludge was then sieved through a 300 µm sieve to obtain a uniform particle size. The sludge was accurately weighed before being added to concrete mixes at specific weight replacement ratios (0%, 5%, 10%, and 15%).

### Replacement of cement with industrial sludge

Four sets of concrete mixes were prepared, in which cement was partially replaced with dried sludge at ratios of 0% (reference mix), 5%, 10%, and 15% by weight of cement. The components were mixed in a

mechanical mixer at constant speed and time until a homogeneous mixture was obtained. The mixture was poured into cubic (150 x 150 x 150 mm) and cylindrical (150 mm diameter, 300 mm height) molds, with the molds shaken well to remove air bubbles. The samples were cured in a curing room at a temperature of 20–25 °C and relative humidity of 90–95% until the required test ages (7, 14, and 28 days) were reached. A series of mechanical and structural tests was conducted to evaluate the effect of replacing cement with DSS on concrete properties. These tests included measuring the fresh and dry density of concrete using the volumetric method to determine the effect of different replacement ratios on concrete specific gravity. Compressive strength tests were also performed on concrete cubes aged 7, 14, and 28 days using a hydraulic compression tester to evaluate the concrete's ability to withstand axial loads. Furthermore, flexural strength tests were performed on prismatic specimens (100 x 100 x 500 mm) to analyze the behavior of concrete under flexural loads and determine its impact on the sludge addition.

### **Physical, mechanical, and analytical tests of concrete**

A series of laboratory tests was conducted to evaluate the physical, mechanical, and structural properties of concrete produced with different DSS replacement ratios. The aim was to understand the effect of this material on concrete performance at different ages. These tests included measuring compressive strength, density, and flexural strength, in addition to structural analyses using XRD, XRF, and SEM techniques.

#### **Compressive test**

Compressive strength testing was performed on concrete cubes and cylinders aged 7, 14, and 28 days using a hydraulic press. The maximum load before failure was recorded, and the compressive strength was calculated in MPa.

A compressive strength test was conducted on concrete elements to evaluate their mechanical properties and determine the rate of strength development of the concrete over time. The test involved concrete cubes and cylinders that were cured and calibrated under standard conditions and then tested at ages of 7, 14, and 28 days to measure the strength increase resulting from the gradual development of hydration processes within the concrete paste.

The test utilized a hydraulic compression press calibrated according to standard concrete testing criteria. The specimens were centrally positioned between the jaws of the press, ensuring uniform load distribution across the specimen surface. The load was gradually increased at a constant rate until failure. Upon recording the maximum load that the specimen could withstand before failure, the compressive strength was calculated in MPa using the standard formula that considers the ratio of the recorded load to the cross-sectional area. This test contributes to assessing the quality and structural efficiency of the concrete mix, as well as evaluating the impact of mix proportions, curing methods, and operating conditions on mechanical properties. It provides a reliable scientific basis for comparing practical results and verifying their conformity to design requirements and engineering standards.

#### **Density test**

A density test was conducted to study the effect of adding dried waste sludge (DSS) on the apparent density of concrete. Density is a crucial physical property directly related to concrete strength and quality. The test methodology involved accurately measuring both the mass and volume of the dry sample. A calibrated electronic scale was used to ensure precise mass measurements, while the volume was determined by measuring the sample's geometric dimensions using precision measuring instruments. Prior to the measurements, the samples underwent a thermal drying process in an electric oven at a constant temperature for a sufficient duration to ensure complete moisture removal and prevent any influence of moisture on the results.

### **Flexural strength**

The concrete flexural strength test was performed using an Automatic Flexural Testing Machine, model LT-C0650 Flexural Testing Assembly for Concrete Beams (made in Turkey), according to the three-point bending method and in accordance with the standard ASTM C78. The test aims to determine the ability of concrete to withstand stresses resulting from bending, where the load is gradually applied in the middle of the specimen until the moment of breakage, and the maximum bearing force is recorded to calculate the flexural strength.

### **X-ray diffraction (XRD) analysis**

X-ray diffraction (XRD) analysis was performed to determine the crystalline structure of the mineral components in the concrete mix. This contributes to understanding the chemical reactions resulting from replacing some conventional materials with dried waste sludge (DSS). This analysis helps identify the mineral phases formed during the hydration process, as well as any changes in crystal structure resulting from the addition. The Bruker D8 Advance X-ray Diffraction System (XRD), manufactured in Germany, was used in this test.

### **X-ray Fluorescence (XRF) analysis**

X-ray fluorescence analysis was performed to determine the chemical composition of major and minor elements in concrete mixes. This was done to evaluate the effect of replacing some conventional components with dried waste sludge (DSS) on the overall composition of the concrete. This analysis helps determine the proportions of oxides such as SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, Fe<sub>2</sub>O<sub>3</sub>, and others, which are directly related to the mechanical and chemical properties of the concrete. The Bruker S8 TIGER X-ray Fluorescence Spectrometer (XRF), manufactured in Germany, was used in this test. This high-precision instrument measures the intensity of fluorescence emitted by excitation of the sample with X-rays, providing accurate quantitative data on the elemental composition.

### **Scanning electron microscope (SEM)**

Scanning electron microscopy (SEM) was used to examine the microstructure of concrete to study pore distribution, the degree of cohesion between components, and the effect of replacing some conventional materials with dried waste sludge (DSS) on the internal structure. This analysis provides important insights into microscopic changes that affect the mechanical properties and long-term durability of concrete. The ZEISS Sigma VP Field Emission Scanning Electron Microscope (FESEM), manufactured in Germany, was used in this examination.

