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A Comprehensive Evaluation of Concrete Behavior Made with Date Seed as a Partial Replacement of Fine Aggregate

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ABSTRACT

The utilization of plant-based materials, particularly agricultural residues, as concrete components offers significant economic and environmental benefits. Moreover, incorporating agricultural residues into concrete formulations can result in lightweight concrete, which is easier to handle and transport due to its lower density. This study experimentally evaluated a comprehensive assessment of the properties of conventional concrete containing 1.25%, 2.5%, 3.75%, and 5% date seeds (DS) as a partial substitute for fine aggregate. The evaluation covered the fresh, hardened, non-destructive, and durability properties of the concrete. Results indicated that DS inclusion reduced concrete density, achieving lightweight characteristics, however, higher DS content significantly decreased strength and durability. Conversely, lower replacement levels demonstrated acceptable performance as the organic nature of DS explains these minor strength reductions. The non-destructive testing results correlated strongly with compressive strength. Elevated temperature testing revealed increased deterioration with higher DS percentages. The findings suggests that while DS can contribute to lightweight concrete, careful control of replacement levels is crucial to maintaining structural integrity.

1. INTRODUCTION

Concrete is a fundamental component in the construction of buildings and bridges. It consists of multiple raw materials: cement, aggregate (coarse and fine), water, and additives. Concrete grades are influenced by multiple factors, including the type of structure, environmental conditions, economic cost, and the quality of the used materials [1]. The key concrete characteristics include mechanical strength, durability, thermal properties, fire resistance and similar attributes, which significantly impact structural design decisions. There are important conditions that must be met in the concrete mixture. It must be homogeneous and workable. Therefore, the properties of materials and mixing methods have an effective effect [2]. Furthermore, durability is an important factor in concrete that must be taken into consideration to enhance the structure's lifetime. The durability factors give concrete the ability to resist degradation and maintain its shape, dimensions, and quality during its service life when exposed to harsh conditions such as weathering, corrosion, and attack by chemical substances [3].

In recent years, due to the development of industries, there has been a large amount of waste, which has prompted researchers to think about reusing these materials to reduce environmental pollution. In many studies on concrete, the primary target has become to obtain sustainable concrete at a lower cost while reducing undesirable CO_2 emissions by utilizing different materials as alternatives to concrete components. Organic and inorganic waste were involved as a replacement for fine or coarse aggregate. Inorganic waste such as (plastic, glass, ceramic, rubber, electronic waste, etc.) were investigated by many researchers [4-8]. Furthermore, researchers have explored the use of organic agricultural waste as a potential substitute for traditional aggregates in concrete production. These investigations were on sawdust, wood ash, cashew shells, sugarcane bagasse ash, papers and walnut shells [9-18] etc. Mohammed et al. [9] found that wood chipping improved workability but reduced strength. Al-Harshawi et al. [10] observed similar strength reductions with recycled wood waste replacing cement but noted excellent workability and a 25% weight reduction. Al-Saad et al. [11] successfully produced lightweight concrete using waste paper aggregates treated with cement or wood glue, achieving significant density reduction. Modani and Vyawahare [12] demonstrated the potential of utilizing untreated bagasse ash as a fine aggregate replacement. Hilal et al. [13] found that crushed walnut shells decreased concrete performance, with a 15% replacement yielding the best results. Priyadarshini et al. [17] used cashew shells as a partial coarse aggregate replacement in concrete, with a 10% substitution yielding optimal strength.

As concluded from the above-mentioned studies, agricultural wastes are suitable to use to produce eco-friendly lightweight concrete.

Date seeds (DS) are considered to be a large agricultural waste material in the Middle East, especially in Iraq and some Arab countries. After consumption of the date, seeds become agricultural waste and can contribute to environmental pollution if not properly managed. In many studies [19-23], researchers replaced the coarse aggregate with date seeds to produce concrete. The most important result was that increasing the DS reduced the workability of the concrete. In contrast, other studies found an enhancement in concrete strength when DS was added in a specific amount.

Adefemi et al. [19] explored the feasibility of using DS as a substitute for CG (crushed granite) in concrete production. Physical and mechanical characteristics were conducted of both materials for comparison. Ninety concrete cubes with varying CG to DS ratios (100:0 to 0:100) were prepared and evaluated for compressive strength after 28 days of water immersion. The results showed that partial replacement of CG by DS, up to 75%, yielded satisfactory compressive strengths, suggesting DS as a suitable alternative for lightweight concrete production in regions where it is readily available. Ahmed et al. [20] investigated the utilization of DS as a partial substitute for coarse aggregate in concrete, analyzing its impact on workability, density, and compressive strength under exposure to sodium chloride (NaCl) and sodium sulphate (Na_2SO_4) solutions. The incorporation of 2-4% DS as a replacement for coarse aggregate initially enhanced workability by 2%, but this improvement diminished over time. A slight reduction in density and compressive strength in plain water, while a more pronounced reduction in compressive strength was noted in salt solutions, especially after 28 days of exposure. Suggesting DS concretes susceptibility to salt damage. Palh et al. [21] explored the incorporation of DS as a partial substitute for coarse aggregate. Twenty-four cylindrical specimens were created, replacing coarse aggregate with 0%, 2%, 3% and 4% DS. The workability decreased as the DS content increased, primarily due to its larger surface area, while the compressive strength results were satisfactory at 2% and 3% replacement levels, suggesting that DS has potential as a feasible partial replacement for aggregate.

Gunarani and Chakkravarthy [22] studied date seed ash as an alternative to cement in certain proportions (2%, 4%, 6%, 8%, and 10%). A 2% date palm seed ash (DPSA) addition notably improves bond strength compared to ordinary Portland cement (OPC), however, optimal performance is attained with a 4% replacement. Shaikh et al. [23] replaced fine aggregate with crushed date seeds in concrete in four different percentages 1%, 2%, 3%, and 4%. Concrete incorporating 3% crushed date seeds achieved maximum compressive strength at 7 and 28 days.

Although date seeds are widely available in Iraq as agro-waste material, their use in concrete production has not been considered in studies or construction. A significant gap remains in the comprehensive evaluation of DS durability and heat resistance, especially as a replacement for fine aggregate.

