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Optimizing Date Seed Utilization in Green Concrete: A Methodological Evaluation

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ABSTRACT

Concrete is one of the most widely used construction materials globally; however, its production contributes significantly to carbon dioxide emissions. In the Middle East, annual date production is substantial, and date seeds, as a byproduct, are typically discarded. This study investigates three methods for incorporating date seeds into concrete: (1) Cement replacement: Using powdered date seeds (PDS) as a partial substitute for cement at 5%, 10%, 15%, and 20% levels; (2) Aggregate replacement: Replacing coarse aggregates with crushed date seeds (CDS) at 10%, 20%, and 30% ratios and (3) Hybrid approach: Combining PDS (0%, 5%, 10%, and 20%) with fly ash (fixed at 20%). Mechanical tests revealed that replacing cement with up to 10% PDS had no significant impact on compressive strength, whereas higher replacement levels reduced strength. Similarly, increasing the aggregate replacement percentage led to a decline in concrete strength. In contrast, the hybrid approach—combining PDS with 20% fly ash—enhanced compressive strength. Based on these findings, the third method emerged as the most effective for improving both the strength and sustainability of concrete. The optimized hybrid mixture was selected for further comprehensive evaluation, including tests for tensile strength, flexural strength, water absorption (porosity), sulfate resistance, and freeze-thaw durability. These assessments aimed to verify not only the mechanical properties but also the long-term durability of the modified concrete under diverse environmental conditions.

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1. Introduction

Concrete is one of the most widely used construction materials globally, playing a vital role in modern infrastructure. However, cement production—a key component of concrete—poses significant environmental challenges, including substantial greenhouse gas emissions and the depletion of natural resources [1–4]. Consequently, the development of sustainable concrete and eco-friendly alternatives has emerged as a critical research priority. To address this, researchers have focused on reducing cement consumption by incorporating sustainable substitute materials. Among these, organic pozzolans have garnered increasing attention due to their demonstrated effectiveness in enhancing concrete properties [5–9].

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The impact of pozzolanic waste materials on the durability, physical, and mechanical properties of cementitious materials has been extensively studied [10–13]. The utilization of waste materials as substitutes for cement in concrete, particularly to mitigate the negative environmental impacts of cement production and enhance the mechanical properties and durability of concrete, has garnered significant attention in recent years. Recycling such waste materials offers a dual benefit: reducing ecological footprints while generating economic savings [14–17]. For instance, studies have explored food industry by-products (e.g., sugar factory residues) and agricultural wastes (e.g., date seeds, walnut shells, eggshells, and peanut shells) as viable cement replacements. These materials act as pozzolanic additives, improving concrete properties while lowering cement consumption and its associated environmental burden. Notably, combining them with supplementary pozzolans (e.g., fly ash) has shown further improvements in durability under harsh conditions.

Among sugar industry wastes, carbonated sludge has also been investigated [18]. Sugar production generates substantial by-products like bagasse, molasses, and calcium carbonate sludge, which can be repurposed for value-added applications. While molasses has been tested in cementitious systems [19–22], bagasse has found reuse across industries [23-30], particularly in food industry [31–33].

A promising strategy to reduce concrete's environmental impact involves partial replacement of conventional materials with agricultural wastes. Walnut shell is one of the agricultural wastes that has been recognized as a pozzolanic material in the concrete industry. Researchers have shown that walnut shell can improve the mechanical properties of concrete while reducing cement consumption [34-38]. These researchers have reported that the addition of walnut shell to concrete can enhance the compressive and flexural strengths while reducing porosity and improve the concrete performance under various environmental conditions, including freeze-thaw cycles. Eggshell has also been studied as another pozzolanic material in concrete research [39-44]. Studies indicate that this material, particularly when combined with other substances such as fly ash, can enhance the mechanical properties and durability of concrete [45-49]. These studies have shown that powdered eggshell, due to its high calcium content and mineral composition, can improve concrete performance under heavy loads and environmental cycles such as freeze-thaw conditions. Another agricultural waste that has been explored as a cement substitute in concrete is the peanut shell. This material, due to its pozzolanic properties, can strengthen the mechanical characteristics of concrete. Some studies have demonstrated that incorporating peanut shell into concrete mixtures enhances its microscopic and mechanical properties, resulting in a stronger and more durable material capable of withstanding various environmental conditions [50-53].

Of these, date seeds stand out due to their untapped potential [54–58]. With millions of tons produced annually, date seeds—largely discarded—contain pozzolanic compounds suitable for cement substitution [57, 58]. However, existing studies lack a systematic comparison of application methods (e.g., powder replacement vs. hybrid use with fly ash).

