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Original Article

Effect of Date Seeds Ash Incorporation with Micro Silica on the Cement Mortar Behavior and Mix Integrity

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Abstract

This study evaluates the performance of cement mortar incorporating micro silica (MS) and thermally treated date seed ash (DS) as sustainable partial cement replacements, in line with the demand for improved construction materials that utilize available resources. In the absence of an understanding of the behavior resulting from combining MS and DS within a hybrid replacement system particularly regarding how different blending ratios influence mortar performance and mix integrity. To achieve this, five mixtures were prepared with a total replacement level of 20% including three hybrid blends and were assessed through flowability, compressive strength, sorptivity, dry density, water absorption, and Ultrasonic Pulse Velocity (UPV) tests. Predictive models have also been developed to estimate chloride and sulfate penetration based on physical and non-destructive indicators. The results showed that the hybrid mixture MS15–DS5 demonstrated the most notable enhancement compared to the control mix, achieving a 6% increase in compressive strength a 42% reduction in sorptivity and clear increases in dry density and pulse velocity indicating a more compact internal structure. The MS10–DS10 mixture also exhibited improved behavior, though to a lesser degree. In contrast, increasing the DS content led to performance deterioration, where MS5–DS15 showed reduced strength and higher sorptivity and DS20 presented the weakest response, with an 8% reduction in compressive strength and a 32% increase in sorptivity. The predictive models also demonstrated high accuracy achieving R^2 of 0.989 and 0.983 for chloride and sulfate penetration, respectively, supporting their ability to estimate future behavior based on physical properties. These results provide a clearer understanding of how combining MS and DS influences mortar behavior and mix integrity, and they contribute to the development of sustainable cementitious mixtures with improved performance when appropriate replacement levels are selected.

Keywords: *Date Seeds, Micro Silica, Flowability, Compressive Strength, Ultrasonic Pulse Velocity (UPV).*

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1. Introduction

Historically, Iraq is one of the richest countries in palm trees. The abundance of this results in a substantial amount of agricultural by-products date seeds (DS) which is scientifically known as "Phoenix dactylifera L". Exploring the use of these DS as partial replacements of cement in concrete presents an opportunity to utilize local resources, reduce construction costs, and promote sustainable construction applications. Recently, producing concrete incorporating with DS is becoming widely considered because of urban development worldwide and the demand for enhancing mix performance and reducing the waste and carbon emission.

Due to the DS significant amount of holocellulose, α-cellulose, and Klason lignin, these substances are characterized as lignocellulosic, considering them ideal for enhancing mechanical strength, structural integrity, and sustainability. The DS (Phoenix dactylifera L.) are high in holocellulose, α-cellulose and Kalson lignin, thus considered as a lignocellulosic material suitable for improving mechanical strength, structural and sustainable properties and for lowering the bulk density specific gravity and absorption capacity [1]. Consequently, this encourages the employment of DS in structural lightweight concrete industry as the produced concrete possess durability characteristics close to that of other conventional lightweight concrete [2], [3]. In the literature, the DS was investigated upon their addition in various proportion to the concrete mix in form of whole seed, granules, powder, or ash substituting as partially or fully instead of cement, fine aggregate (FA) or coarse aggregate (CA) in mortar or concrete mixture, see Table 1. Subsequent studies concluded a continuous reduction in compressive strength of proposed mix concrete upon replacing CA with whole DS [4]-[6]. Shah et al. [7] attributed this drop to the characteristics of the DS used such as shape, porosity, texture, and capacity of water absorption.

Adefemi et al., [3] advised using the DS only to partially replace the CA rather than fully if adequate compressive strength is desired. whereas Palh et al., [6] suggested the treatment by DS to be limited for structural components that are subjected to low or moderate strength requirements. Granules or powder of DS was explored as partly substitution of FA or cement material in the concrete mix, it is produced by collecting the seeds, cleaning them from impurities and drying them off till the seeds become dry and grinding them to a certain micro size. Sarathkumar et al., [8] studied mechanical properties of the concrete properties such as compressive, split tensile and flexural strength after utilization of DS incorporation with tamarind seed TS as a partial replacement of FA. The results indicated that a combination comprising 10% DS and 1.5% TS as replacements for FA nearly matches the strength of the control concrete mix; dissimilarity, increasing these replacement proportions will reduce both the concrete's strength and workability. These results aligned with those reported by Rajasekaran & Balamurugesan, [9] who substituted DS and TS with the CA. Under acidic conditions, Elazizi et al., [10] considered DS powder as a partial replacement of ordinary Portland cement (OPC). Depending on the dosage, they observed that the compressive strength of the mortar samples rise progressively at varied ages and the admixture behaves as a natural setting accelerator and contributes in enhancing durability.