Therefore, in the current work, DS was incorporated as a partial substitute of fine aggregates with 1.25%, 2.5%, 3.75%, and 5% by volume. Slump, dry density, water absorption, compressive strength, splitting tensile strength, and flexural strength were evaluated. Additionally, durability was also investigated including rapid chloride permeability, elevated temperature, Schmidt rebound hammer, and ultrasonic pulse velocity test.

2. MATERIALS AND METHODS

2.1 Cement

The cement used for this study was OPC Type 1 (CEM I 42.5 N) with a specific gravity of 3.15. The chemical composition and physical properties of cement were determined according to ASTM C150-04 [24] which are summarized in Tables 1 and 2, respectively.

Table 1. Chemical composition of cement

Chemical Oxide	Cement	Limits of ASTM C150-04 (%) [24]
CaO	61.63	-
Al_2O_3	5.26	-
SiO_2	20.5	-
Fe_2O_3	3.87	-
K_2O	0.88	-
SO3	2.63	≤ 5
MgO	2.61	≤ 2.8
Na_2O	0.29	-
Lime saturation factor (L.S.F)	0.81	0.66–1.02
Loss on Ignition (L.I.O.)	2.61	≤ 3
Insoluble residue (I.R)	0.52	< 1.5%
Compound		
C_3S	51.55	-
C_3A	4.55	-
C_2S	19.55	-
C_4AF	12.85	-

Table 2. Physical properties of cement

Physical Properties	Test Results	Limits of ASTM C150-04 [24]
Initial setting time (minutes)	125	≥ 45
Final setting time (minutes)	325	≤ 375
Fineness (m^2 / kg)	315	≥ 280
Compressive strength (MPa)		
3 days	14.7	≥ 8
7 days	22.3	≥ 15

2.2 Aggregate

Local river sand was incorporated as fine aggregate (FA) with a maximum size of 4.5 mm, while crushed gravel with a maximum size of 19 mm was used as aggregate (CA). The physical properties of the fine and coarse aggregates are summarized in Tables 3 and 4, respectively. Figure 1 illustrates the grading curves of the fine and coarse aggregates used in this study. The sieve analysis of both fine and coarse aggregates was within the limits specified by ASTM C33-18 [25].

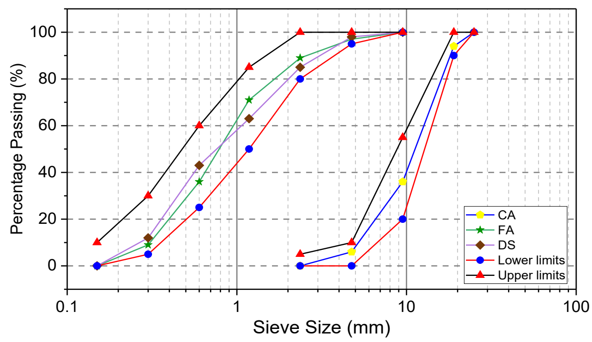


Figure 1. Grading curves for aggregate and DS

Table 3. The physical properties of fine aggregate

Physical Properties	
Bulk density (kg/m^3)	1681
Specific gravity	2.56
Fineness modulus	2.98
Absorption %	1.1
Sulfate content (SO_3) %	0.04
Maximum particle size (mm)	5

Table 4. The physical properties of coarse aggregate

Physical Properties	
Sulfate content (SO_3) %	0.04
Bulk density (kg/m^3)	1520
Specific gravity	2.61
Maximum particle size (mm)	19
Absorption %	0.7

2.3 Date seed

Date seeds are hard, oblong objects with a ventral groove and a small embryo. Their weight ranges from 0.5 to 4 grams, constituting 6 to 20% of the fruit's weight, depending on the date's maturity, variety, and quality. These seeds offer various applications: their oil, rich in antioxidants, is valuable in cosmetics; they can replace coffee; they serve as a raw material for activated carbon; and they function as an adsorbent for water-containing dyes [24].

Figure 2. Date seed preparing process: a) washing and cleaning the date seed, b) after drying under the sunlight, c) after drying in the oven, d) the grinder used for finning the size, e) final result

Table 5. The physical properties of date seed

Physical Properties	
Bulk density (kg/m^3)	868
Specific gravity	1.31
Fineness modulus	2.98
Absorption %	8.5

DS was obtained from date palm type (sayer), from one of Basra farms in the south of Iraq. To ensure their suitability for concrete, the date seeds underwent a thorough cleaning process: They were washed with regular water to remove any leftover date flesh and dust. Then, the seeds were laid out in direct sunlight for two days at a scorching 60°C to significantly reduce moisture content. Finally, the seeds were oven-dried until they could be easily crushed into fine particles resembling sand as shown in Figure 2 and the grading curves of the DS and fine aggregate are illustrated in Figure 2.

The physical properties of date seeds are listed in Table 5. While their specific gravity, bulk density, and absorption capacity fall short of conventional fine aggregate values, the fineness modulus aligns. Furthermore, the size distribution of DS complied with ASTM C33-18 aggregate grading requirements [25], as depicted in Figure 1.

2.4 Superplasticizer

To enhance the workability of the concrete mixtures, MasterGlenium 54, a high-performance superplasticizing admixture, was used in this study. MasterGlenium 54, based on a unique carboxylic polymer with long lateral chains, greatly improves cement dispersion. The use of this superplasticizer allows for the production of flowable concrete, offering benefits such as reduced vibration, decreased labor requirements, and improved surface finish. The characteristics of superplasticizers based on the manufacture datasheet are presented in Table 6.

Table 6. Characteristics of superplasticizer

Mixture Properties	Superplasticizer
Name	Master Glenium 54
Color tone	Whitish to straw-colored liquid
State	Liquid
Density	1.07 kg/liter
Chemical description	Based on a unique carboxylic ether polymer with long lateral chains
Recommended dosage (% binder content)	0.50 and 1.75 L / 100 kg of cement (cementitious material).
Chloride content	Nil (BS EN 934-2)

2.5 Mixing proportions and procedure

A mix design was developed to achieve a compressive strength target of 30 MPa. Consequently, a total of five concrete mixtures were prepared with a constant water-cement ratio of 0.45. To achieve the aforementioned target, strength with a workable consistency, a slump of 100±20 mm with the addition of superplasticizer was incorporated. In the design of the current study mixtures, all parameters were kept constant except the content of fine aggregate (river sand). The sand content was progressively substituted with DS at various percentages of 1.25%, 2.5%, 3.75%, and 5% (by volume of sand). Table 7 provides a breakdown of the specific quantities of each material required per cubic meter of concrete for each mix design.