This study introduces a novel approach by not only investigating the use of date seeds as a substitute in concrete but also systematically evaluating and comparing different methods of its application. Unlike previous studies, which have not comprehensively assessed various techniques—such as grinding the date seeds into powder, using date seeds as a direct replacement, or combining date seeds with supplementary cementitious materials (e.g., fly ash), this study addresses this gap by: (1) Evaluating three different methods of date seeds incorporation including: cement replacement with powdered date seeds (PDS) (5–20%), aggregate replacement with crushed date seeds (CDS) (10–30%) and hybrid use of PDS (0–20%) + fly ash (20%); and (2) Comprehensively assessing mechanical properties (compressive/tensile/flexural strengths) and durability (water absorption, sulfate resistance, freeze-thaw cycles). By identifying the optimal approach, this work advances sustainable construction practices while offering a practical solution to repurpose agricultural waste, ultimately reducing the construction sector's environmental footprint.

2. Materials and Methods

2.1. Collection and Preparation of Materials

In all experiments, Type II Portland cement was used (see Table 1). The water-to-cement ratio (w/c) was maintained between 0.4 and 0.45 based on the test type: 0.42 for aggregate replacement with CDS and 0.45 for the other two cases, in accordance with ASTM C192 standards. We used drinking water from Sabzevar city, which met pH requirements (see Table 2 for complete characteristics).

All aggregates complied with ASTM C33 requirements. The sand used in this study had a maximum particle size of 4.75 mm, 5% moisture content, and a fineness modulus of 3.45. To enhance concrete's mechanical properties, coarse aggregates—including pea gravel (4.75-9.5 mm) and crushed stone (9.5-19 mm)—were used, both with 0% moisture content. All aggregates were sourced from Sarakhs Tangshur-Sardar Road, Iran.

Table 1.
Chemical Composition of Type II Portland Cement

Oxides		(%)		Key Factors		(%)	
		MIN	MAX			MIN	MAX
Silicon Dioxide	SiO2	20.50	22.0	Lime Saturation Factor	LSF	92.0	97.0
Aluminium Oxide	Al2O3	4.60	5.30	Silica Module	SiM	2.40	2.60
Ferric Oxide	Fe2O3	3.50	4.00	Alumina Module	AlM	1.20	1.40
Calcium Oxide	CaO	63.00	65.00	Tricalcium Silicate	C3S	50.00	60.00
Magnesium Oxide	MgO	1.50	2.50	Dicalcium Silicate	C2S	15.00	25.00
Sulphur Trioxide	SO3	1.50	2.50	Tricalcium Aluminate	C3A	5.00	8.00
Potassium Oxide	K2O	0.50	0.70	Tetracalcium Aluminate	C4AF	10.0	12.00
Sodium Oxide	Na2O	0.30	0.50				
Loss on Ignition	L.O.I	1.00	2.50				
Insoluble Residue	I.R.	0.10	0.70				
Free Lime	Free CaO	0.70	1.40				

Table 2.
Chemical and physical characteristics of drinking water used in experiments compared with relevant standards

Property	**Unit**	**Desired Maximum**	**Permissible**	**Used Water**
Odor	TON	Max 2 units at 12°C and Max 3 units at 25°C	-	3 at 25°C
Color	TCU	-	15	12
pH	-	6.5 - 8.5	6.5 - 9	7.2
Hardness	ppm	200	500	450
TDS	ppm	1000	1500	1400
Turbidity	NTU	≤ 1	5	4

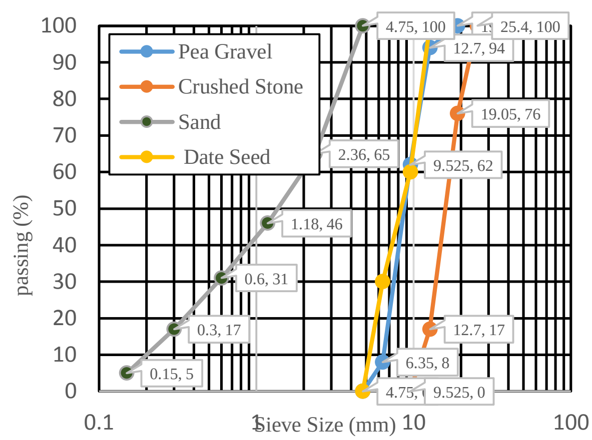

Figure 1. Aggregate Gradation Based on ASTM C33

All aggregates complied with ASTM C33 requirements. The sand used in this study had a maximum particle size of 4.75 mm, 5% moisture content, and a fineness modulus of 3.45. To enhance concrete's mechanical properties, coarse aggregates—including pea gravel (4.75-9.5 mm) and crushed stone (9.5-19 mm)—were used, both with 0% moisture content. All aggregates were sourced from Sarakhs Tangshur-Sardar Road, Iran.