On other hand, many investigators considered DS ash as partial or full replacement to pozzolanic fine material in concrete mixture or in mortar. The DS ash can usually be prepared by calcining the seeds in oven at high temperature which may reach 650 co or more for a certain period of time exceeding several hours, that could be achieved during one or two stages. Gunarani & Chakkravarthy, [11] studied how the existence of DS ash for various curing duration could impact the strength possessions of a cement sand mortar. Results recognized that replacing OPC in the mortar with 2% DS ash can offer additional bond strength and cause to double the compressive strength if compared to 4% which deemed an optimal value while replacement with 8% enhanced alkaline character. Consequently, it can be recommended for a situation where coating of acid resistance is performed. Alsalami et al., [12] examined the potential of producing a high performance concrete by using whole DS, Crushed DS and DS ash as replacement of concrete components. The three forms of DS were replaced discretely by weight of the CA, FA and cement respectively by means of various shares up to 20%. Main conclusion was that even though the compressive strength has declined to about 28%–40%, it still consider within tolerable limits. Smith, [13] reported the DS ash as a good pozzolana, it reduces the workability and capacity of water absorption while increases the consistency, initial and final setting times of cement pastes. So, the treatment is considered an appropriate particularly for construction works that include long haulage distances. With the intention of enhancing the compressive strength, it was endorsed to use up to 10% DS ash. Other attempt by Saeed et al., [14] investigated the effect of swapping out the DS ash partially to function as a filler material in the composition, and comparing the characteristics of the DS ash with two pozzolanic materials: fly ash and natural pozzolana. The DS ash concrete mixes with 10%, 20%, and 30% replacement levels demonstrated higher compressive and tensile strengths and lower, density, and workability in comparison to natural pozzolan and fly ash. The study was combined with numerical investigation by Saeed et al., [15] mainly for evolution of the thermal properties and the heat of hydration. Results showed a significant reduction in the heat of hydration in DS powder concrete, with levels comparable to the fly ash. Saeed et al. [16] studied the effect of calcined DS powder beside a commercial retarder, the results showed that the thermally treated DS powder had a significant effect on delaying the initial and final setting time of concrete and decreasing the evolution of heat of hydration and peak temperature when the replacement quantities enlarged. The density of the calcined DS concrete, thermal conductivity, specific heat capacity, and UPV also decreased with increasing DS powder dosage. Alkhaldi, [17] used DS ash in concrete mixtures, according to the results. Maximum strength was obtained by replacing 20% of the cement with DS ash. The use of DS ash significantly lowered carbon emission linked with the concrete manufacturing process. Author suggested to performing much research to validate his findings and investigate the long-term durability effects of DS ash-incorporated concrete Auta et al., [18] considered the composition of ES powder and DS ash. Finding stated that DS ash was high in silica content reaching 42.75% of its dry weight while other minerals oxides together (SiO2+Al2O3+Fe2O3) represent only 45.38% of its dry weight. However, The ES ash was rich in lime content 55.45% of its dry weight. Amanah and Khalil, [19] carried out an experimental program to evaluate the suitability of incorporating DS besides ES powder in concrete.

The results illustrated that the optimal replacement content is 15% replacement of DS as volume fraction of natural CA in the concrete. This content reduces thermal conductivity, flexural strength, and compressive strength, by about 6%, 9.81%, and 19.37%, respectively, compared to the concrete mixtures containing only eggshells powder at 28-day age. Furthermore, the water absorption and permeability of DS concrete were increased whenever DS level ascended, but permeability and water absorption values were lower than 10% and 50 mm, respectively, which indicate the good quality of this concrete. This investigation demonstrates that ES powder and DS can be successfully used as waste materials to produce high-strength, sustainable concrete with acceptable properties.

Although the individual effects of micro silica and date-seed-derived materials have been explored in previous studies, the interaction between these two materials within a hybrid replacement system remains insufficiently characterized. This work focuses on evaluating hybrid MS–DS mixtures to better understand how their combined incorporation influences strength development and key physical properties.

2. Materials and Methodology

2.1 Materials Used Characterization

The experimental program in this study included the characterization of the raw materials used in the mortar mixtures. A natural river sand conforming to ASTM C33 [20] requirements was used as the fine aggregate. The sand exhibited a specific gravity of 2.62, an SO_3 content of 0.14% a fineness modulus of 2.90 and a maximum particle size of 2.36 mm. The gradation curve of the sand is presented in Fig.1. In addition, three mineral-based materials ordinary Portland cement (OPC), micro silica (MS), and thermally treated date seeds ash (DS) were utilized for producing the mix samples. The OPC used was Type I and met ASTM C150 [21] standards. Additionally, micro silica, an ultrafine and highly reactive pozzolanic is primarily composed of amorphous silica per ASTM C1240 [22] . To enhance its physical and chemical characteristics, the date seed underwent a multi-step treatment process.