Table 7. Concrete mixture proportions

Materials (kg/m^3) Mixture ID	Percentage of Crushed Date Seed	Cement	Water	Coarse Aggregate	Fine Aggregate	DS	Superplasticizer
D0	0	420	190	1062	706	0	3
D1	1.25	420	190	1062	697.175	4.77	3
D2	2.5	420	190	1062	688.35	9.55	3
D3	3.75	420	190	1062	679.53	14.32	3
D4	5	420	190	1062	670.7	19.10	3

Figure 3. Concrete mixer

The mixing and sampling method for fresh concrete was according to BS 1881-125 [26]. The fresh concrete was mixed using a revolving pan mixer (Figure 3). To prevent the absorption of mixing water from the dry mixture ingredients, the aggregate condition was saturated surface-dry (SSD). Fine aggregate and date seed powder were placed in the mixer first, then the cement was mixed for 30 seconds. Subsequently, the coarse aggregate and half the mixing water were added, and the mixer was rotated for an additional one minute.
The superplasticizer was premixed with mixing water before being placed into the mixer. Mixing continued for approximately 2 minutes until a homogeneous paste was achieved. The fresh concrete was then immediately cast into clean, oiled molds. After 24 hours of air drying, the samples were demolded and immersed in water for 28 days. Normal tap water was used for both mixing and curing.

3. TEST DESCRIPTION ON FRESH AND HARDENED CONCRETE

3.1 Fresh concrete test (Slump test)

After the process of mixing the concrete ingredients was completed and the required homogeneous texture was achieved, a slump test was performed to assess the workability and consistency of the fresh concrete. This test was conducted according to ASTM C143-03 [27] on all the concrete mixtures as illustrated in Figure 4.

3.2 Hardened concrete tests

The effect of adding DS on the specimens' mechanical behavior was evaluated through several tests on the hardened concrete. These tests included dry density, water absorption, compressive strength, and splitting tensile strength, flexural strength, Schmidt rebound hammer, and ultrasonic pulse - velocity as non-destructive techniques for the last two tests, respectively. Eighteen 100 mm cubic specimens, nine 100×200 mm cylindrical specimens, and three 100×100×400 mm prisms were cast for each concrete mixture. The measurement of concrete dry density at 28 days was performed on cubic specimens according to ASTM C642-97 [28] and water absorption, also following ASTM C642-97, after a 28-day curing period. Compressive strength was determined according to BS 1881: Part 116 [29] (Figure 5) using a universal load testing machine. The average splitting tensile strength of three concrete specimens (cylinders) was tested at 7, 28, and 56 days according to ASTM C 496- 96 [30] as illustrated in Figure 6. The center-point loading test was implemented to compute the flexural strength of concrete prisms at age 28 days conforming to ASTM C293-02 [31] as in Figure 7. A Schmidt rebound hammer test, conforming to ASTM C805 [32], was conducted on concrete cubes before compressive strength testing (Figure 8). Ultrasonic pulse velocity UPV was determined by measuring the travel time of a 50-54kHz pulse transmitted through the concrete specimen by the electro-acoustical transducer. The pulse velocity was calculated based on the known path length [33]. The pulse velocity of cubes was tested using an ultrasonic device shown in Figure 9 following ASTM C 597-02 [34].

Figure 4. Slump test

Figure 5. Compressive strength test

Figure 6. Splitting tensile strength test

Figure 7. Flexural strength test

Figure 8. Schmidt rebound hammer test

Figure 9. Ultrasonic pulse velocity test

3.3 Durability of concrete tests

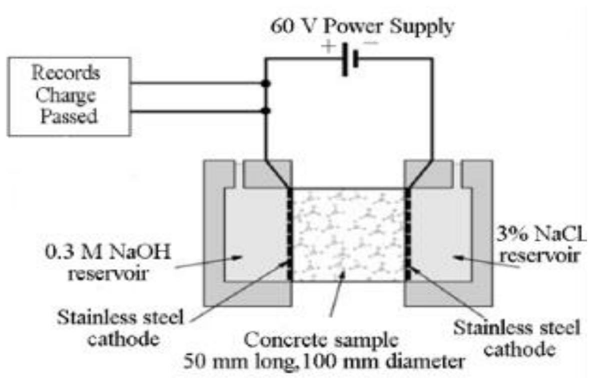
The effect of adding DS on the durability of concrete was evaluated through several tests. These tests were chloride permeability and elevated temperature which are described in the following subsections.

3.3.1 Rapid chloride permeability test (RCPT)

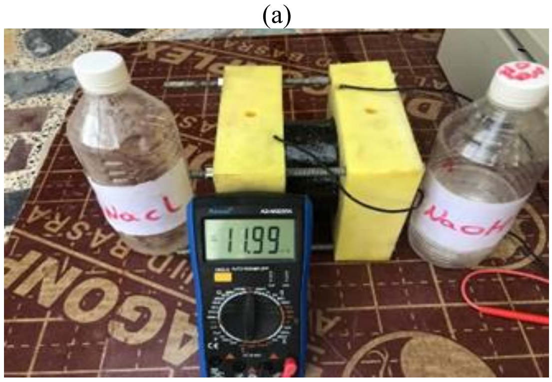
The RCPT, a method for measuring chloride ion penetration in concrete, was performed as follows. Disc-shaped specimens, 100mm in diameter and 50mm high, were cut from 100×200 mm cylinders after a 28-day curing period, conforming to ASTM C1202 [35] and AASHTO T277 [36]. The borders of the specimens were coated with sealing material before being placed in the device. A constant 60V DC was maintained across the sample ends throughout the test for 6 hours, as shown in Figure 10. The sample had one end immersed in a 3% sodium chloride (NaCl) solution and the other end in a 0.3M sodium hydroxide (NaOH) solution. Readings were taken every half an hour. After 6 hours, the specimen was removed, and the total amount of charge (coulombs) that had passed through the sample was computed as in Eq. (1).

$$C_f = 900(A_0 + 2A_{30} + 2A_{60} + 2A_{90} + 2A_{120} + \ldots\ldots + 2A_{330} + 2A_{360}) \quad (1)$$

where, C_f represents the total charge flow through the concrete cell in coulombs, calculated by integrating the current, A_t (amperes), measured at time t (minutes) under a constant 60V DC voltage. The total charge, measured in coulombs, passing through the concrete specimen was used to assess chloride penetration resistance according to the criteria outlined in Figure 11.