## **RESULTS AND DISCUSSION**

### **Concrete mix design calculations**

The concrete mix design calculations are conducted for a target compressive strength of 30 MPa and a slump of 100 mm, assuming a total volume of 1 cubic meter for simplicity. The free water/cement ratio for the target strength is determined to be approximately 0.45 by the American Concrete Institute (ACI) code (2016). The free-water content required for the targeted workability is calculated using an empirical equation from the ACI code for a 100 mm slump, resulting in 280 kg/m<sup>3</sup>. This leads to determining the cement content as 622 kg/m<sup>3</sup>. The total aggregate content is calculated by subtracting the combined mass of cement and water (902 kg/m<sup>3</sup>) from the target density of the concrete (2400 kg/m<sup>3</sup>), which equals 1498 kg/m<sup>3</sup>. It is assumed that the fine aggregate, natural sand with a fineness modulus of 2.5, and the coarse aggregate, crushed granite with a maximum size of 20 mm, comprise 40% and 60% of the total aggregate

content, respectively. This results in an acceptable aggregate content of 599 kg/m<sup>3</sup> and a coarse aggregate of 899 kg/m<sup>3</sup>.

The results of the effect of DSS incorporation on concrete strength and workability, which are directly affected by water-cement ratio, DSS incorporation, and overall mix design of DSS concrete with variable replacement ratios, are listed in Table 1, which shows how the mix ratios change with variable replacement ratios.

Table 1. Proportions of mix components for various percentages of replacement in concrete

Replacement (%)	W/C Ratio	Cement (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Fine Aggregate (kg/m <sup>3</sup> )	Coarse Aggregate (kg/m <sup>3</sup> )	Sludge (kg/m <sup>3</sup> )
0	0.45	622.0	280	599	899	0.0
5	0.45	590.9	280	599	899	74.9
10	0.45	559.8	280	599	899	149.8
15	0.45	528.7	280	599	899	224.7

### Concrete cube strength

Compression tests were carefully conducted on concrete cubes (150 x 150 x 150 mm) at ages of 7, 14, and 28 days, using different DSS replacement ratios of 0%, 5%, 10%, and 15%, as shown in Table 2. This evaluation aimed to investigate the effect of different replacement ratios on the mechanical properties of concrete, focusing on average compressive strength and density as key performance indicators.

The physical and mechanical properties of each cube were accurately recorded, including weight, average compressive strength (MPa), and density (kg/m<sup>3</sup>). The results, as shown in Fig. 1 and Fig. 2, demonstrate a clear relationship between cube age, replacement ratio, and their effect on compressive strength and density. In general, the concrete cubes showed a gradual increase in compressive strength with age, reflecting the evolution of concrete properties over time. For example, the average compressive strength of cubes with a 0% replacement ratio increased from 38.63 MPa after 7 days to 46.99 MPa after 28 days, with a slight decrease in density from 2386 to 2359 kg/m<sup>3</sup>.

Table 2. Average compressive strength and density of concrete cubes at different ages and different DSS replacement ratios (3 cubes per replacement)

Replacement (%)	Age (Days)	Average compressive strength (MPa)	Average density (kg/m <sup>3</sup> )
0	7	38.63 ± 0.15	2386 ± 1
	14	39.72 ± 0.15	2377 ± 1
	28	46.99 ± 0.10	2359 ± 1
5	7	26.16 ± 0.06	2303 ± 1
	14	27.06 ± 0.06	2309 ± 1
	28	29.15 ± 0.06	2282 ± 1
10	7	21.73 ± 0.06	2274 ± 1
	14	24.01 ± 0.00	2286 ± 1
	28	28.46 ± 0.06	2213 ± 1
15	7	27.14 ± 0.06	2291 ± 1
	14	30.52 ± 0.06	2294 ± 1
	28	35.53 ± 0.06	2292 ± 1

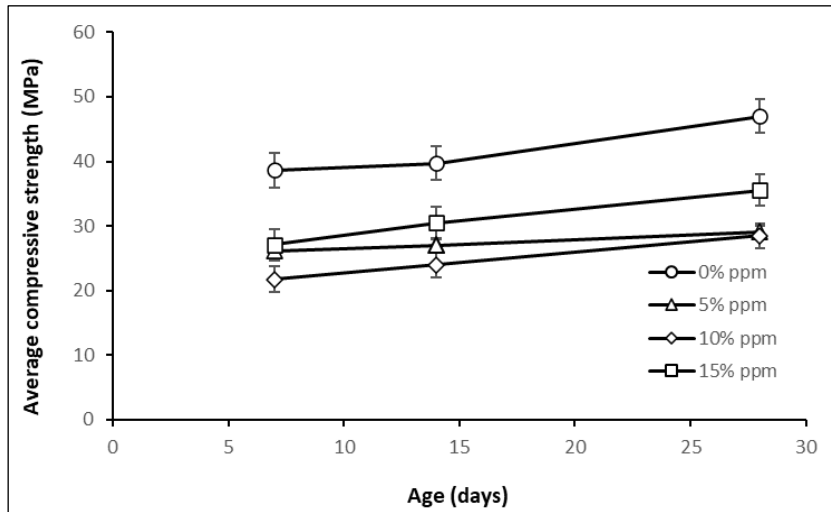


Fig. 1. Average compressive strength vs age for different DSS replacement ratios (3 cubes per replacement).

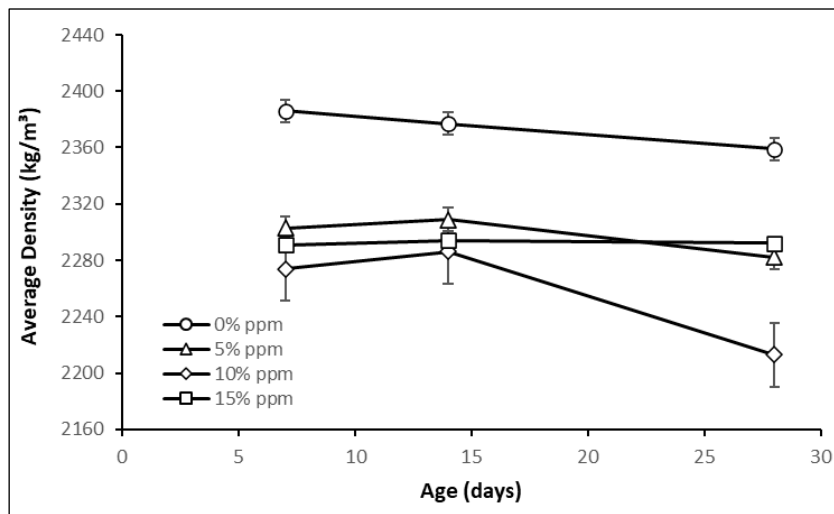


Fig. 2. Average density vs age, with different DSS replacement ratios (3 cubes per replacement).