Table 1. Date seed form, replacement type, target material, size, and proportions in previous studies

References	Form of DS	Type	Material Replaced	Size	Ratio
Almograbi, [2]	Whole	Full	CA	≤ 4.75 mm	100%
Adefemi et al., [3]	Whole	Partial & full	CA	----	0-100%
Akib et al., [4]	Whole	partial	CA	-----	0- 25%
Ahmed et al., [5]	Whole	partial	CA	4.75- 10 mm	0- 4%
Palh et al.,[6]	Whole	partial	CA	4.75-10 mm	0- 4%
Shah et al., [7]	Whole	Partial &full	CA	-----	0-100%
Sarathkumar et al., [8]	Crushed	Partial	FA	≤4.75 mm	10- 20%
Rajasekaran &Balamu-rugesan [9]	Whole	Partial	CA	----	10-25%
Elazizi et al., [10]	powder	partial	OPC	≤ 212 μm	0- 4%
Gunarani & Chakkravarthy, [11]	Ash	partial	OPC	≤ 90 μm	0-10%
Alsalami et al., [12]	Whole, crushed and ash	partial	CA, FA, cement	-	5- 20%
Smith, [13]	Ash	partial	OPC	≤ 75 μm	0-20%
Saeed et al.,[14]	powder	Partial	OPC	75 μm	0.5-5%
Saeed et al.,[15]	Calcined powder	Partial	OPC	75 μm	10-30%
Saeed et al., [16]	Calcined	Partial	OPC	75 μm	5-30%
Alkhaldi, [17]	ash	Partial	OPC	-	0-40%
Auta et al., [18]	ash	Partial	OPC	90 μm	0-12.5%
Amanah & Khalil [19]	Whole	Partial	CA	5-10 mm	0-35%

The seeds were first thoroughly rinsed to remove impurities, then air-dried for two days. This was followed by oven drying at 70°C for 48 hours to eliminate any remaining moisture. The dried seeds were then ground and passed through a mesh 75 μm to ensure uniform particle size. The powder was subjected to two thermal treatments: initially heated to 450°C for four hours to break down organic material and reduce carbon content, then treated at 650°C for two hours to boost crystallinity and chemical reactivity. Gradual cooling inside the furnace helped prevent microcracks and structural stress. The final dark powder product is referred to as DS . Fig.2. demonstrates part of the preparation and calcination of the DS used. The physical and chemical properties of OPC, MS, and DS are summarized in Table 2 , including the pozzolanic activity index (PAI) were compared with ASTM C1240 for MS and ASTM C618 for DS, in accordance with ASTM C618, a pozzolanic activity index of ≥75% is required.DS primarily acts as a fine filler rather than an actively pozzolanic material , which is consistent with the X-ray Diffraction (XRD) pattern Fig.3. , indicating that after calcination at 650°C it shows a partial transition from amorphous to more crystalline phases ,It is also silica-rich, in agreement with Auta et al. (2023) [18]. Meanwhile, MS exhibits a broad amorphous feature characteristic of non-crystalline silica, and OPC displays sharp reflections corresponding to clinker minerals (alite and belite).

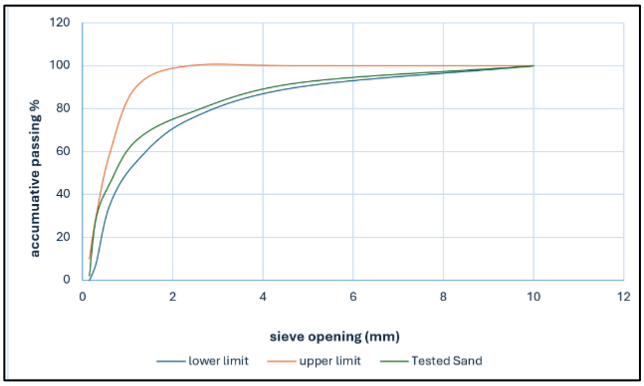

Figure 1. Fine aggregate gradation curve according to ASTM C33 limits

Figure 2. Sequential processing stages for thermally treated date seed powder: (a) washing and air drying, (b) oven drying at 70°C, (c) grinding, and sieving, (d) pyrolysis at 450°C, (e) activation at 650°C.