(a)



(b)

Figure 10. Rapid chloride permeability test, a) Chloride permeability test diagram [37], b) Chloride permeability current study device

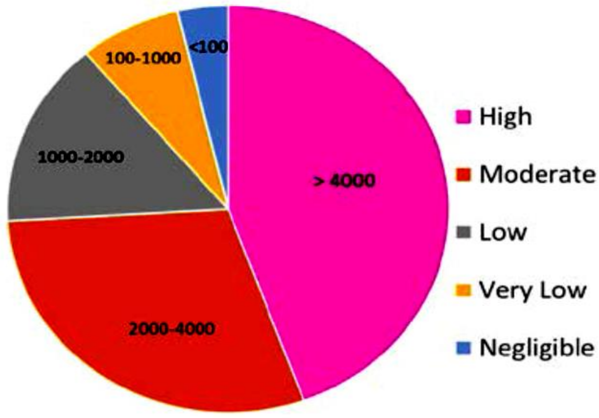


Figure 11. RCPT rating measured in Coulombs per ASTM C1202 [37]

Figure 12. Electric furnace used for elevated temperature test

3.3.2 Elevated temperature

Three cube samples were examined for each different heat value, 150°C, 300°C, and 450°C. Cubes were weighed, subjected to a one-hour heat at each specified temperature in an electric furnace (Figure 12), cooled, reweighed, and following assessed for compressive strength. The effect of the elevated temperature was evaluated using Eq. (2) [38].

$$Percentage\ weight\ loss = \frac{w_1 - w_2}{w_1} \times 100(\%) \quad (2)$$

where, $w_1 = cube\ weight\ before\ subjected\ to\ heat, (g)$, $w_2 = cube\ weight\ after\ subjected\ to\ heat\ (g)$.

4. RESULTS AND DISCUSSION

4.1 Slump test

Table 8. Slump test results

Mixture ID	Percentage of DS	Slump (mm)	Percentage Reduction in Slump
D0	0	130	--
D1	1.25	120	8
D2	2.5	100	23
D3	3.75	90	31
D4	5	70	46

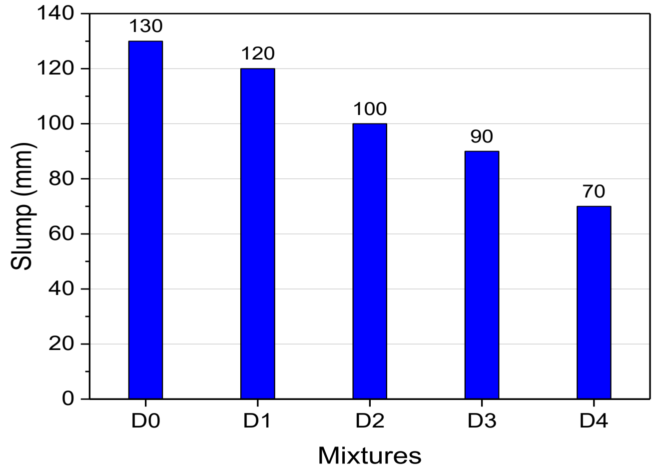


Figure 13. Slump test results chart

Table 8 and Figure 13 present slump test results, indicating a decrease in workability with increasing DS content. A slight reduction was recorded for the D1 mixture with 1.25%. However, the reduction percentage was huge for the mixture with 5% of replacement (D4). This significant reduction is due to the water absorption effects of the DS, which affects the concrete overall consistency.

4.2 Dry density

The dry density results are tabulated in Table 9 and graphically exhibited in Figure 14. The density of mixtures D1and D2 with 1.25% and 2.5% of DS respectively at 28 days was within the range of 2355 kg/m³ to 2560 kg/m³, which is recommended for normal-weight concrete [39]. The use of DS as a replacement for fine aggregate slightly reduced the density of the concrete mixtures. Although the percentage replacement of DS was small, the reduction was 6.4% for the 5% replacement of DS (D4). It seems that incorporating DS could produce lightweight concrete with a higher percentage of replacement.

Table 9. Dry density results

Mixture ID	Dry Density (kg/m^3) at 28 Days	Percentage Reduction in Dry Density
D0	2383	--
D1	2354	1.2
D2	2314	2.9
D3	2280	4.3
D4	2231	6.4

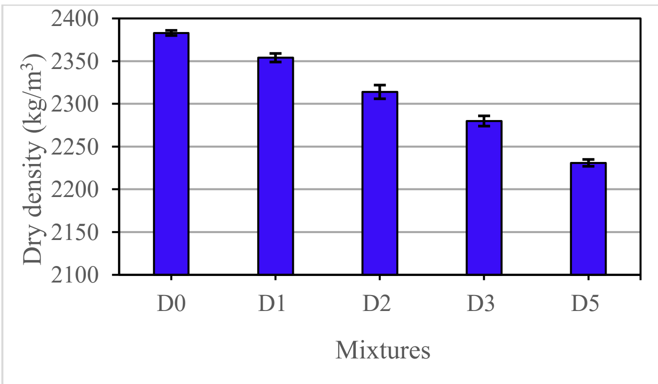


Figure 14. Dry density results chart

4.3 Water absorption

The results of the water absorption test measured at 28 days were summarized in Table 10 and depicted in Figure 15. The percentage increased in water absorption was very high with 11%, 28%, 44% and 56% for D1, D2, D3 and D4 respectively relative to control mixture. Increased water absorption was observed as the DS content increased, a result of DS's high porosity.