Date seeds were primarily obtained from a date syrup production factory in Dashtestan, Bushehr Province, Iran - one of the country's main date processing centers that generates substantial date seed waste. After collection, the date seeds were transferred to the laboratory for processing. To evaluate date seed effects through three different approaches, processing occurred in three stages:

1. PDS as Partial Cement Replacement

Date seeds were dried in an oven at 110°C for 24 hours to reduce moisture content. After drying, they were ground using either a ball mill or hammer mill to achieve a particle size below 75 µm (comparable to cement). The powder was substituted for cement at replacement levels of 5%, 10%, 15%, and 20%.

1. CDS as Coarse Aggregate Replacement

Date seeds were first crushed with a jaw crusher, then sieved to match the size distribution of coarse aggregates. CDS replaced coarse aggregates at levels of 10%, 20%, and 30%.

3. Combined Use of PDS and Fly Ash

This method incorporated PDS (processed as in Method 1) with fly ash. A fixed 20% fly ash replacement was selected due to its well-documented benefits including: (1) Pozzolanic reaction with calcium hydroxide enhances strength and durability and (2) Reduces cement consumption and carbon emissions without compromising structural integrity. PDS were tested at 0%, 5%, 10%, and 20% alongside 20% fly ash baseline. The control sample contained 20% fly ash and 0% PDS.

To figure out the best method, compressive strength was measured for all three methods mentioned above. The optimal method underwent additional tests: splitting tensile and flexural strengths, water absorption, sulfate attack and freeze-thaw resistances.

3.1. Test Method

To evaluate the quality of the produced concrete, the following tests were conducted:

Compressive Strength: The compressive strength test was conducted in accordance with ASTM C39. The concrete cube specimens of 150 × 150 × 150 mm were prepared and cured for 7, 28, and 90 days. Before testing, their surfaces were inspected to ensure they were flat and free of irregularities. Then the specimens were centered in the compression testing machine, ensuring that the top surface was in direct contact with the loading plate. A continuous and uniform load was then applied at a specified rate (0.25 ± 0.10 MPa/s) until the specimen failed. Finally, the maximum load sustained before failure was recorded. The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen.

Splitting Tensile Strength: The splitting tensile strength test was conducted on cylindrical specimens with dimensions of 15x30 cm, following ASTM C496. This test evaluates the tensile strength of concrete by applying a diametral compressive load until failure. The applied load generates tensile stresses perpendicular to the loading direction, causing the specimen to split along its vertical axis. This test is essential for assessing the indirect tensile strength of concrete (as given by Eq. 1), which influences its cracking resistance and structural performance.

$$\sigma_t = \frac{2 \times P}{\pi \times d \times t} \tag{1}$$

Where σ_t, P, d and t are respectively the splitting tensile strength (MPa), applied compressive load at failure (N), diameter of the specimen (mm) and thickness (or length) of the specimen (mm).

Flexural Strength: The flexural strength test was conducted on beam specimens (10×10×50 cm) in accordance with ASTM C78. This test evaluates concrete's resistance to bending forces through a third-point or center-point loading until failure. It provides critical insights into the tensile behavior of concrete under flexural stress, which is essential for designing beams, pavements, and other structural elements subjected to bending loads. Flexural strength was calculated using Equation 2:

$$\sigma_{fb} = \frac{3 \times P \times l}{2 \times b \times d^2} \tag{2}$$

Where σ_{fb}, P, l, b and d are respectively flexural strength (MPa), maximum applied load at failure (N), span length (distance between supports, mm), width of the specimen (mm) and depth (or height) of the specimen (mm.)

Water Absorption (w): The water absorption test was conducted in accordance with ASTM C642 to evaluate concrete porosity. This test quantifies the water absorption capacity of concrete specimens, serving as a direct indicator of porosity. Specimens were first oven-dried at 105 ± 5°C until reaching constant mass (W_d). The dried specimens were then fully submerged in water at room temperature for 48 hours to achieve saturation. After removal from water, surface moisture was carefully removed with a damp cloth to determine the saturated surface-dry mass (W□). Finally, the specimen's submerged mass ($W_{□ub}$) was measured. Water absorption and total porosity were calculated using Equations 3 and 4, respectively.

