BIOENG

Brazilian Journal of Biosystems Engineering (2026), 20 1310

REGULAR ARTICLE

Evaluation of the Mechanical and Thermal Properties of Sustainable Geopolymer Mortars Incorporating Olive Seed Ash and Date Seed Ash

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Regular Section

Academic Editor: *Celso Antonio Goulart*

Statements and Declarations

Data availability

The data presented in this study are available on request from the corresponding author.

Institutional Review Board Statement

Not applicable.

Conflicts of interest

The authors declare no conflict of interest.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Code/Software availability

Not applicable.

Use of Generative AI

Not applicable.

Author contribution (CRediT)

A.Q.M.: Conceptualization, Data curation, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing, Methodology, Formal analysis; D.A.A.A.S.: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

Abstract

This study explores the use of Date Seeds Ash (DSA) and Olive Seeds Ash (OSA) as partial replacements for fly ash (FA) in geopolymer mortar to promote sustainable alternatives to Ordinary Portland Cement. Mortar mixtures were prepared with 5, 10, 15, and 20 wt.% of DSA and OSA. The mechanical (compressive and flexural strength), physical (bulk density), and thermal (thermal conductivity) properties were evaluated. Results showed that increasing DSA/OSA content led to a gradual decrease in strength and bulk density, mainly due to the higher porosity and lower pozzolanic activity of the ashes compared to FA. However, this increased porosity improved thermal insulation by reducing thermal conductivity. Overall, DSA and OSA demonstrated potential as eco-friendly additives in geopolymer mortars, contributing to waste utilization and carbon emission reduction in the construction sector.

Keywords

Sustainable materials; Date Seeds Ash; Olive Seeds Ash; Thermal Conductivity; Agricultural waste

1. Introduction

According to the International Energy Agency (IEA), Ordinary Portland Cement (OPC) production accounts for approximately 6–7% of global anthropogenic CO_2 emissions. Although the environmental impacts of OPC are well known, its global demand is projected to nearly double by 2050. This trajectory necessitates the urgent development of sustainable binder alternatives capable of mitigating carbon emissions and addressing the ecological burdens of conventional cement manufacturing. Within this framework, geopolymer concrete (GPC) has emerged as a technologically viable and environmentally favorable substitute. GPC leverages alkali-activated aluminosilicate precursors, enabling substantial reductions in embodied energy and CO_2 emissions compared to OPC-based systems(Fahim Huseien et al., 2017) (Zhou et al., 2016) (Abdulrehman et al., 2025). Geopolymer mortars (GPMs) represent a sustainable alternative to OPC-based systems, synthesized through complete substitution of OPC with aluminosilicate-rich precursor materials activated by alkaline silicate solutions—predominantly utilizing industrial by-products like fly ash(Temuujin et al., 2010). This method reduces carbon emissions and utilizes industrial and agricultural waste, supporting global sustainability efforts(Gunarani & Chakkravarthy, 2017). The resulting three-dimensional amorphous aluminosilicate networks, formed via geopolymerization of aluminosilicate sources in highly alkaline media, confer enhanced thermal stability and chemical resistance to aggressive environments(Shi et al., 2021)(Kono et al., 2018). Furthermore, the production of geopolymer binders generally requires 2–3 times less energy and generates 4–8 times lower CO_2 emissions compared to OPC(Bazan et al., 2020)(Kozub et al., 2023). These advantages make geopolymers highly attractive for applications requiring fire resistance, thermal insulation, and environmental compatibility(Agustini et al., 2020). However, modern construction practices, driven by rapid urbanization, often rely on conventional mortars with limited thermal insulation properties, unlike traditional systems that effectively utilized natural, climate-adapted materials(Benaniba et al., 2020). In response, recent studies have focused on enhancing the performance of geopolymer systems by incorporating various waste materials. For instance, (Liu et al., 2020),partial substitution of metakaolin with 5–20 wt.% rice husk ash in metakaolin-based geopolymer systems was shown to enhance thermal stability and augment 28-day compressive strength by up to 24% relative to unmodified formulations. This performance improvement is attributed to accelerated geopolymerization kinetics and associated microstructure densification resulting from RHA incorporation. Similarly, (Kozub & Castro-Gomes, 2022) demonstrated that substituting quartz sand with ≤50% ground walnut shells in fly ash-based geopolymer composites reduced density and thermal conductivity by ~50%, albeit at the expense of mechanical strength due to elevated porosity. Similarly, (Bourzik et al., 2024), validated partial sand replacement with recycled geopolymer binder, achieving reduced thermal conductivity with marginal mechanical strength loss. Concurrently, (Agustini et al., 2020), optimized the water-to-solid ratio (0.22) for fly ash geopolymers, balancing low thermal conductivity (0.75 W/m·°C) and high early compressive strength (34.12 MPa at 7 days). This study investigates the use of Date Seed Ash (DSA) and Olive Seed