Table 10. Water absorption results

Mixture ID	Specimen Weight Before Immersing in Water (g)	Specimen Weight After Immersing in Water (g)	Water Absorption (%)
D0	2383	2396	0.54
D1	2354	2369	0.6
D2	2314	2330	0.69
D3	2280	2299	0.78
D4	2231	2252	0.84

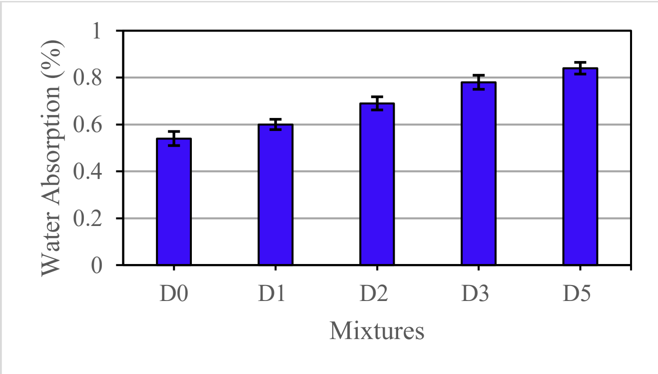


Figure 15. Water absorption results chart

4.4 Compressive strength

The influence of adding DS to concrete as a partial replacement to fine aggregate on the compressive strength of the average of three cubes at ages of 7, 28, and 56 days are summarized in Table 11 and graphically in Figure 16. The addition of the DS influenced negatively on the compressive strength of all mixtures compared to the control mixture. The reduction in strength was recorded for higher replacement up to 42%, 32%, and 29% at 7, 28, and 56 days respectively, for a mixture with 5 % of replacement (D4). Despite the overall behavior of decreasing compressive strength with increasing DS content, the mixture with 1.25% D1 replacement exhibited only minor reductions in compressive strength of 9%, 5%, and 3% at 7, 28, and 56 days, respectively. Considering that DS is an organic material utilized as a replacement for natural fine aggregate, these relatively small reductions are deemed reasonable. The lower compressive strength values observed in this study with increasing DS content can be attributed to the many main factors:

1) High water absorption: DS particles absorb significant amounts of water, reducing the water-cement ratio and leading to incomplete cement hydration, which weakens the concrete matrix.
2) Increased porosity: The porous nature of DS introduces additional voids in the concrete, which reduces compactness and density with increasing water ingress, negatively affecting durability.
3) Organic nature and cement hydration interference: Organic compounds in DS can retard cement hydration, delay C-S-H gel formation, and decompose over time, creating voids that further weaken the structure.
4) Weak Interfacial Transition Zone (ITZ) and bonding Issues: Low specific gravity and an organic surface reduce DS bonding cement paste, leading to weak interface transition zone formation, increased microcracking, and early structural failure.

Therefore, to enhance the feasibility of using DS in concrete applications, the following strategies should be considered:

1) Pre-treatment of DS: Coating DS particles with silica fume or pozzolanic materials to enhance bonding and using chemical treatments to remove organic content that may interfere with hydration.
2) Optimal mix design: Adjusting the water-cement ratio to compensate for DS water absorption and incorporating supplementary cementitious materials (SCMs) like fly ash to improve durability.
3) Hybrid aggregate systems: Blending DS with traditional fine aggregates rather than complete replacement to minimize strength loss, as in a 1.25% DS mix.

Table 11. Compressive strength results

Mixture ID	Compressive Strength (MPa)		
	7 days	28 days	56 days
D0	25.8	32.6	35.0
D1	23.5	31.1	34.1
D2	20.4	28.5	31.6
D3	16.7	25.6	27.2
D4	14.9	22.2	24.9

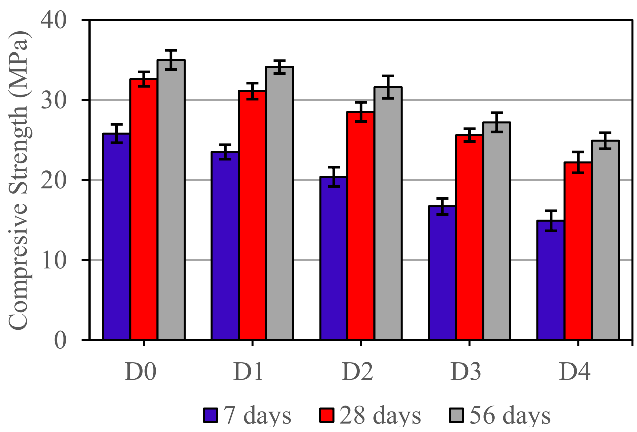


Figure 16. Compressive strength results chart

4.5 Splitting tensile strength

The experimental test outcomes of the splitting tensile strength of the average of three cylinders at ages 7, 28, and 56 days are listed in Table 12 and depicted in Figure 17. The behavior of concrete mixtures with DS for the splitting tensile strength was the same as in the compressive strength. The loss in tensile strength was observed up to 52 %, 33%, and 35% in 7, 28, and 56 days, respectively for a mixture with 5% of replacement (D4). Despite the overall trend of decreasing tensile strength with increasing DS content, the mixture with 1.25% D1 replacement exhibited only slight reductions of 8%, 5%, and 4% at 7, 28, and 56 days, respectively. Given that DS is an organic material utilized as a replacement for natural fine aggregate, these relatively small strength losses are considered acceptable.

Table 12. Splitting tensile strength and flexural strength results

Mixture ID	Splitting Tensile Strength (MPa)			Flexural Strength (MPa)
	7 days	28 days	56 days	28 days
D0	2.54	2.92	3.25	4.81
D1	2.33	2.77	3.12	4.59
D2	2.09	2.48	2.76	4.31
D3	1.61	2.27	2.48	4.02
D4	1.23	1.95	2.11	3.73

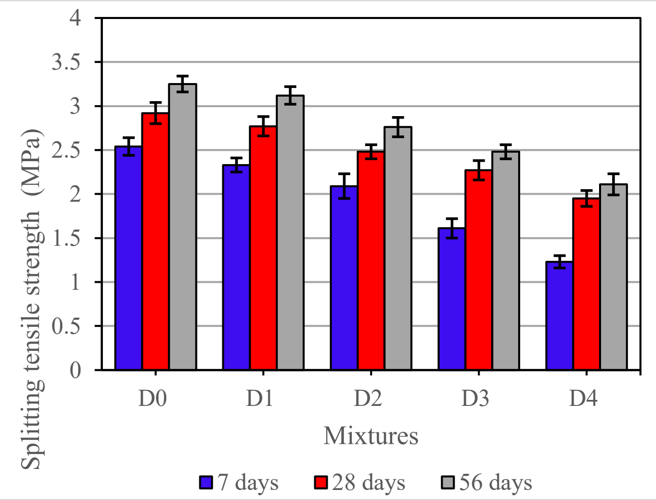


Figure 17. Splitting tensile strength results chart

4.6 Flexural strength test

Flexural strength measurements were conducted on all mixtures at 28 days on the average of three prisms are summarized in Table 12. As illustrated in Figure 18, the incorporation of DS caused a reduction in flexural strength. The relationship between DS percentage and flexural strength at 28 days is further detailed in Figure 19, which presents the flexural strength values and their corresponding percentage reductions compared to the control mixture. It is observed that the reduction in flexural strength raised by increasing the content of DS in the mixture. There is a high reduction (22%) in a concrete mixture of 5% date seed. On the other hand, a slight reduction was recorded for the mixture with 1.25% replacement (D2), which is only 5%.