Table 2. Chemical Composition and Physical Properties of the Materials Used

Oxide Component	MS	ASTM C1240-٢٠	OPC	DS
CaO	2.58	-	60.86	2.5
SiO_2	92.0	≥ 85.0	18.64	56.2
Al_2O_3	0.34	-	7.71	9.8
Fe_2O_3	1.31	-	1.98	3.0
MgO	0.2	-	4.35	1.6
SO_3	–	-	2.26	–
L.O.I	2.17	≤6.0	0.96	2.95
Specific surface (m^2/g)	16	≥15	0.4325	1.1
% Retained on 45 μm	7	≤ 10	–	27
PAI at 7 days (ASTM C311-11) (%)	112%	≥ 105%	–	71%

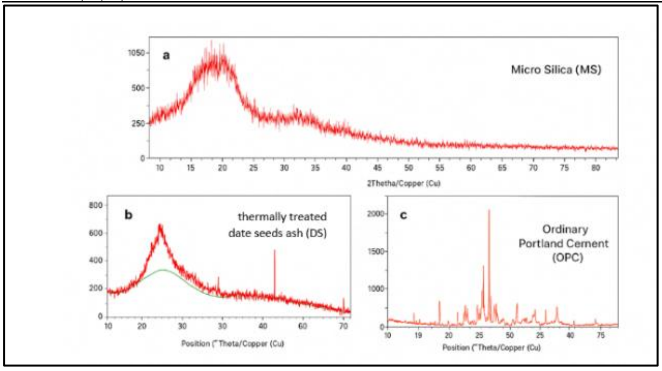

Figure 3. XRD patterns of (a) MS, (b) DS and (c) OPC

2.2 Testing Program and Mix Preparation

The experimental program was designed to evaluate the fresh, mechanical and physical properties of mortar incorporating MS and DS. A mortar mixture were prepared with a fixed total cement replacement of 20% distributed between MS and DS, as shown in Table 3. A constant water/cement ratio of 0.42, 1% superplasticizer, and 700 kg/m³ of sand were used for all mixtures to ensure consistent conditions across the experimental matrix. The dry components cement, sand, MS, and DS were first blended to achieve uniform distribution. Water premixed with the superplasticizer was then gradually added until the required flow diameter. This controlled sequence ensured mix integrity, which in this study refers to the ability of the mortar to maintain a homogeneous, cohesive and segregation free structure throughout mixing, casting, and curing. Maintaining mix integrity required achieving uniform particle dispersion, preventing bleeding and ensuring stable and repeatable fresh and hardened behavior across all batches. The fresh mortar was then cast into standardized molds and compacted manually using a metallic rod to eliminate entrapped air. After 24 hours, specimens were demolded and transferred to water curing at 23 ± 2°C following ASTM C192 until the testing age of 28 days. A comprehensive suite of tests was performed to assess the performance of the mixtures. Flowability was measured using ASTM C1437. Compressive strength was evaluated on 50×50×50 mm cubes following ASTM C109 with molding and compaction performed as specified in the standard. Sorptivity was assessed in accordance with ASTM C1585**.** While ultrasonic pulse velocity (UPV) measurements were performed following ASTM C597, which specifies the procedure for determining the pulse velocity through a specimen as a non-destructive testing method. Density, total water absorption, and porosity were determined based on ASTM C642. Uniformity and consistency across these properties provided further indicators of mix integrity. The synergy index (SI) was calculated to quantify combined effects of MS and DS, and hybrid durability models were developed to estimate chloride and sulphate penetration. The overall preparation and testing sequence is illustrated in Fig.4 .

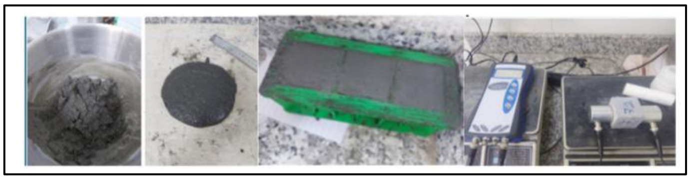

Figure 4. Mortar preparation steps and UPV testing using an ultrasonic pulse velocity.

Table 3. Mix Design of Mortars Containing MS and DS

Mix ID	Cement (kg/m³)	MS (%)	DS (%)
CM (Control)	350	0	0
MS20	280	20	0
MS15–DS5	280	15	5
MS10–DS10	280	10	10
MS5–DS15	280	5	15
DS20	280	20	0

3. Results and discussion

3.1 Workability Assessment Using Flow Table Test

The workability of the fresh cementitious mixes was assessed using the flow table method in accordance with ASTM C1437 [23]. As shown in Fig.٥, the CM mix free from supplementary materials exhibited the highest flow diameter of 180 mm, reflecting its higher workability. The incorporation of MS20 resulted in a 22% reduction in flowability compared to CM which is attributed to the high surface area and ultrafine texture of MS particles that increase water demand and restrict particle mobility. These findings are consistent with the reports of authors [24]– [27]. Gradual replacement of MS with DS modified the fresh-state behavior of the mixes. Compared to the CM the MS15–DS5 and MS10–DS10 mixtures showed reductions in flowability of 19% and 11%, respectively indicating that substituting part of the micro silica with date-seed ash decreases the overall water demand. On the other hand, the MS5–DS15 mixture exhibited only an 8% reduction, which suggests that increasing the proportion of DS begins to offset the viscosity-enhancing effect of MS resulting in slightly improved flowability without compromising cohesion Increasing DS content to DS20 caused a 14% reduction, likely due to the fibrous and irregular organic nature of DS, which introduces inter-particle friction and hinders dispersion at higher dosages [13], [14]. Overall, the results demonstrate a sensitive balance between the viscosity-enhancing effect of MS and the flow-improving contribution of DS powder. Thus, all mixtures fall within the range of normal workable mortar.