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https://doi.org/10.18011/bioeng.2026.v20.1310

Received: 11 October 2025 / Accepted: 19 May 2026 / Available online: 30 June 2026

Ash (OSA) as partial replacements for fly ash in sustainable geopolymer mortar. The research evaluates their impact on physical and mechanical properties (bulk density, thermal conductivity, compressive strength, and flexural strength) to develop low-carbon construction materials and valorize agricultural waste.

2. Materials and methods

2.1 Materials and compositions

The Zahdi variety, a popular cultivar in the area, provided the date seeds used in this investigation. After being sun-dried to eliminate any natural moisture, date seeds were calcined in a muffle furnace at a precise temperature of 600°C for two hours to form ash. In order to obtain particle sizes ≤300 µm, the calcined product was then ground up using a ball mill and sieved. The oxide composition of date seed ash (DSA), as measured by X-ray fluorescence (XRF) investigation, is summarized in Table 1.

Table 1. Chemical composition of Date Seed Ash.

Chemical Constituents	Percentage%
SiO_2	35.39
Fe_2O_3	0.78
CaO	13.04
MgO	6.36
Al_2O_3	0.65
K_2O	7.40
Na_2O	3.60
LOL	8.41

The olive seeds utilized in this study were of the Ba'shiga variety, obtained from olive oil production residues in Mosul, Iraq. This type of agricultural waste is generated in substantial quantities each year as a by-product of the olive oil industry. The seeds were first sun-dried to minimize moisture content, then calcined at 600 °C for two hours to produce ash. The resulting olive seed ash (OSA) was ground using conventional milling methods and manually sieved to achieve a particle size of less than 300 microns. Table 2 illustrates the chemical composition of OSA.

Table 2. Olive Seed Ash Chemical Composition and Percentage content.

Chemical Constituents	Percentage%
Al_2O_3	4.25
SiO_2	65.17
Fe_2O_3	1.50
MgO	4.15
CaO	6.17
K_2O	8.28
SO_3	3.87
PK_2	3.81
Na_2O	1.27

The Class F fly ash (FA) used in this investigation complies with (ASTM C618-19, 2019). The supplier of this siliceous material was EUROBUILD Company (UAE). At the Central Laboratory of Al-Nahrain University, quantitative chemical characterization was carried out using X-ray fluorescence spectroscopy (XRF). Table 3 provides specifics on the Fly ash oxide composition.

Sodium hydroxide (NaOH), meeting specifications(ASTM E291-18, 2018), was employed as the alkaline activator. The reagent-grade solid (supplied commercially) exhibits high aqueous solubility, forming concentrated alkaline solutions essential for geo-polymerization. Critical physicochemical properties of the NaOH are detailed in Table 4 as supplied by the manufacturer.

Table 3. Fly ash type (F) Chemical Composition and Percentage content.

Chemical Constituents	Percentage%
Al_2O_3	26.74
Fe_2O_3	6.8
SiO_2	41.62
CaO	12.8
SO_3	5.83
K_2O	0.47
MgO	5.83
TiO_2	0.73
P_2O_5	0.4
Na_2O	0.86

Table 4. The analysis results of used sodium hydroxide NaOH

Chemical Contents	ASTME291Requirements	Results
Iron oxides (%)	≤ 0.01	0.005
Na_2SO_4 (ppm)	≤ 200	71
NaOH (%)	≥ 97.5	98.14
Na_2CO_3 (%)	≤ 0.40	0.36
Ni+2 (ppm)	≤ 5.0	2.24
Cu+2 (ppm)	≤ 4.0	0.18
Mn (ppm)	≤ 4.0	0.04
Water Insoluble (ppm)	≤ 200	62
SiO_2 (ppm)	≤ 20	14
NaCl (%)	≤ 0.15	0.07

Sodium silicate solution (Na_2SiO_3) served as a co-activator in this study(ASTM C494/C494M-17, 2017). This commercially sourced aqueous solution (UAE supplier) exhibits high alkalinity and viscosity, with its reactivity governed by the SiO_2/Na_2O molar ratio (modulus) and concentration. Table 5 displays certified chemical composition data that was supplied by the manufacturer.