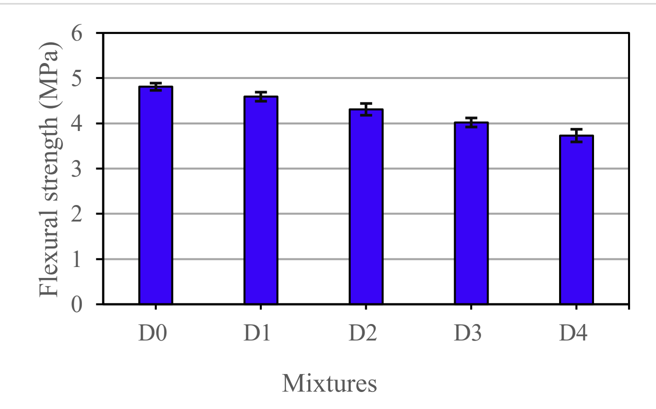


Figure 18. Flexural strength results chart

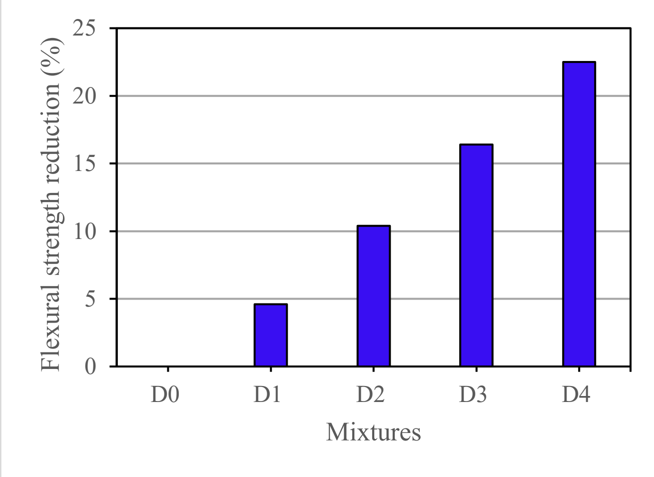


Figure 19. Flexural strength reduction results chart

The reasons for reductions in splitting and flexural strength are the same as those mentioned for compressive strength.

4.7 Schmidt rebound hammer test

The outcomes of the Schmidt rebound hammer tests conducted on all mixtures at the age of 28 days are summarized in Table 13. The trend of the Schmidt rebound hammer number in Figure 20 was the same as the trend of the compressive strength, splitting tensile and flexural strength. The higher addition percentage of the DS decreased the Schmidt rebound hammer number in all mixtures with DS relative to the control mixture. As the DS content increased, the Schmidt test revealed a deterioration in specimen quality. The rebound numbers derived from all mixtures provided underestimations of the experimentally determined compressive strengths at 28 days.

Despite the big difference between the two tests (Schmidt rebound hammer and the compressive strength), there is an excellent agreement in the results with coefficient R^2 is 0.9905 as depicted in Figure 21(a), with the following empirical equation for estimation:

$$\text{Compressive strength (MPa)}=-0.0086\,(\text{Rebound number})^2+0.9416\,(\text{Rebound number})+12.716 \quad (3)$$

Furthermore, from the results, there was another excellent agreement in the relationship between Schmidt rebound hammer and splitting tensile strength, with coefficient R^2 is 0.9959 with the following empirical equation for estimation, as shown in Figure 21(b):

$$\text{Splitting tensile strength (MPa)}=0.0004\,(\text{Rebound number})^2+0.0725\,(\text{Rebound number})+1.1929 \quad (4)$$

Table 13. Schmidt rebound hammer and UPV results

Mixture ID	Schmidt Rebound Hammer Number	Ultrasonic Pulse Velocity UPV (km/sec.)
D0	29	4.57
D1	25	4.52
D2	20	4.43
D3	17	4.32
D4	11	4.24

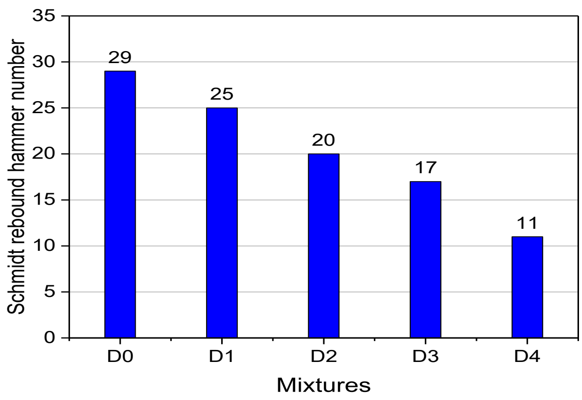
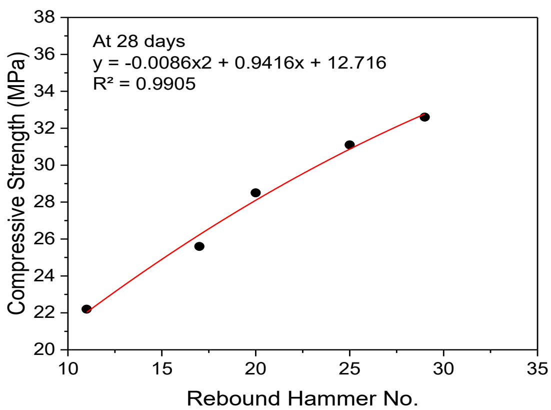
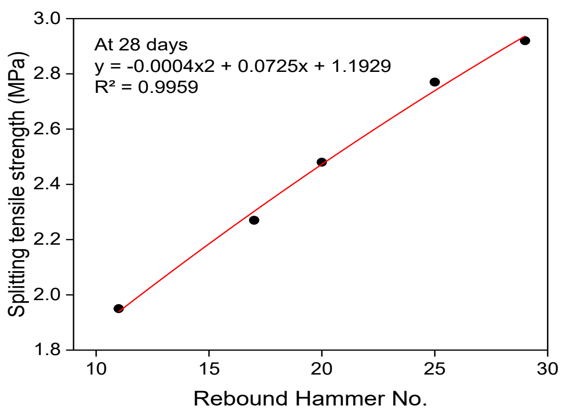