The values obtained are consistent with the study by Mojapelo et al. (2025) which analyzed the effect of replacing cement with wastewater sludge ash (WSA), where the results showed that moderate replacement rates (up to 15%) lead to an initial decrease in compressive strength compared to the reference mix, but with continued treatment, internal cohesion increases as a result of pozzolanic reactions, thus improving strength in the long term.

Cubes containing 15% DSS showed a significant improvement in average compressive strength from 27.14 to 35.53 MPa over the same period, with a relative stability in density, ranging between 2291 and 2292 kg/m<sup>3</sup>. These results reflect the potential positive impact of certain replacement ratios on concrete

strength development and provide important insights for improving concrete mix design to meet structural performance requirements.

Interestingly, mixes containing 15% DSS, while exhibiting lower early compressive strength than the reference mix, showed a significant improvement at 28 days, reaching 35.53 MPa, a level acceptable for use in non-critical structural applications. This suggests that the pozzolanic reactions of the oxide-rich materials in DSS contributed to improved internal cohesion over time, partially compensating for the initial weakness caused by increased porosity. Furthermore, the slight decrease in density at high replacement ratios was not accompanied by a significant decrease in compressive strength, indicating that concrete can maintain good mechanical properties even with reduced weight, which is important in the design of lightweight structures. These trends are consistent with the study by Mojapelo et al. (2025).

It is also interesting that mixes with 5% DSS showed performance very close to the reference mix, indicating the possibility of replacing part of the traditional materials without negatively affecting compressive strength, which supports the trend towards sustainable concrete (Ahmad et al., 2023).

### Strength evaluation of concrete cylinders (300 x 150 mm)

A comprehensive evaluation of concrete properties was conducted through compression tests on 300 x 150 mm concrete cylinders at different ages (7, 14, and 28 days) using DSS replacement ratios of 0%, 5%, 10%, and 15%. This study aimed to analyze the effect of DSS replacement on the mechanical properties of concrete and determine its suitability as a replacement component in concrete mixes.

The tests included measuring the weight, average compressive strength (MPa), and density of each cylinder, as shown in Table 3. The results, as shown in Fig. 3 and Fig. 4, demonstrated that the replacement ratio clearly affects the strength and density of concrete. Increasing the DSS ratio led to a decrease in compressive strength, especially at early ages. For example, cylinders with a 0% replacement ratio increased their average compressive strength from 23.38 MPa after 7 days to 31.07 MPa after 14 days, then decreased slightly to 29.19 MPa after 28 days, with a relatively stable density between 2398 and 2406 kg/m<sup>3</sup>. In contrast, cylinders with 15% DSS exhibited lower strength, increasing from 14.93 MPa after 7 days to 18.78 MPa after 28 days, with a decrease in density from 2252 to 2271 kg/m<sup>3</sup>.

Table 3. Average compressive strength and density of concrete cylinders at different ages and different DSS replacement ratios (3 cylinders per replacement)

Replacement (%)	Age (Days)	Average compressive strength (MPa)	Average Density (kg/m <sup>3</sup> )
0	7	23.38 ± 0.06	2398 ± 1
	14	31.07 ± 0.06	2406 ± 1
	28	29.19 ± 0.06	2402 ± 1
5	7	19.50 ± 0.08	2304 ± 1
	14	24.08 ± 0.06	2320 ± 1
	28	25.81 ± 0.06	2347 ± 1
10	7	15.79 ± 0.06	2293 ± 1
	14	19.67 ± 0.06	2320 ± 1
	28	18.92 ± 0.06	2277 ± 1
15	7	14.93 ± 0.06	2252 ± 1
	14	16.00 ± 0.08	2271 ± 1
	28	18.78 ± 0.08	2271 ± 1

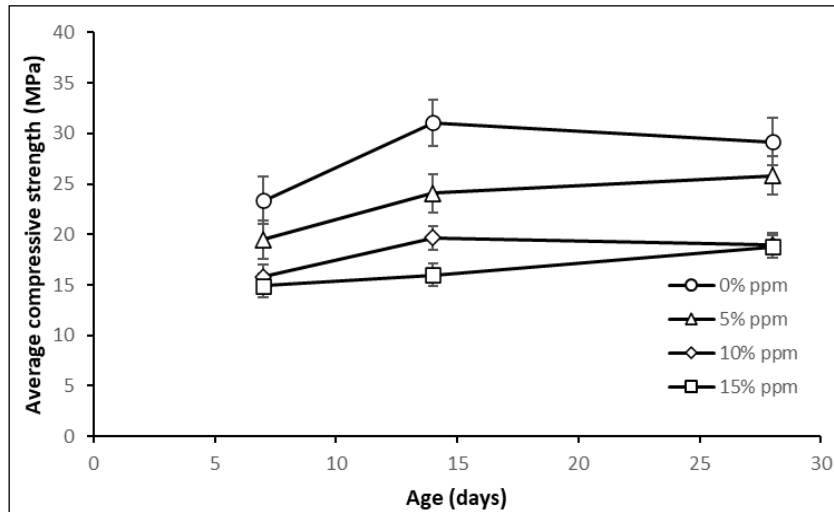


Fig. 3. Average compressive strength vs. different DSS replacement ratios (3 cylinders per replacement).