$$Water\ Absorption(\%) = \frac{(Ws - Wd)}{Wd} \times 100 \tag{3}$$

$$Total\ Porosity\ (\%) = \frac{(Ws - Wd)}{(Ws - Wsub)} \times 100 \tag{4}$$

Sulfate Attack Resistance (Weight Loss Method): To assess the chemical durability of concrete against sulfate attack, 50 mm cube specimens were immersed in a 5% sodium sulfate ($Na_2\ SO_4$) solution for 90 days following standard durability testing protocols. Prior to immersion, all specimens were fully cured and surface-dried to ensure uniform exposure conditions. Sulfate attack resistance was quantified by measuring mass loss percentage, which indicates cement matrix degradation caused by sulfate-induced expansion and cracking. After exposure, specimens were removed, surface-dried, and weighed. The mass difference before and after immersion was used to calculate the percentage mass loss, with greater values corresponding to reduced chemical resistance. The sulfate attack resistance (expressed as percentage mass loss) was calculated using Equation 5.

$$R_s = \frac{Winitial - Wsulfate}{W\ initial} \times 100 \tag{5}$$

Where R_s, $Winitial$ and $Wsulfate$ are respectively sulfate attack resistance (expressed as percentage weight loss), initial weight of the specimen (before sulfate exposure) and weight of the specimen after sulfate exposure.

Resistance to Freeze-Thaw Cycles: The freeze-thaw resistance of concrete was evaluated in accordance with ASTM C666 (Method A) to assess durability under cyclic freezing and thawing conditions. After 14 days of initial curing, specimens were saturated in limewater prior to testing. Each freeze-thaw cycle consisted of: (1) Cooling to -18°C (freezing); (2) Heating to +4°C (thawing) and (3) Maintaining specimens fully submerged in water throughout. Specimens were periodically removed (every 30 cycles) for evaluation by: (1) Measuring mass loss of surface-dried specimens; (2) Recording length changes and (3) Conducting visual inspections for surface deterioration (cracking, spalling). Freeze-thaw resistance was quantified using Equation 6.

$$\text{Weight Loss (\%)} = \frac{Winitial - Wfinal}{W\ initial} \times 100 \tag{6}$$

Where $Winitial$ and $Wfinal$ are respectively the initial weight of the specimen before cycles and weight after a specified number of cycles (e.g., after 30 cycles).

4. Test Results

4.1. Compressive strength results

4.1.1. Effect of PDS as a Partial Cement Replacement

This study demonstrates the viability of PDS as a sustainable partial cement replacement in concrete. Compressive strength was evaluated at replacement levels of 5%, 10%, 15%, and 20% across 7-, 28-, and 90-day curing periods (see Figure 2). The results show a gradual decline in compressive strength as the replacement ratio increases. The control sample (with no substitution) achieved compressive strengths of 28 MPa, 38 MPa, and 45 MPa respectively at these intervals, providing a strong baseline for comparison. While the early-age strengths (7-day compressive strength) showed slight variations, the results were generally encouraging. At 5% and 10% replacement levels, the compressive strength decreased by approximately 3% to 7% across different ages. Specifically, at 7 days, the strength dropped from 28 MPa (control sample) to 27.16 MPa (5% PDS) and 26.32 MPa (10% PDS). This demonstrates that even at early curing stages, the integrity of the concrete remains intact with PDS.

A similar trend was observed at 28 and 90 days, with reductions of about 4% to 6% compared to the control sample, showcasing a performance that is well within the acceptable range for structural applications. These results highlight how small adjustments in cement composition can yield comparable mechanical properties while reducing cement consumption. The results also confirmed the suitability of PDS as a sustainable alternative. The strength reductions have been attributed to the limited pozzolanic reactivity of PDS and the dilution of cementitious compounds. However, the reduction remained within an acceptable range, indicating that up to 10% replacement could be feasible for sustainable concrete production. The long-term performance of the concrete was particularly impressive. At 90 days, strengths of 42.75 MPa and 40.3 MPa for 5% and 10% substitution levels indicate the ongoing pozzolanic activity of PDS. This underscores its ability to contribute to strength development over time, making it a promising supplementary cementitious material.

Even at higher substitution levels (15% and 20%), the results remained within a feasible range for applications where sustainability is prioritized over peak mechanical performance. At a 15% replacement ratio, a more noticeable strength decline occurred, with a 10% to 12% reduction in strength at different ages. The compressive strength at 28 days dropped from 38 MPa (control sample) to 33.44 MPa, highlighting the negative impact of excessive cement replacement. When the replacement level reached 20%, the strength loss became significant, with reductions of approximately 15% to 18%. The 90-day compressive strength decreased from 45 MPa (control sample) to 36.90 MPa, confirming that an excessive amount of PDS negatively affects the hydration process.