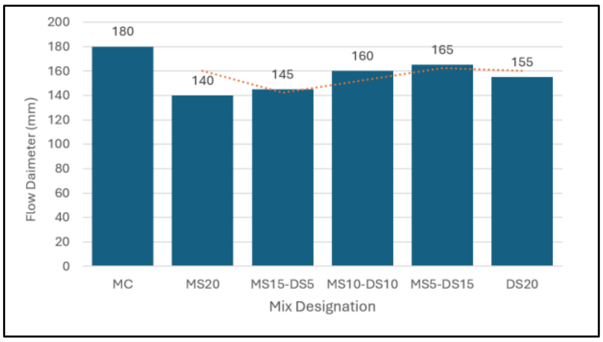

Figure 5. Flow table test results for different mixes

3.2 Compressive Strength

In accordance with ASTM C109/C109M-20b [28], the compressive strength of all cementitious mixes was evaluated at 7, 14, and 28 days of water curing. As shown in the Fig. 6, all mixes exhibited a gradual increase in strength with age, reflecting the combined effect of cement hydration and pozzolanic reactions. At 7 and 14 days, the mixes incorporating micro silica MS20 and MS15-DS5 clearly outperformed the reference mix CM, indicating the early reactivity of micro silica in producing additional calcium silicate hydrate (C–S–H) gel [25]– [27]. In contrast, the mixes with higher date seed (DS) content (MS5-DS15 and DS20) exhibited relatively lower strength for all age due to the porous and fibrous nature of DS particles. By 28 days, the CM mix achieved a compressive strength of 34.3 MPa, while the MS20 mix reached the highest value of 37.8 MPa (a 10.2% increase compared to the control). The hybrid mix MS15- DS5 also demonstrated strong performance with 36.37 MPa , 6.0% increase confirming that this replacement level preserves the mechanical benefits of micro silica while introducing a sustainable organic component. The MS10-DS10 mix recorded 35.0 MPa at 28 days , 2.0% higher than the control but 7.4% lower than MS20, while MS5-DS15 dropped to 32.1 MPa (6.4% lower than the control) and the DS20 mix showed the lowest strength of 31.4 MPa an 8.5% reduction. This is corroborated by the satisfactory crack pattern observed in the tested specimens at 28 days as shown in Fig. 7 . These findings are consistent with previous studies [13]–[16], which reported that excessive DS content weakens strength development due to the formation of non-load-bearing voids.

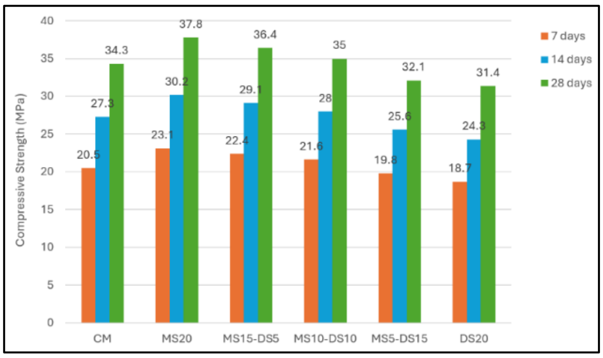

Figure 6. Compressive strength development of mixes over time.

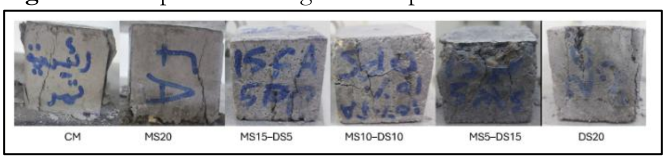

Figure 7. Fracture patterns after 28-day compressive strength testing for mixes.