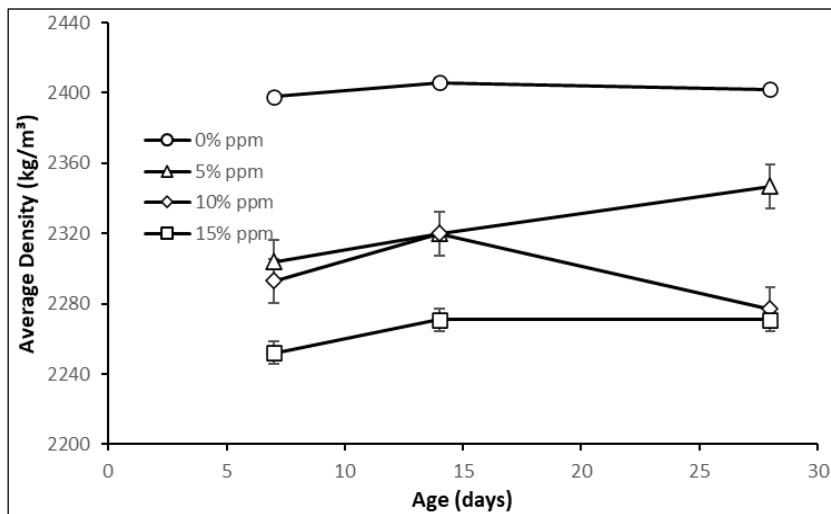


Fig. 4. Average density vs age with different DSS replacement ratios (3 cylinders per replacement).

Interestingly, mixes containing 5% DSS exhibited performance close to that of the reference mix at 28 days, suggesting the possibility of replacing some conventional materials without significantly impacting compressive strength, which supports the trend toward sustainable concrete. Furthermore, despite a significant decrease in strength at 15% DSS, the concrete retained a compressive strength exceeding 18 MPa, making it suitable for some non-structural applications.

The values obtained are consistent with the study by Amminudin et al. (2020), which analyzed the effect of replacing cement with DSS at 5–15% ratios. A decrease in strength was observed at higher ratios due to increased porosity, while moderate ratios showed acceptable performance.

A similar trend was found in the study by Vembu & Ammasi (2022), which used DSS as a replacement for fine aggregate. Their results showed that replacement up to 10% could improve some properties, but higher ratios led to a decrease in strength. A recent study by Shanthi Vengadeshwari et al. (2025) confirmed that the pozzolanic interactions in DSS contribute to improved long-term strength, despite poor early performance at high ratios.

### Analysis of concrete prism test results

The data gathered from testing concrete prisms (3 prisms per replacement) with dimensions of 500 x 100 x 100 mm provides insight into the impact of different replacement percentages on flexural strength over varying ages. Fig. 5 presents the flexural strength results for the various replacement percentages.

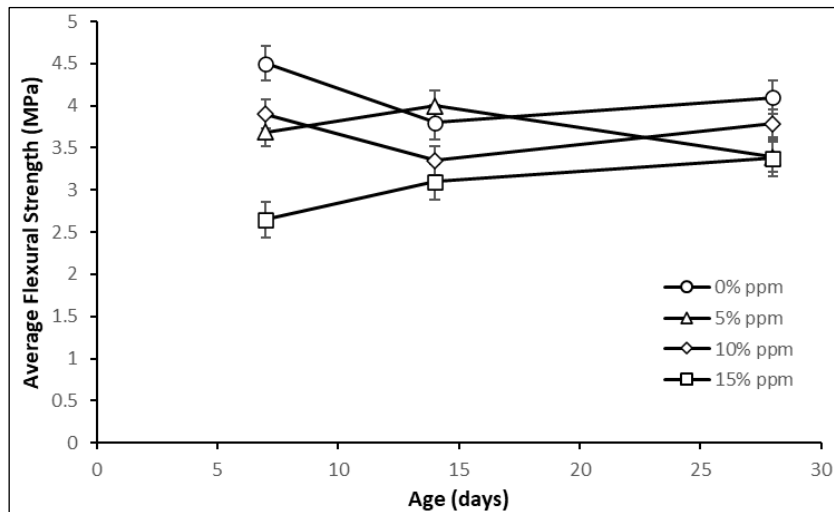


Fig. 5. Flexural strength results of concrete beams at different DSS replacement ratios (3 prisms per replacement).

The weight and density characteristics of each test group are presented in Fig. 6. Analysis of the concrete prism test results reveals several critical insights. A general inverse correlation is observed between the flexural strength of the concrete prisms and the percentage of material replacement, with higher replacement percentages corresponding to lower flexural strength across all curing ages. This underscores the superior structural integrity of concrete with lower replacement percentages (Ramirez et al., 2017). Notably, prisms with 0% replacement consistently exhibit the highest flexural strength, confirming that the original concrete composition is optimal for flexural resistance. While an initial strength gain is observed within the first seven days, particularly for prisms with higher replacement percentages, this strength tends to diminish over time, suggesting potential limitations in long-term performance.

Additionally, as the replacement percentage increases, the weight and density of the prisms decrease, likely due to the lower density of the replacement materials compared to the original concrete constituents. This reduction in density is accompanied by a decline in strength at higher replacement percentages after 28 days, raising concerns about compromised durability and long-term structural performance. These findings highlight the importance of balancing mechanical properties, sustainability, and cost-effectiveness when selecting materials for specific applications. Consequently, the results provide valuable guidance for material selection in construction, particularly in scenarios where structural integrity is paramount.