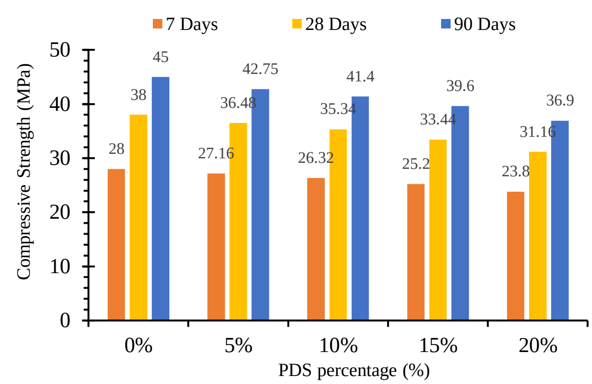

Figure 2. Compressive strength of concrete samples with different PDS replacement as cement at various ages

4.1.2. Effect of CDS as Coarse Aggregate Replacement

Figure 3 presents the compressive strength development of concrete mixtures containing CDS as partial coarse aggregate replacement at 0% (control), 10%, 20%, and 30% replacement levels. Strength measurements were conducted at 7, 28, and 90 days of curing. The results show a gradual reduction in compressive strength as the percentage of CDS replacing coarse aggregate increases. At 10% replacement, the compressive strength slightly decreases across all ages, with a reduction of about 4% to 5% compared to the control sample. However, the reduction at this level remains within an acceptable range, suggesting that small amounts of CDS replacement may still produce structurally viable concrete.

At 20% replacement, a more significant decline in compressive strength is observed, with reductions of approximately 10% to 14% at different curing ages. The decrease in the proportion of strong natural aggregates results in a less dense and cohesive microstructure, and thus further contributing to strength loss.

When 30% of the coarse aggregate is replaced, the compressive strength shows a substantial decline of 18% to 22% compared to the control sample. This considerable reduction suggests that at higher replacement levels, the weaker nature of date seed aggregates dominates the concrete matrix, leading to lower mechanical performance. Therefore, while partial replacement at lower percentages may be feasible, exceeding 20% to 30% replacement significantly compromises the mechanical integrity of the concrete and is not recommended for structural applications requiring high strength.

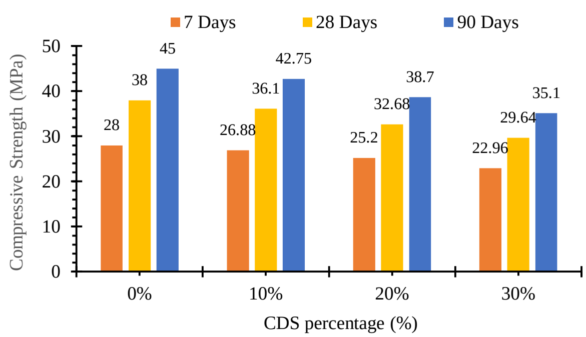

Figure 3. Compressive strength of concrete samples with different CDS replacement as coarse aggregate at various ages

4.1.3. Effect of Combining PDS with Fly Ash

This phase evaluated concrete mixtures containing PDS as a cement replacement alongside 20% fly ash. PDS replacement levels ranged from 0% to 20% (5% increments). The sample containing 20% fly ash and 0% PDS was considered the control mix for comparative evaluation. Compressive strength development was assessed at 7, 28, and 90 days (see Figure 4).

The results indicate a gradual decline in compressive strength with increasing percentages of PDS. At 7 days, the control mix showed the highest compressive strength of 29.5 MPa, which decreased slightly to 27.4 MPa for the mixture with 20% PDS. A similar trend is observed at 28 and 90 days, where the control sample reached 40.5 MPa and 48 MPa respectively, while the 20% replacement sample achieved 37.4 MPa and 44 MPa.

Although the reduction in compressive strength is evident with higher percentages of PDS, the results demonstrate that even with 20% substitution, the concrete maintained a reasonably high compressive strength. This suggests that PDS, when used in combination with fly ash, can be a feasible supplementary cementitious material, particularly in applications where environmental sustainability and resource efficiency are prioritized over maximum strength.

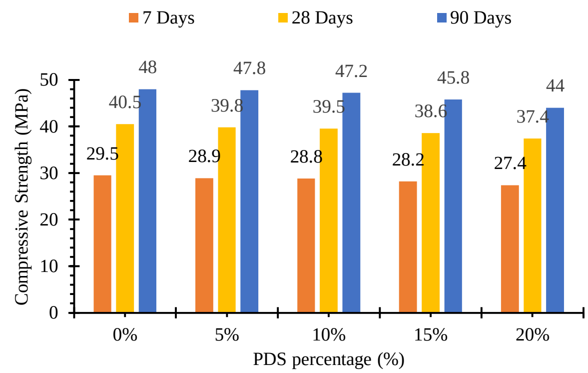

Figure 4. Compressive strength of concrete samples with different percentages of PDS replacement alongside 20% fly ash at different ages

Moreover, the rate of strength development between 28 and 90 days indicates continued pozzolanic activity, especially in the mixtures with lower percentages of PDS. This long-term gain highlights the potential for the use of agricultural waste such as date seeds in sustainable concrete production, supporting both waste valorization and carbon footprint reduction in the construction industry.