Figure 20. Schmidt Rebound Hammer test results



(a)



(b)

Figure 21. The relationship between rebound number at 28 days vs. a) compressive strength, and b) splitting strength

4.8 UPV test

The results of the ultrasonic pulse velocity UPV test measured at the age of 28 days for all mixtures are listed in Table 13. The trend of the UPV in Figure 22 was the same as the trend of the compressive strength, splitting tensile strength and Schmidt rebound hammer number in Figure 16, Figure 17, and Figure 20, respectively. The addition of the DS reduced slightly the UPV for mixtures by 1.25% and 2.5% while it decreased significantly in mixtures with 3.75% and 5% of DS relative to the control mixture. The anticipated reduction in UPV was attributed to the formation of porous concrete caused by DS particles. This porosity compromised the bond between DS and cement paste, leading to decreased UPV values in samples with increased DS content relative to control specimens.

There is a reasonable agreement in Ultrasonic Pulse Velocity results with compressive strength and splitting tensile strength with coefficients (R^2=0.9964) and (R^2=0.9895), respectively as shown in Figures 23(a) and (b), with the following empirical Eqs. (4)-(5) for estimation:

$$\text{Compressive strength (MPa)}=-20.209\ (\text{Rebound number})^2+208.62\ (\text{Rebound number})-498.87 \quad (5)$$

$$\text{Splitting tensile strength (MPa)}=-0.4211\ (\text{Rebound number})^2+6.5319\ (\text{Rebound number})-18.148 \quad (6)$$

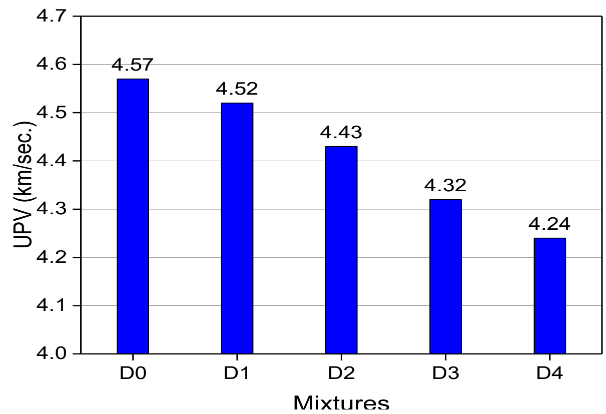
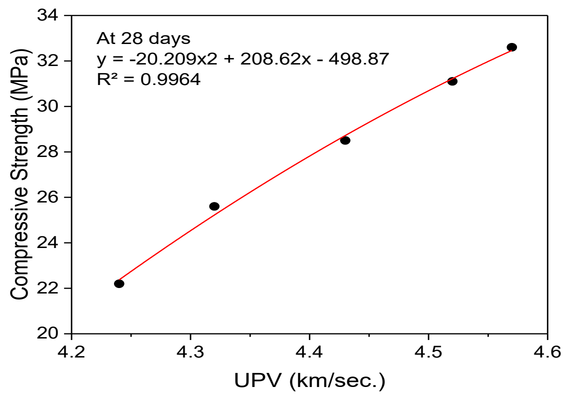
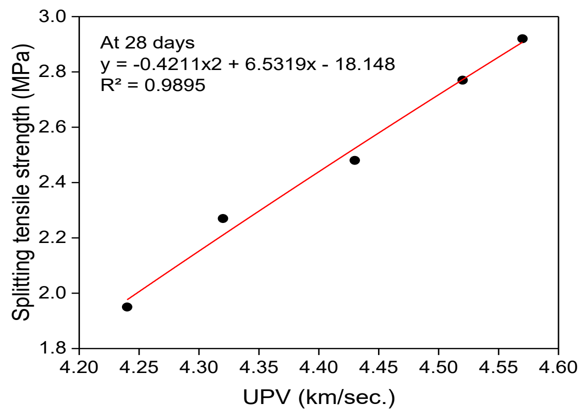


Figure 22. Ultrasonic Pulse Velocity (UPV) Tests



(a)



(b)

Figure 23. The relationship between Ultrasonic pulse velocity (UPV) at 28 days vs. a) compressive strength and b) splitting tensile strength

4.9 Rapid chloride permeability test (RCPT)

Table 14 presents the charge passed (in coulombs) after 6 hours for the average of three samples subjected to the RCPT. According to Figure 11, all samples exhibited in moderate range of chloride permeability. From the results depicted in Figure 24, the chloride ion penetration increased by increasing the DS ratio replacement with 5%, 13%, 21% and 26% for D1, D2, D3 and D4, respectively relative to the control mixtures. Less ion penetration means less permeability and less electrical conductance. Chloride ion permeability is influenced by several factors, including water-cement ratio, cement type and quantity, the use of replacement materials within the mortar mixture, and the age of the specimen [40, 41]. Therefore, adding an organic material with high porosity increased the chloride permeability.

Table 14. RCPT results

Mixture ID	Chloride Ion Permeability	Percentage Increase in Chloride Ion Permeability
D0	2214	--
D1	2328	5
D2	2504	13
D3	2685	21
D4	2788	26