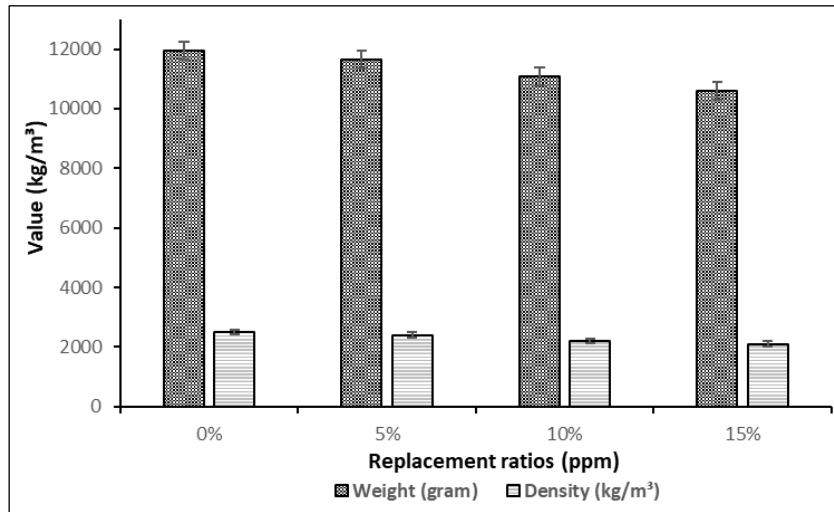


Fig. 6. Weight and density results of concrete prisms at different DSS replacement ratios.

### Comparative analysis

Concerning compressive strength, concrete with 0% replacement consistently demonstrates the highest values across 7, 14, and 28 days of curing, as shown in Fig. 7. The average strength increases from 38.63 MPa at seven days to 46.99 MPa at 28 days, reflecting a progressive solidification effect. However, at 5% replacement, a significant reduction in strength is observed, with averages decreasing to 26.16 MPa at seven days and reaching 29.15 MPa at 28 days, representing an approximate 40% reduction compared to 0% replacement. For 10% replacement, a further decline is noted, with averages of 21.73 MPa at seven days and 28.46 MPa at 28 days, indicating a more pronounced impact of DSS on strength. Interestingly, at 15% replacement, the initial strength at seven days (27.14 MPa) is higher than that of 10% replacement, and it improves significantly to 35.53 MPa at 28 days, suggesting a potential adaptive response of the concrete mix to DSS over time. These observations underscore the complex interplay between replacement percentages and concrete performance, warranting further investigation to optimize the use of DSS in concrete applications.

The concrete cylinders exhibit varying compressive strengths influenced by different DSS percentages, as shown in Fig. 8. At 0% replacement, the average compressive strength gradually increases from 23.38 MPa at seven days to 29.19 MPa at 28 days. With 5% DSS replacement, there's a noticeable decrease, averaging 19.50 MPa at seven days and slightly improving to 25.81 MPa at 28 days, approximately a 12% increase in strength over time. A more significant decline is observed at 10% replacement, starting at 15.79 MPa and only marginally rising to 18.92 MPa. At 15% replacement, the initial average is the lowest at 14.93 MPa but shows a notable increase to 18.78 MPa by 28 days. These results suggest a consistent pattern where higher DSS replacement rates initially decrease the compressive strength, but some recovery is evident over time.

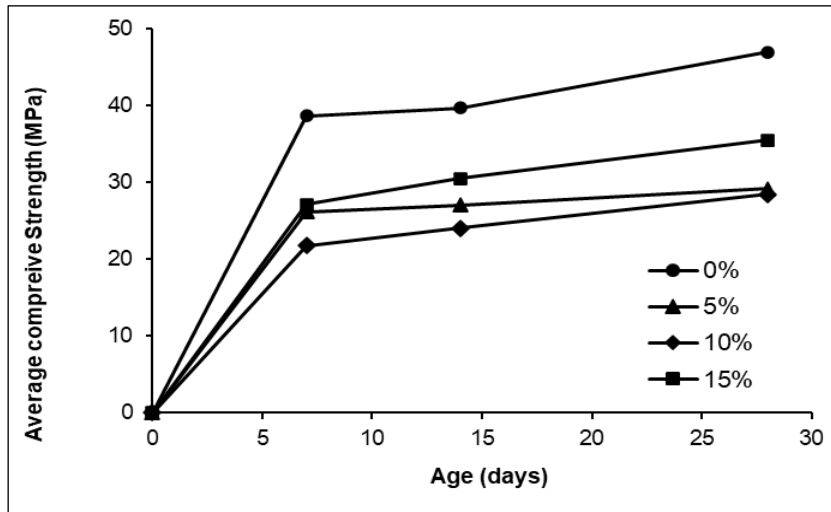


Fig. 7. Compressive strength comparison in concrete cubes at various DSS replacement ratios over time.

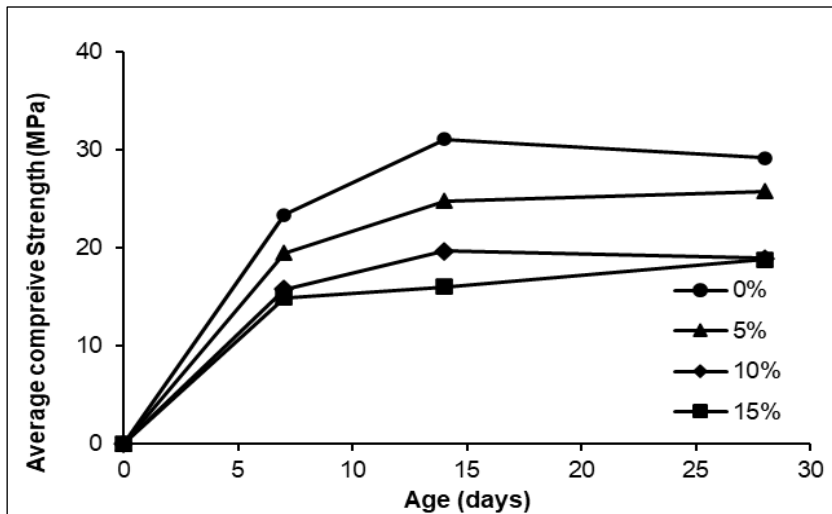


Fig. 8. Compressive strength variations in concrete cylinders with different DSS replacement rates over time.

The flexural strength of concrete posts containing varying percentages of DSS (0%, 5%, 10%, and 15%) was evaluated at different curing ages (7 and 28 days), as shown in Fig. 5. This study aimed to understand the effect of replacing DSS as an additive in concrete mixes on the mechanical performance of concrete and to determine its suitability for improving flexural properties.