By getting precisely into the results, one can observe that at 5% replacement, the compressive strength decreased by 2.0% at 7 days, 1.7% at 28 days, and 0.4% at 90 days, compared to the control sample. The minimal strength loss at 90 days suggests that the pozzolanic activity of fly ash and fine organic particles from the PDS may compensate for the reduced cement content over time. At 10% replacement, the compressive strength showed a reduction of 2.4% at 7 days, 2.5% at 28 days, and 1.7% at 90 days relative to the control sample. This indicates that up to 10% PDS can still maintain acceptable strength levels, possibly due to improved particle packing and delayed pozzolanic contribution. At 15% replacement, strength losses became more pronounced, with 4.4% at 7 days, 4.7% at 28 days, and 4.6% at 90 days. The decrease is still within acceptable ranges for certain non-structural applications, though the trend shows that higher dosages begin to adversely affect mechanical performance. At the highest replacement level of 20% replacement, compressive strength declined by 7.1% at 7 days, 7.7% at 28 days, and 8.3% at 90 days. Although strength remains relatively high, this level of replacement may be more suitable for low-strength applications or where sustainability is prioritized over mechanical performance. In summary, incorporating PDS up to 10% as a partial cement replacement in the presence of fly ash results in minimal strength reduction, especially at later curing ages. This highlights the potential of agricultural waste utilization in green concrete technology, aligning with environmental goals without significantly compromising material performance.

4.1.4. Which Method Prevails? A Comparative Assessment

The compressive strength tests were performed for all three proposed methods of incorporating date seed into concrete including replacing cement with PDS, replacing coarse aggregate with CDS, and combining PDS with fly ash. The results indicated varying degrees of strength reduction depending on the replacement level and the method used. While partial cement and aggregate replacement with date seed showed acceptable performance at lower percentages, the third method—combining PDS with 20% fly ash—demonstrated superior compressive strength values, especially at 28 and 90 days of curing.

Based on these results, the third method was identified as the most effective and promising approach for enhancing both strength and sustainability in concrete. Therefore, this combination was selected for further investigation. Additional tests, including tensile strength, flexural strength, water absorption (porosity), sulfate attack and freeze-thaw resistances, were conducted to comprehensively evaluate the mechanical and durability performance of concrete containing this optimized mix.

4.2. Splitting Tensile Strength Results

The splitting tensile strength of concrete mixtures containing 20% fly ash and varying percentages of PDS was evaluated to assess the indirect tensile behavior of the modified concrete. As shown in Figure 5, a gradual decrease in tensile strength was observed with increasing replacement levels of PDS. The control mixture (0% PDS with 20% fly ash) achieved a tensile strength of 3.8 MPa. When 5% and 10% of cement were replaced with PDS, the tensile strength slightly declined to 3.6 MPa and 3.4 MPa, respectively. Despite the reduction, these values remain within acceptable limits for structural applications, especially where moderate tensile performance is sufficient.

The tensile strength exhibited a dose-dependent decrease at higher PDS substitution levels (15-20%), measuring 3.1 MPa (15%) and 2.8 MPa (20%). This trend can be attributed to the lower pozzolanic reactivity of organic materials compared to cement, as well as the dilution of the binder matrix. Nevertheless, the decline is consistent and indicates a predictable behavior, which is valuable for mix design optimization in sustainable construction.

Overall, the results suggest that the incorporation of up to 10% PDS alongside 20% fly ash can maintain adequate tensile strength, while higher levels may limit structural use but still offer potential in non-load-bearing or low-stress elements where environmental benefits are prioritized.

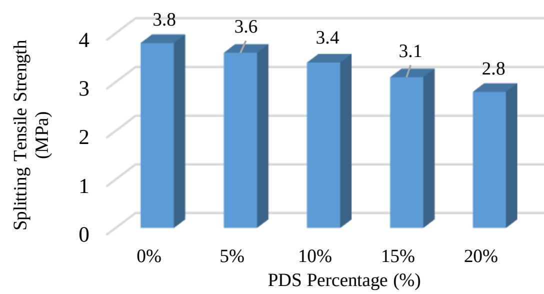

Figure 5. Splitting Tensile Strength of Concrete with Different Percentages of PDS and 20% Fly Ash

4.3. Flexural Strength Results

The flexural strength of concrete containing 20% fly ash with PDS replacements (0-20%) was evaluated through three-point bending tests. As shown in Figure 6, the results demonstrate a consistent decrease in flexural strength as the replacement percentage of PDS increased. The control mixture (0% PDS) exhibited the highest flexural strength of 5.5 MPa. Upon replacing 5% of the cement with PDS, the strength declined to 5.2 MPa, and further dropped to 4.9 MPa at the 10% replacement level. This trend of reduction continued as the replacement percentage increased: at 15%, the flexural strength decreased to 4.5 MPa, and at 20% replacement, it reached its lowest value of 4.2 MPa.