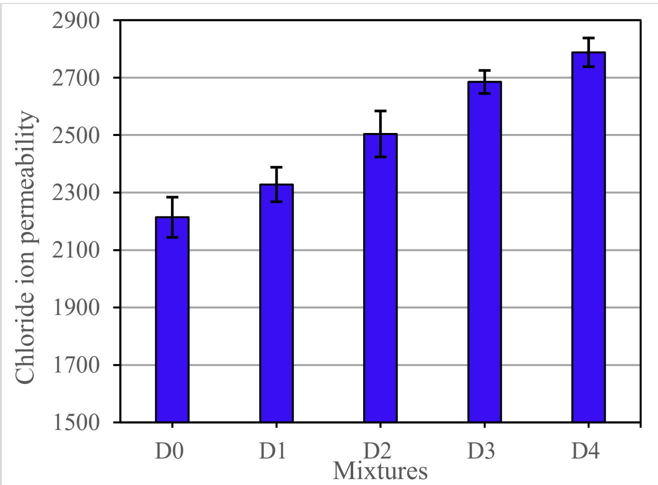


Figure 24. The Rapid Chloride permeability results chart

4.10 Elevated temperature

The results of the influence of the elevated temperature test on the weight and compressive strength of the mixtures with and without DS are listed in Table 15. Slightly reduced in compressive strength was recorded under 150°C for all mixtures with 2.1%, 2.6%, 2.8%, 4.3%, and 5.9% for D0, D1, D2, D3, and D4, respectively. While a significant reduction observed under higher temperature at 450°C with 8.6%, 10.6%, 14.4%, 22.3%, and 28.4% for D0, D1, D2, D3, and D4, respectively. The mixtures with lower DS percentages (i.e., D1 and D2) had almost the same resistance to heat as the control mixture. Figure 25 shows the percentage of weight loss for specimens at varied temperatures. The results showed that the weight reduction increased in mixtures with more DS content. However, this reduction was not significant. The mixture with 5% of DS contents (D5) suffered from a reduction of 2.7%, 6.3%, and 8.2% at 150°C, 300°C, and 450°C, respectively, relative to the control mixture. Weight loss is likely due to spalling attributed to the internal water pressure generated at approximately 450°C, as well as the dehydration process of hydrated calcium silicate hydrate, which induces micro-cracks through increased internal stresses [3, 42]. The visual aspect of the specimens after heat exposure is presented in Figure 26.

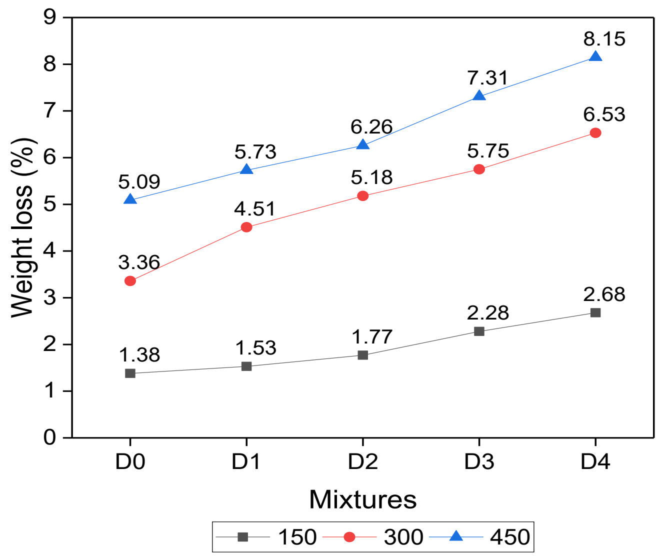


Figure 25. The effect of elevated temperature on weight loss of concrete with DS

Table 15. The effect of elevated temperature on concrete compressive strength with different DS ratios

Mixture ID	Temperature	Specimen Weight Before Subjected to Heat (g)	Specimen Weight After Subjected to Heat (g)	Compressive Strength (MPa)	Reduction in Compressive Strength (%)
	150°	2390	2357	31.9	2.1
D0	300°	2384	2304	30.8	5.5
	450°	2375	2254	29.8	8.6
	150°	2353	2317	30.3	2.6
D1	300°	2351	2245	29	6.8
	450°	2356	2221	27.8	10.6
	150°	2313	2272	27.7	2.8
D2	300°	2316	2196	25.6	10.2
	450°	2318	2173	24.4	14.4
	150°	2284	2232	24.5	4.3
D3	300°	2278	2147	22.2	13.3
	450°	2285	2118	19.9	22.3
	150°	2236	2176	20.9	5.9
D4	300°	2235	2089	18.6	16.2
	450°	2232	2050	15.9	28.4

(a) Before heating

(b) After heating at 150

(c) After heating at 300

(d) After heating at 450

Figure 26. Color change for models containing different percentages of DS under heating

5. CONCLUSION

The current study experimentally evaluated the feasibility of incorporating DS as a partial replacement for fine aggregates in concrete, with replacement levels of 1.25%, 2.5%, 3.75%, and 5% by volume of fine aggregate. The investigation covered fresh, hardened, non-destructive, and durability properties to assess the practical implications of DS-based concrete in construction.

1) Slump decreased significantly with higher DS contents due to water absorption by DS particles, with a 46% reduction at 5% replacement.
2) The concrete density exhibited a reduction of up to 6.4% at a 5% DS replacement, demonstrating its potential for the manufacture of lightweight concrete which is suitable for lightweight construction applications.
3) As the DS content increased, reductions were observed in compressive, tensile, and flexural strengths. Specifically, at a DS level of 5%, the compressive strength exhibited a significant decline of 29%. In contrast, a lower DS content of 1.25% resulted in only a marginal reduction of 2.6% at 56 days.
4) Non-destructive testing methods, including the rebound number and ultrasonic pulse velocity (UPV), demonstrated a strong correlation with mechanical strength, particularly compressive strength. These results validate their accuracy and effectiveness as reliable technical for assessing material quality and structural integrity.
5) A high dosage of DS content (3.75%-5%) leads to a substantial reduction in compressive strength, while decreases of up to 42%. Consequently, its application is suitable for structural elements that require low to moderate compressive strength. Nevertheless, the incorporation of high DS dosages contributes significantly to sustainable construction by repurposing agricultural waste and reducing dependence on conventional building materials, thereby facilitating the production of environmentally friendly concrete.
6) DS-based concrete exhibited higher chloride permeability porosity, limiting its use in aggressive environments due to its impact on long-term durability.
7) The elevated temperature test showed that higher DS content in mixtures led to greater weight loss and significant compressive strength reduction, especially at 450°C, limiting, the thermal resistance of DS-based concrete for fire-prone applications.

Future research should enhance the use of DS in concrete through pre-treatment methods, such as surface coating and chemical modification, to reduce water absorption and improve bonding. Optimizing particle size can increase packing density and minimize porosity. Comprehensive durability studies, including freeze-thaw cycles and sulfate attach tests, along with microstructural analysis using SEM and XRD, are essential. Additionally, identifying the optimal DS content, refining processing methods, and integrating supplementary materials like fly ash can improve the performance of DS-based concrete for high-performance applications.

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