The results showed a clear trend in the effect of replacement ratios on flexural strength. At a 0% replacement ratio, the average flexural strength was 4.47 MPa after 7 days and decreased slightly to 4.12 MPa after 28 days, indicating relative stability in performance. At a 5% replacement ratio, the strength started at 3.68 MPa and decreased to 3.35 MPa after 28 days, indicating a slight negative effect. In contrast, higher replacement ratios (10% and 15%) showed a greater decrease in strength at 7 days, recording 3.89

and 2.65 MPa, respectively, and then slightly improved after 28 days to reach 3.79 and 3.37 MPa. This limited improvement at later ages suggests that the effect of DSS is more pronounced in the early stages of curing, reflecting the initial interaction characteristics of the replaced material with the cement.

Fig. 9 shows compressive strength trends in concrete prisms with various DSS replacement percentages over time. A comprehensive statistical analysis was conducted on concrete compressive strength data obtained with different DSS replacement ratios to understand the extent of variation and identify general trends in mechanical performance. The results showed that the standard deviation and variance increased with increasing DSS ratios, indicating that mixes containing higher DSS ratios exhibit greater variation in strength. The data also indicates a nonlinear relationship between DSS ratio and reduced compressive strength, especially during the early stages of curing. These relationships can be further elucidated through regression analysis, which could produce accurate predictive models of concrete performance at different DSS replacement ratios, contributing to improved mix design according to structural performance requirements.

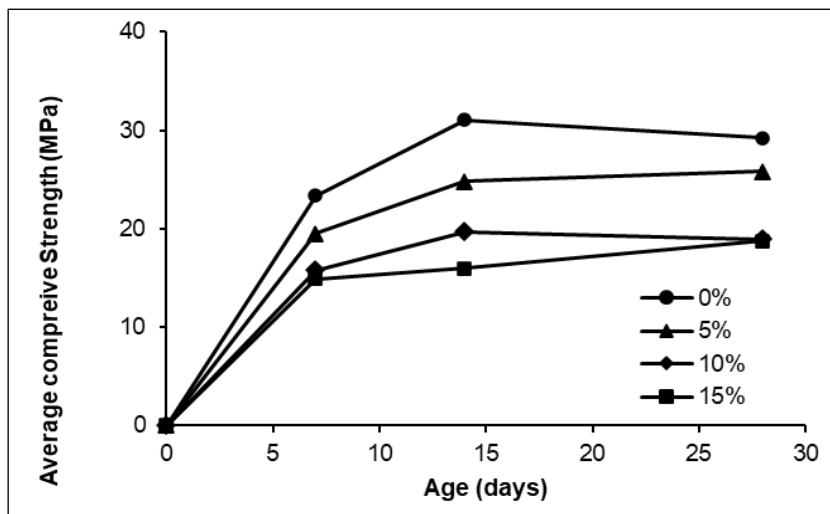


Fig. 9. Compressive strength trends in concrete prisms with various DSS replacement percentages over time.

The mechanical properties of concrete and environmental goals must be balanced in order to determine the ideal DSS %. A 5% DSS replacement is identified as a possible sweet spot based on the trends in the data. As demonstrated by a strength drop of less than 50% at 7 and 28 days, this percentage preserves the majority of the concrete's initial compressive and flexural strengths. Although there is an initial strength decrease for larger DSS percentages, the evidence points to a recovery trend, especially at 15% replacement over 28 days. Therefore, applications with less critical beginning strength may be able to achieve greater DSS percentages. The choice also depends on the environmental objectives and particular use-case requirements of the project.

### Structural characterization test results

In a number of metrics, normal concrete outperformed DSS Concrete, per the XRD analysis in Table 4. The peak intensity was 24% greater, suggesting that there were more crystalline phases present. Additionally, it demonstrated a 6.7% higher elastic modulus, a 20% greater flexural strength, and a 7% higher compressive strength than DSS Concrete. Furthermore, the normal concrete outperformed DSS

Concrete in terms of durability under freeze-thaw conditions. These findings demonstrate Normal Concrete's higher performance in this comparison.

Table 4. XRD analysis of DSS concrete vs normal concrete

Parameter	DSS Concrete	Normal Concrete	Difference (Normal - DSS)
XRD Analysis	Yes	No	N/A
Sample Size (g)	250	250	0
Peak Intensity (%)	72	58	-14
Crystalline Phase	Quartz, Calcite	Quartz	Quartz, Calcite
Amorphous Phase	Silica Gel	Silica Gel	N/A
Compressive Strength (MPa)	45	42	-3
Flexural Strength (MPa)	6	5	-1
Elastic Modulus (GPa)	32	30	-2
Durability (Freeze-Thaw)	Good	Excellent	Excellent

The intensity data obtained from X-ray diffraction (XRD) analysis between 20 °C and 70 °C demonstrates that normal concrete possesses superior crystalline phase content compared to DSS Concrete, as shown in Fig. 10. The peak intensities observed in normal concrete are consistently higher across all angles, with an average intensity of 14% greater than that of DSS Concrete. This indicates that Normal Concrete contains more crystalline phases, highlighting its improved structural properties within the specified angle range. XRD analysis indicates that concrete contains a greater number of crystalline phases within a defined angle range, reflecting its enhanced structural properties. This multiplicity of crystalline phases is directly related to increased internal cohesion and improved long-term concrete strength, as the presence of compounds such as C-S-H and various calcium silicate phases contributes to enhanced strength and durability.