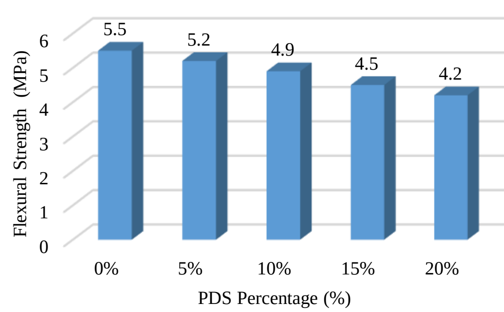

Figure 6. Flexural Strength of Concrete with Different Percentages of PDS and 20% Fly Ash

This progressive reduction in flexural strength is attributed to the decreasing cementitious content and the relatively lower binding capacity of organic materials like PDS. Despite the reductions, the values up to 10% replacement remain within the acceptable range for structural concrete, especially in applications where moderate flexural strength is sufficient. For higher replacement levels, although the strength decreases, the trend is predictable, which is valuable for sustainable concrete mix design.

4.4. Water Absorption and Porosity

Water absorption and porosity - critical indicators of concrete permeability and durability - were evaluated for mixtures containing 20% fly ash with PDS replacements (0-20%). As presented in Figure 7, both water absorption and porosity increased with the rising content of PDS. At 0% replacement, the control mix showed a water absorption of 5.2% and a porosity of 12.5%, indicating a relatively dense and impermeable matrix. With 5% and 10% replacement, water absorption rose to 5.5% and 5.9%, respectively, while porosity reached 13.1% and 13.8%. This slight increase is likely due to the less dense structure introduced by the organic date seed particles.

As the replacement level increased to 15% and 20%, the water absorption values rose to 6.3% and 6.8%, and porosity reached 14.4% and 15.0%, respectively. This behavior can be attributed to the reduced amount of cementitious material and the increased presence of porous, low-reactivity particles. The organic nature and irregular surface texture of PDS may also contribute to higher void content and moisture retention capacity in the hardened matrix. In conclusion, while the use of PDS enhances sustainability, it also leads to an increase in permeability-related properties. For durability-critical structures, the replacement level should ideally be limited to 10% to balance mechanical performance with long-term resilience.

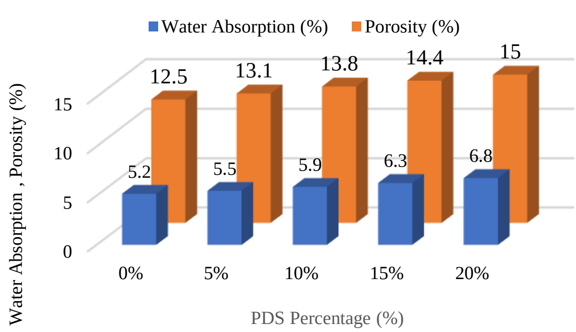

Figure 7. Water Absorption and Porosity of Concrete with Different Percentages of PDS and 20% Fly Ash

4.5. Sulfate Resistance – Weight Loss Analysis

Sulfate resistance for mixtures containing 20% fly ash and PDS (0-20%) was evaluated through 90-day immersion in 5% Na_2SO_4 solution, with results shown in Figure 8. The control sample (0% PDS) exhibited a weight loss of 2.1%, indicating good sulfate resistance due to the presence of fly ash, which helps reduce permeability and improves the matrix density. As the percentage of PDS increased, a gradual rise in weight loss was observed. At 5% and 10% replacement levels, the weight loss increased to 2.3% and 2.6%, respectively—still within acceptable durability thresholds. However, at 15% and 20% replacement, the weight loss reached 3.0% and 3.5%, respectively, suggesting a weakening resistance against sulfate attack. This can be attributed to the reduced content of reactive cementitious materials and the introduction of organic components, which may increase porosity and reduce the matrix's resistance to chemical degradation.