Table 5. The analysis results of used sodium silicate Na2CO3.

Chemical Constituents / Properties	Values
H_2O (%wt.)	55.1
SiO_2 / Na_2O (%)	2.4 ± 0.05
Specific Gravity	1.534 – 1.540
Viscosity (CPS) at 20°C	600 – 1200
SiO_2 (%wt.)	32– 33
Density(g/cm^3) at 20°C	2.4 ± 0.2
Na_2O (%wt.)	13.10 – 13.70

Because of its wide range of particle sizes, the sand used in this study came from the Al-Okhadir region. Since fine sand performed better in the geopolymer matrix, the sand was sieved through a 1.18 mm mesh to eliminate coarse particles and keep the finer portion, resulting in a more uniform fine aggregate appropriate for the creation of geopolymer mortar. The sand's characteristics met Iraqi Specification No. 45/1984 (IQS No. 45/1984, 1984). Table 6 displays the sand's grading and analysis results.

Table 6. The gradient experimental for sand.

Specification nº. 45/1984	Passing the cumulative sample (%)	Mesh Size (mm)
100	100	10
90-100	93.1	4.75
75-100	78.52	2.36
55-90	63.48	1.18
35-59	46.33	0.6
ago/30	17.0	0.3
0-10	0.09	0.15

2.2 Experimental conditions and mix proportions

Using a mechanical mixer, the dry constituents (fly ash, fine aggregate) and the additives (OSA and DSA) were combined for two to three minutes to begin the mixing process. The dry mixture was then gently mixed with the alkaline activator solution and the necessary amount of water. To guarantee that all of the ingredients were evenly distributed and to create a homogenous mixture, mixing was carried out for a further four to five minutes. Following the casting of the fresh mortar into molds, all specimens were cured under ambient dry laboratory conditions at room temperature (R.T.) for 28 days without water immersion. The results are reported as mean ± standard deviation (mean ± SD, n = 3). In this study, RM refers to the geopolymer mortar without any additives (control mix), X denotes the geopolymer mortar incorporating varying percentages of olive seed ash (OSA), and A represents the geopolymer mortar containing different percentages of date seed ash (DSA).

Table 7. Geopolymer mortar mixes.

Mix	Fly ash (g)	Alkaline Liquids (g)	NaOH: Na_2SiO_3	Molarity of NaOH	Additional Water%	OSA (%)	DSA (%)
RM	300	150	1:2.5	10	10%	0	0
X1	300	150	1:2.5	10	10%	5%	0
X2	300	150	1:2.5	10	10%	10%	0
X3	300	150	1:2.5	10	10%	15%	0
X4	300	150	1:2.5	10	10%	20%	0
A1	300	150	1:2.5	10	10%	0	5%
A2	300	150	1:2.5	10	10%	0	10%
A3	300	150	1:2.5	10	10%	0	15%
A4	300	150	1:2.5	10	10%	0	20%

2.3 Mechanical, physical, and thermal characterization

Compressive strength serves as a fundamental indicator of a mortar's capacity to withstand axial loads, representing a critical mechanical property for construction materials. In this study, Compressive strength tests (Figure 1) were conducted on mortar specimens prepared in accordance with (ASTM C109/C109M-20, 2020). The mix design employed a binder-to-sand-to-water ratio of 1:2.75:0.485 by weight. The fresh mortar was poured into cubic molds, each having dimension of 5 cm × 5 cm × 5 cm and cured under specified conditions before testing.

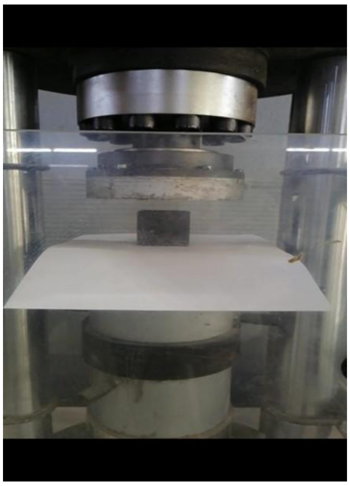

Figure 1. Compressive strength test.

Flexural strength (f_r) indicates the mortar's ability to withstand bending stresses and is a crucial mechanical property for materials exposed to structural flexural loads. In this study, flexural strength tests (Figure 2) were conducted on mortar specimens prepared according to (ASTM C348-21, 2021). The specimens were prismatic, measuring 40 mm × 40 mm × 160 mm.