3.3 Synergy Index in Hybrid Mixes

In this work, synergy was quantified as the direct ratio between the measured compressive strength (f_{obs}) of the hybrid mix and the expected compressive strength based on the linear rule-of-mixtures f_{exp}, as expressed in Equation (1):

$$SI = \frac{f_{obs}}{f_{exp}} \qquad (1)$$

the single-additive strengths were first established using MS20 and DS20 as reference boundaries. Strengths at intermediate replacement levels 5%, 10%, and 15% were then obtained through linear interpolation, assuming that each material MS and DS contributes proportionally to its dosage. This linear-additive approach reflects the first order behavior of blended cementitious systems [29] and is consistent with methodologies used to assess combined admixture efficiency in multi-component cement blends [30], [31]. Accordingly, the expected strength of each hybrid mix was calculated as:

$$f_{exp} = xf_A + yf_B \qquad (2)$$

where $x$and $y$represent the fractional shares of MS and DS, represent the compressive strengths of the corresponding single additive reference mixtures at the same total replacement level At 28 days, the MS10–DS10 mixture exhibits the highest synergy SI ≈ 1.016, followed by MS15–DS5 1.009. The MS5–DS15 mixture shows a neutral to slightly antagonistic response SI ≈ 1.000–0.976. These results, as shown in Fig. 8, indicate that balanced proportions of the two additives provide gains beyond the linear expectation, whereas increasing the share of the less-reactive component diminishes performance.

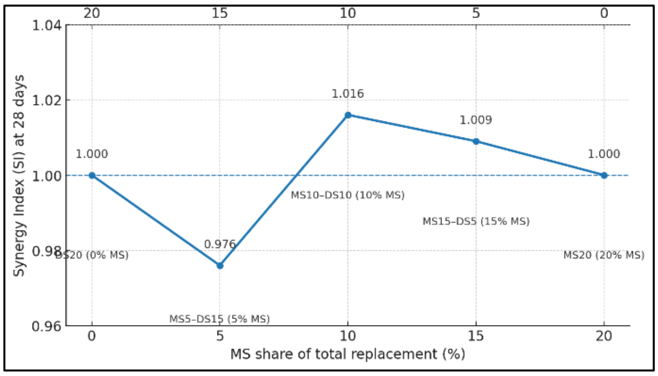

Figure 8. Synergy index (SI) at 28 Days for MS–DS Mixes vs. MS/DS replacement shares.

3.5 Interrelationship Between Microstructural Properties and Ultrasonic Pulse Velocity at 28 Days

After 28 days of water curing, a comprehensive evaluation of dry density, total water absorption, porosity, and ultrasonic pulse velocity (UPV) was performed to assess the microstructural integrity of the mixes, in accordance with ASTM C642 [32] and ASTM C597 [33]. The CM mix recorded a dry density of 2162 kg/m³, porosity of 12.0%, water absorption of 5.1% and a UPV of approximately 4.1 km/s. The MS20 mix exhibited the most refined microstructure, with a 53.3% reduction in porosity from 12.0% to 5.6% and 11.8% decrease in water absorption from 5.1% to 4.5%, and an increase in dry density from 2162 to 2200 kg/m³. It also achieved the highest UPV of 4.6 km/s, indicating a denser and less permeable internal matrix. On the other hand, the DS20 mix recorded the lowest dry density 2135 kg/m³ , highest porosity 13.6% , highest water absorption 6.2% and the lowest UPV 3.6 km/s , reflecting poor microstructural compactness and higher discontinuity due to organic content. Hybrid mixes such as MS15–DS5 and MS10–DS10 demonstrated more balanced characteristics. The MS15–DS5 mix showed the highest dry density (2218 kg/m³), with porosity of 5.8%, absorption of 5.0%, and UPV of 4.4 km/s. The MS10–DS10 achieved 2216 kg/m³, 6.0%, 5.3% and 3.7 km/s respectively, indicating that blending MS and DS in appropriate ratios enhances microstructural cohesion. DS15–MS5 exhibited a dry density of 2160 kg/m³ porosity of 9.8%, water absorption of 5.6% and UPV of 3.8 km/s indicating a noticeable decline in microstructural compactness due to the dominance of organic content and limited contribution from the low MS content. As shown in Fig. 9, dry density shows a clear inverse trend with both porosity and water absorption, while exhibiting a direct and consistent increase with UPV. These trends confirm the progressive enhancement or degradation in internal compactness across the mixtures.