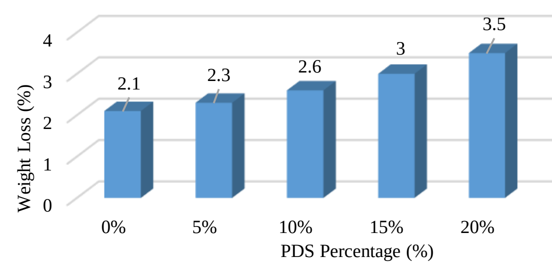

Figure 8. Weight Loss of Concrete Specimens after 90 Days of Sulfate Exposure with Different Percentages of PDS and 20% Fly Ash

These results highlight that while partial incorporation of PDS contributes to sustainability, higher substitution levels negatively affect chemical durability. To ensure long-term performance in sulfate-rich environments, it is recommended to limit the replacement level to 10% or lower when using this combination.

4.6. Freeze-Thaw Resistance

Freeze-thaw durability was assessed through three cycles of testing for concrete containing 20% fly ash and varying PDS contents (0-20%). The mass loss progression is detailed in Table 3 and Figure 9. The control sample (0% PDS) showed excellent resistance, with only 0.45% total weight loss after three cycles. Concrete with 5% and 10% PDS showed slightly higher but still acceptable weight losses of 0.65% and 0.83%, respectively, suggesting adequate durability under moderate freeze-thaw conditions. However, higher replacement levels (15% and 20%) resulted in more significant degradation. At 20% replacement, the total weight loss reached 1.50%, along with visible surface scaling and minor cracking. This decline in resistance is likely due to the increased porosity and reduced matrix density caused by the organic content of PDS. Overall, the results suggest that replacing cement with up to 10% PDS in combination with fly ash does not significantly compromise freeze-thaw resistance, but

Table 3.
Results of Freeze-Thaw Tests on Concrete Specimens including 20% Fly Ash and Different Percentages of PDS.

PDS (%)	Initial Weight (gr)	Weight after Cycle 1 (gr)	Weight Loss (%)	Weight after Cycle 2 (gr)	Weight Loss (%)	Weight after Cycle 3 (g)	Weight Loss (%)
0%	8000	7990	0.13%	7976	0.30%	7964	0.45%
5%	8010	7986	0.30%	7969	0.51%	7958	0.65%
10%	7995	7967	0.35%	7945	0.63%	7929	0.83%
15%	8030	7988	0.52%	7960	0.87%	7937	1.16%
20%	7985	7934	0.64%	7900	1.06%	7865	1.50%

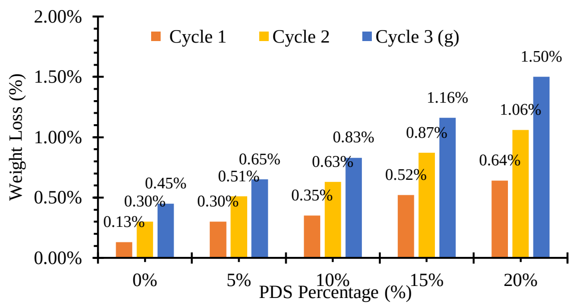

Figure 9. Weight loss (calculated from freeze-thaw tests) of concrete specimens including 20% fly ash and different percentages of PDS

higher replacement levels may lead to premature deterioration in harsh environments.

5. Conclusion

Based on the experimental findings, this study demonstrates that date seeds, an abundant agricultural byproduct in the Middle East, can be effectively incorporated into concrete to enhance sustainability while maintaining structural performance, reducing cement consumption and utilizing agricultural byproducts. Among the three methods investigated, the key findings are as follows:

1. PDS as Cement Replacement: Replacing cement with up to 10% PDS showed no significant reduction in compressive strength, whereas higher replacement levels (15–20%) led to decreased strength.
2. CDS as Coarse Aggregate Replacement: Partial replacement of coarse aggregates with CDS (10–30%) led to a consistent decrease in concrete strength, making this method less favorable for structural applications.
3. Combination of PDS and Fly Ash: The hybrid approach of blending PDS (up to 20%) with 20% fly ash improved compressive strength, suggesting a synergistic effect that enhances performance.
4. Based on these results, the optimal method for utilizing date seeds in concrete is their combination with fly ash, as it not only improves mechanical properties but also contributes to eco-friendly construction by reducing cement consumption, repurposing agricultural waste and promoting sustainability.
5. The optimal mix—5–10% PDS with 20% fly ash—maintained acceptable compressive, tensile, and flexural strengths while improving sustainability. Although higher replacement levels increased porosity and slightly reduced durability, mixes within the recommended range exhibited sufficient sulfate and freeze-thaw resistance for non-aggressive environments.
6. These findings support the use of date seed-fly ash blends in eco-friendly concrete production, offering a practical solution to reduce cement consumption and repurpose agricultural waste without compromising structural performance.
7. The study paves the way for further research into optimizing mix designs to maximize both environmental and performance benefits. Future research should explore long-term durability, thermal properties, economic feasibility for broader industrial adoption and other potential applications of date seed-modified concrete

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