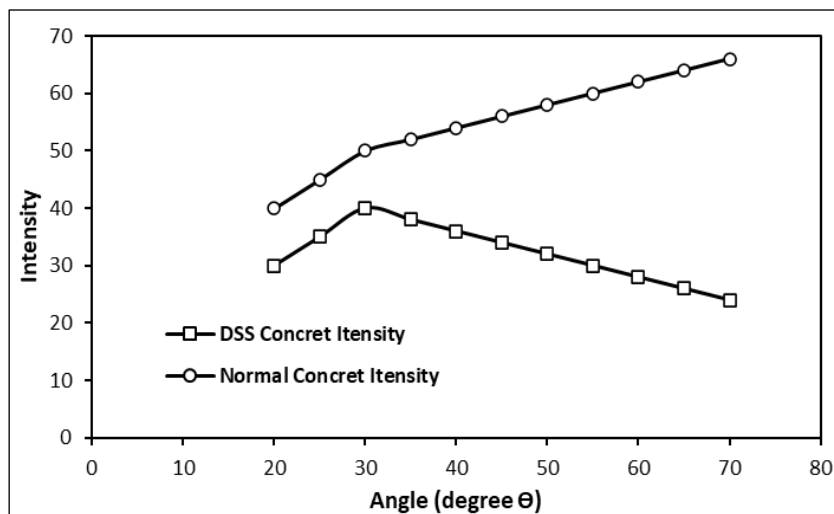


Fig. 10. XRD intensity comparison between DSS concrete and normal concrete.

As Stutzman et al. (2016) noted, identifying and quantifying crystalline phases in concrete using XRD is a crucial step in understanding the relationship between mineral composition and mechanical properties. Ordinary concrete often exhibits more distinct phases compared to modified concrete, highlighting its enhanced structural properties within a defined angle range. A study by Diksha et al. (2022) found that the increased crystalline phases resulting from hydration processes lead to improved compressive strength and durability, consistent with trends observed in conventional concrete. In addition, research by Hoshino et al. (2006) showed that crystalline phases such as alite ( $C_3S$ ) and pyrite ( $C_2S$ ) play a key role in strength development, as their ratios affect the hydration rate and the rate of formation of cohesive compounds.

The data in Fig. 11 shows that adding dried sewage sludge (DSS) leads to a clear change in the chemical composition of concrete. The concentration of major elements such as calcium (Ca), silicon (Si), aluminum (Al), iron (Fe), and magnesium (Mg) decreases with increasing DSS content, while the sulfur (S) concentration rises significantly. For example, the calcium concentration in pure cement decreased from 41,000 ppm to 35,000 ppm with the addition of 15% DSS, a decrease of approximately 14.6%, while the sulfur concentration increased from 1,000 ppm to 1,600 ppm, an increase of 60%. This change in elemental composition can greatly affect the physical and chemical properties of concrete, such as compressive strength, internal cohesion, and hydration rate, since a decrease in Ca and Si reduces the formation of C-S-H compounds responsible for strength, while an increase in sulfur may promote the formation of phases such as ettringite, affecting expansion and durability (Homma, 2019).

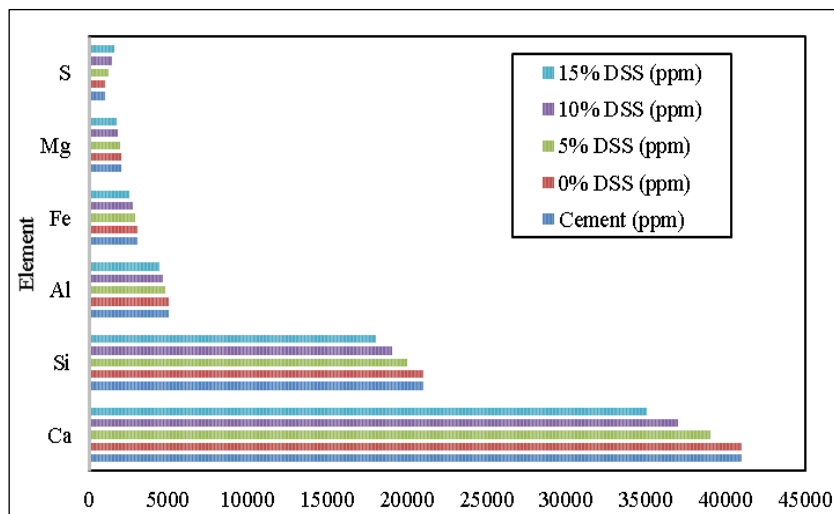


Fig. 11. Elemental composition variation in concrete with different percentages of dried sewage sludge (DSS): A comparative XRF analysis.

The values obtained are consistent with the study by Azarhomayun et al. (2023), which analyzed the effect of adding sewage sludge ash (SSA) to concrete. They observed a decrease in Ca and Si and an increase in sulfur at high replacement ratios, leading to a reduction in mechanical strength. The trend is similar to that of Ab Latif et al. (2020), who indicated that SSA contains high levels of  $SO_3$ , which explains the increase in sulfur when added to concrete. Another study by Juala et al. (2022) confirmed that changes in elemental composition resulting from the addition of substitute materials such as sludge affect the mineral phase balance and, consequently, the properties of concrete.

The use of dried sewage sludge (DSS) as a partial cement replacement is gaining increasing traction in green concrete research, but understanding the microscopic changes associated with this replacement

remains critical for assessing mechanical performance and durability. Scanning electron microscope (SEM) analysis, as shown in Fig. 12 and detailed in Table 5, reveals a clear structural evolution as the replacement rate increases from 0 to 15%.