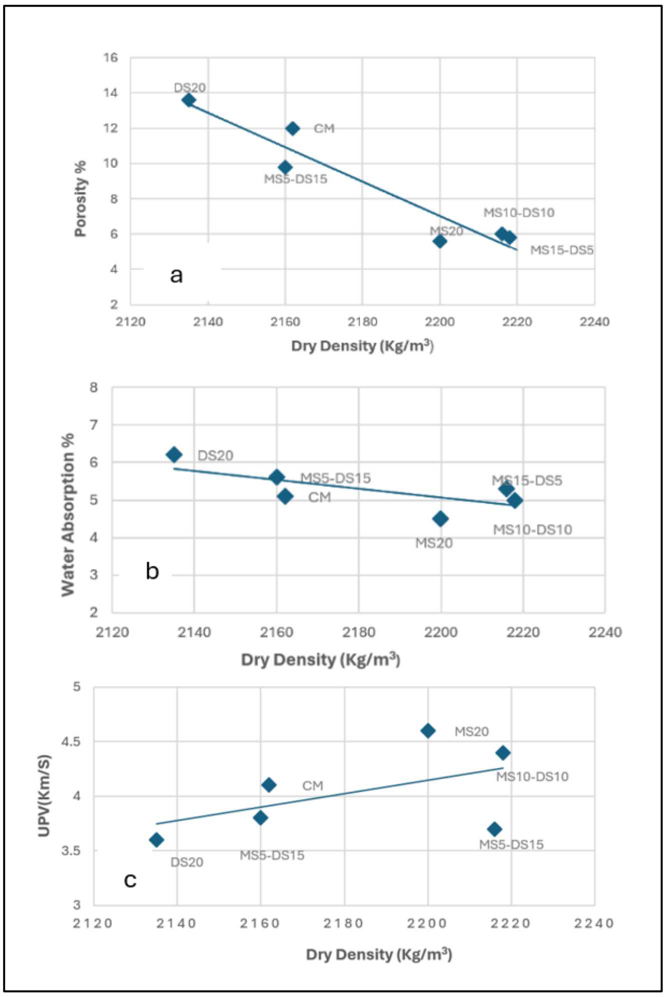

Figure 9. a. Porosity vs dry density, b. Water absorption vs dry density, c. UPV vs dry density.

3.4 Sorptivity Response of Mixes

The sorptivity of the cementitious mixes was evaluated at 28 days in accordance with ASTM C1585 [34]. Which involves recording the amount of water absorbed per unit surface area at specific time intervals. The results are typically plotted as a function of cumulative absorption versus the square root of time with the sorptivity coefficient determined from the slope of the initial linear portion of the absorption curve. As shown in Fig. 10, the results revealed a clear correlation between mix composition and sorptivity behavior. The CM mix exhibited a sorptivity value of 0.092 mm/√min, serving as a baseline reference. The inclusion of MS20 significantly reduced the sorptivity to 0.042 mm/√min marking a 54.3% decrease. This reduction is attributed to the high pozzolanic reactivity of MS which promotes the formation of additional calcium silicate hydrate (C–S–H) gel thereby reducing pore connectivity and enhancing matrix density and impermeability. Conversely, the mix containing DS20 recorded the highest sorptivity value of 0.121 mm/√min representing a 31.5% increase compared to the control. This increase is likely due to the fibrous and porous nature of the organic filler which fosters the development of a more interconnected capillary network that facilitates water transport within the matrix. Hybrid mixes exhibited intermediate behavior. The MS15-DS5, MS10-DS10, and MS5-DS15 mixes showed sorptivity values of 0.053, 0.062 and 0.090 mm/√min respectively, reflecting the balance between the pozzolanic action of MS and the influence of organic material. These results indicate that moderate amounts of DS powder can retain the densifying benefits of MS, while excessive substitution reverses these advantages by reintroducing porosity. Overall, the data confirm a clear inverse relationship between MS content and sorptivity and a direct relationship between sorptivity and increased organic content beyond optimal levels. This underscores the importance of carefully calibrating additive proportions to develop cementitious mixtures with low permeability and enhanced durability, particularly in moisture-sensitive or aggressive service environments.

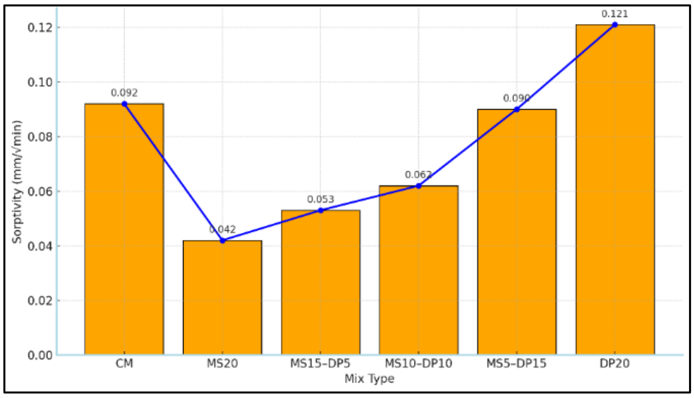

Figure 10. Sportively Values for Different Mixes

3.5 Prediction of Chloride and Sulfate Ion Penetration

A hybrid model was developed to predict the penetration depths of chloride ion D_{cl} and sulfate ions D_{SO_4} penetration depths in the investigated cementitious mixtures[35]. The process begins with the semi-empirical relations shown in Equations (2) and (3) which generate baseline penetration-depth estimates as functions of UPV, and volumetric porosity (φ) from:

$$D_{Cl} = 20 \cdot \varphi \cdot exp(-0.5 \cdot UPV), \quad (3)$$

$$D_{SO_4} = 18 \cdot \varphi \cdot exp(-0.45 \cdot UPV) \quad (4)$$

These baseline values provide a physically interpretable starting point that reflects the influence of pore connectivity and the inverse association between UPV and internal discontinuities.

To improve the predictive capability beyond this two-parameter formulation, the baseline depths were integrated with five experimentally measured microstructural indicators sorptivity (S) , water absorption (A), dry density (ρ), UPV, and volumetric porosity (φ) and used to train a supervised data-driven regression model Random Forest . This integration enables the model to capture nonlinear and higher order interactions among the microstructural properties that are not explicitly represented in the semi-empirical relations.

The predicted chloride and sulfate penetration depths listed in Table 4 were evaluated by direct comparison with the baseline depths obtained from the semi-empirical expressions, which served as the ground-truth reference for computing the model accuracy (R^2). The strong agreement between the hybrid predictions and the baseline reference $R^2 = 0.989$ for chloride and 0.983 for sulfate demonstrates the robustness of the approach. The corresponding response-surface representations in Fig. 11 (a–b) visualize the trends between UPV, porosity, and penetration depth, further supporting the predictive structure of the model.

Table 4. Predicted chloride and sulphate penetration depths

Mix ID	Chloride penetration depth D_{Cl} (mm)	Sulphate penetration depth D_{SO_4} (mm)
CM	29.2	42.60
MS20	9.8	15.30
MS15-DS5	10.7	18.28
MS10-DS10	12.0	29.10
MS5-DS15	21.1	34.80
DS20	26.5	41.70

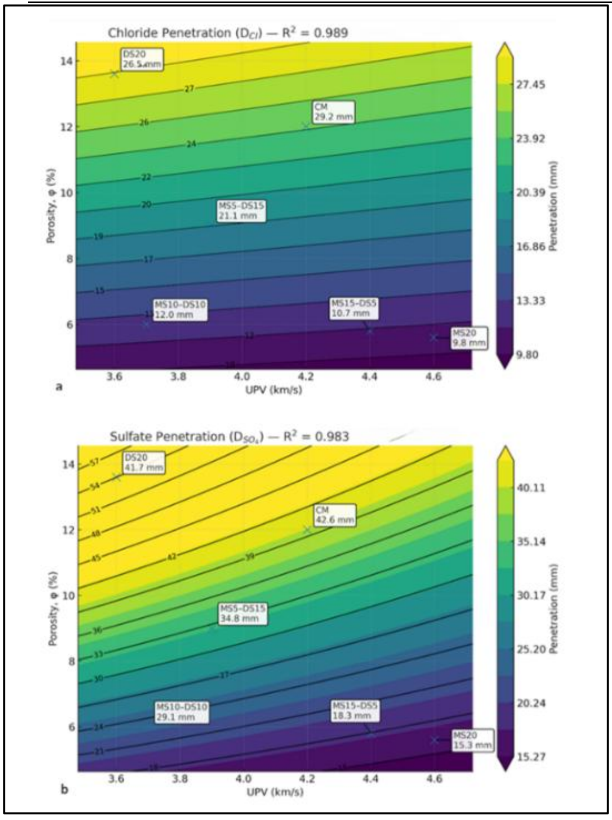

Figure 11. Predicted; (a) chloride and (b) sulphate penetration based on porosity and UPV.

4.Conclusion

This study concludes that the performance limits of cement mortar containing micro silica and date seed ash are primarily controlled by the proportional balance between the two materials. The hybrid mixtures showed the most favorable results, with MS15–DS5 achieving the greatest overall improvement through a 6% increase in compressive strength, a 42% reduction in sorptivity and notable enhancements in dry density and ultrasonic pulse velocity. The MS10–DS10 mixture also performed well, showing a 32.6% decrease in sorptivity a slight 2% strength gain, and improved density and pulse velocity, indicating reduced pore connectivity and better particle packing.

A clear decline began with MS5–DS15 where the higher ash content led to a 6% drop in strength increased sorptivity, higher total absorption and lower ultrasonic velocity signaling greater pore interconnection. The DS20 mix represented the lowest performance boundary, with a 3١.5% rise in sorptivity an 8% strength reduction, and decreases in density and pulse velocity, confirming the loss of mix integrity when DS is used alone. The progression from the strongest hybrid mixtures (MS15–DS5, MS10–DS10) to the weakest (MS5–DS15**)** followed by DS20 mix demonstrates that effective improvement occurs only within the hybrid range of 5–10% whereas exceeding this range results in consistent mechanical and physical deterioration.

In summary, the study establishes that maintaining DS within controlled hybrid proportions supported by MS is essential for preserving mix integrity and structural quality, while higher DS levels lead to systematic declines across all measured properties.

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6.References

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