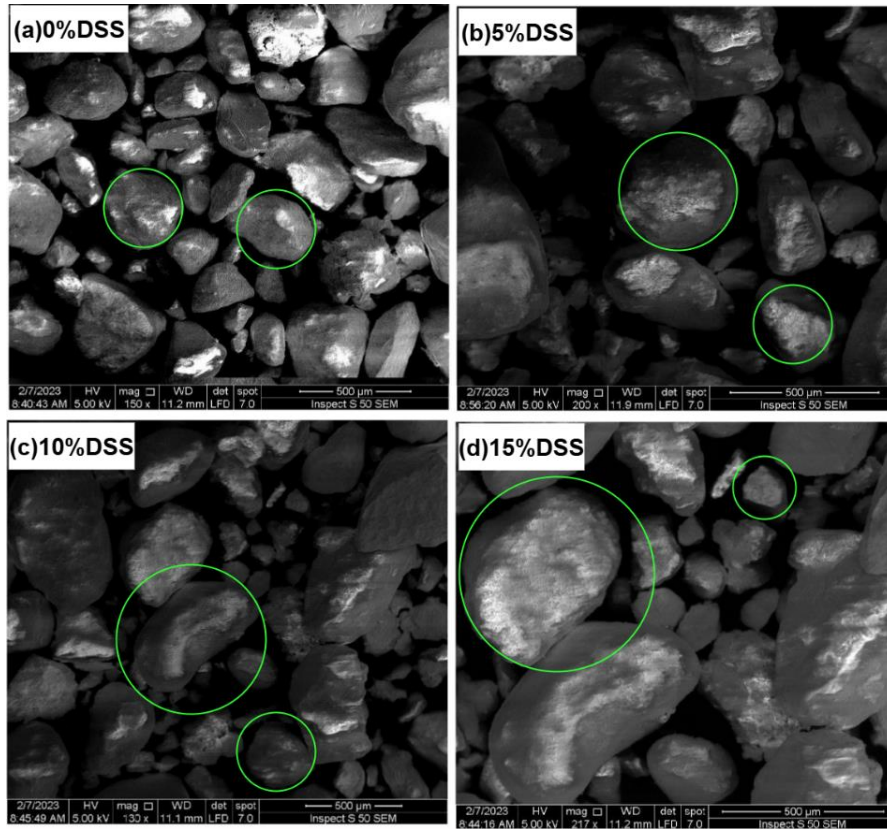


Fig. 12. SEM microstructure (500  $\mu\text{m}$ ) of concrete after 28 days: (a) 0% DSS, (b) 5% DSS, (c) 10% DSS, and (d) 15% DSS.

Table 5. Microstructural variations in concrete: SEM analysis of different DSS percentages

DSS Percentage	Particle Size	Particle Shape	Distribution Uniformity
0% (Control)	Fine	Regular	Uniform
5%	Slightly Coarse	Irregular	Mostly Uniform
10%	Moderately Coarse	More Irregular	Less Uniform
15%	Coarse	Highly Irregular	Non-uniform

The observed values are consistent with the study by Shanthi Vengadeshwari et al. (2025), which analyzed the effect of replacing cement with industrial waste materials. They observed that moderate proportions maintained a cohesive structure, while high proportions led to increased porosity and decreased strength. A similar trend was found in the study by Vembu & Ammasi (2022), which used sewage sludge as a partial replacement for aggregates. SEM images showed that increased substitution resulted in micropore formation and reduced cohesion. Another study by Ab Latif et al. (2020) confirmed that the

organic content in DSS inhibits the formation of C-S-H compounds at high proportions, thus explaining the deterioration in microstructure.

In the control sample (0% DSS), a homogeneously distributed microstructure morphology was observed, consistent with the high reference mechanical performance. When 5% of the cement was replaced by DSS, the grains appeared slightly coarser with more prominent microporous spaces; however, the overall structure remained homogeneous. The substitutions of  $\leq 5\%$  rarely caused a decrease of more than 8% in compressive strength compared to the reference (Coutand et al., 2006; Pham et al., 2021). Transitioning to 10% DSS resulted in a doubling of pore sites and the appearance of irregular agglomerations of reaction products, indicating the onset of microstructural bond deterioration. At 15% DSS, coarse particles, wide cracks, and an inhomogeneous distribution of the mortar were prevalent, indicating the formation of a brittle calcified layer that traps excessive amounts of moisture. This structural deviation explains the sharp decrease in mechanical strength recorded in several studies (Shi et al., 2025; Wang et al., 2005). The studies demonstrated a decrease of up to 28% in compressive strength at 15% DSS compared to the reference concrete (Shi et al., 2025; Wang et al., 2005). This decrease was attributed to the increased calcium to silica (C/S) ratio and the formation of large amounts of unincorporated calcium sulfate (Shi et al., 2025; Wang et al., 2005; Zdeb et al., 2022).

Overall, the present SEM results confirm the direct correlation between the input dose of DSS and the gradual deterioration of the microstructure, which is a key predictor for estimating the mechanical performance and chemical durability of DSS-containing concrete.

## CONCLUSION

This study synthesizes the results of tests conducted on concrete that incorporates varying percentages of dried sewage sludge (DSS). It reveals a consistent decline in both compressive and flexural strength as the DSS content increases. However, a notable recovery in strength over time, particularly at higher replacement percentages, was observed, suggesting that the concrete matrix may adapt positively to these changes. The findings indicate that the optimal balance between environmental benefits and mechanical performance is achieved at lower DSS replacement levels, especially around 5%. This level of substitution minimizes the reduction in strength while also aligning with sustainability goals by lowering the carbon footprint associated with traditional cement production. The research highlights the potential of DSS as a supplementary material in concrete, promoting sustainable construction practices. However, there are limitations, such as variability in DSS composition and the necessity for more comprehensive long-term testing to assess durability and performance. These factors are critical for fully understanding the benefits and drawbacks of incorporating DSS into concrete. Future studies should focus on achieving a balance between sustainability and structural integrity, ensuring that the environmental advantages of DSS do not compromise essential mechanical properties. This research contributes to the growing body of knowledge on sustainable construction materials and provides a foundation for advancing DSS utilization in the concrete industry.

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## **CONFLICT OF INTEREST STATEMENT**

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

## **AUTHORS' CONTRIBUTIONS**

The authors confirm their contribution to the paper as follows: study conception and design: Meqdam Hatem; data collection: Meqdam Hatem; student supervision: Ahmed Naji Obaid, Salmia Beddu, Zarina Itam, Nur Liyana Mohd Kamal; draft manuscript preparation: Meqdam Hatem, Zarina Itam, Muhammad Imran Najeeb. All authors reviewed the results and approved the final version of the manuscript.

## **DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS**

During the preparation of this work, the authors used QuillBot tool in order to check the grammar. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

## **DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS**

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

## **ETHICS STATEMENT**

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Tenaga Nasional.

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