Figure 2. Flexural Strength test.

The density of the mortar mixtures in both wet and air-dried states was determined by measuring the specimen dimensions using a Vernier caliper and their mass with an electronic balance having an accuracy of ±0.10 g. Cube specimens measuring 50 × 50 × 50 mm were employed to calculate the bulk wet density. Sample preparation and curing procedures adhered to the guidelines outlined in (ASTM C567/C567M-19, 2019). The density was obtained by dividing the specimen's mass by its volume. Before testing, the specimens were oven-dried at a constant temperature of 105 ± 5°C for 24 hours to remove moisture content.

Thermal conductivity measurements (Figure 3) were then carried out using a PA Hilton Thermal Conductivity Tester (Model H112N), which operates based on a comparative method in accordance with the ISO 8301 standard for thermal conductivity testing (ISO 8301:1991, 1991). The objective of this evaluation was to ascertain the material's efficiency in heat transfer, giving insight into its potential performance under thermally demanding conditions.

Figure 3. Thermal conductivity samples.

3. Results and discussion

A clear trend was observed where the compressive strength of the mortar progressively decreased as the percentage of Olive Seed Ash (OSA) and Date Seed Ash (DSA) used to partially replace fly ash increased. Specifically, after 28 days of curing, the mortar showed compressive strengths of 20 MPa, 19 MPa, 18 MPa, 14 MPa, and 12.8 MPa for the RM, X1, X2, X3, and X4 levels of fly ash replacement with Olive Seed Ash (OSA), respectively. Similarly, for fly ash replacement with Date Seed Ash (DSA), the compressive strengths recorded were 20 MPa, 18 MPa, 15.5 MPa, 13 MPa, and 11.5 MPa at the RM, A1, A2, A3, and A4 replacement levels, respectively. This decrease is attributed to the lower content of reactive oxides, such as SiO_2 and Al_2O_3, in OSA and DSA compared to fly ash. This reduction decreases the degree of geopolymerization, leading to increased porosity and a weaker matrix formation. Due to differences in chemical composition, OSA exhibited higher performance than DSA, with an improvement ranging from approximately 5% to 16% in compressive strength depending on the replacement level (Silvestro et al., 2023). The compressive strength test results are shown in Figure 4.

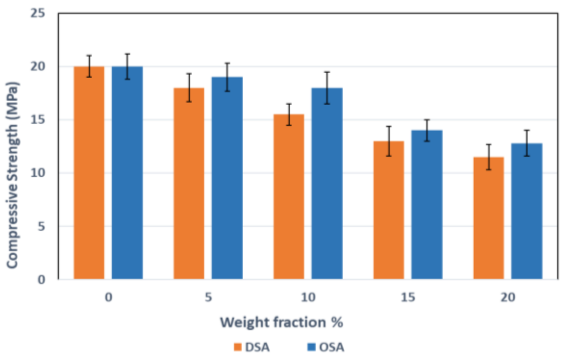

Figure 4. Compressive strength of mortars with OSA and DSA replacements.

The flexural strength (F.S) results are shown in Figure 5. After 28 days of curing, the mortar demonstrated flexural strengths of 4.5 MPa, 4.0 MPa, 3.8 MPa, 3.3 MPa, and 2.9 MPa for the RM, X1, X2, X3, and X4 mixes, respectively, where fly ash was replaced with Olive Seed Ash (OSA). Similarly, for the Date Seed Ash (DSA) replacements, the flexural strengths measured were 4.5 MPa, 3.8 MPa, 3.2 MPa, 2.8 MPa, and 2.6 MPa at RM, A1, A2, A3, and A4 replacement levels, respectively. Fly ash is well-known for its high silica (SiO_2) and alumina (Al_2O_3) contents, which are critical for forming a stable geopolymer network via alkali activation. In contrast, although olive seed ash and date seed ash contain significant amounts of silica, they generally lack sufficient reactive aluminosilicate phases necessary for effective geopolymerization. This deficiency limits the binder's ability to develop a dense and durable matrix. Moreover, the microstructural analysis of olive seed ash reveals a porous and irregular morphology compared to the relatively spherical and less porous structure of fly ash. The increased porosity introduces weak zones within the mortar matrix, negatively impacting both density and mechanical performance (Ghazzawi et al., 2024). Previous studies on similar agricultural residues, such as olive pomace ash, have shown that the inclusion of highly porous materials tends to increase the void content, leading to a notable decline in compressive strength (Inas et al., 2025).

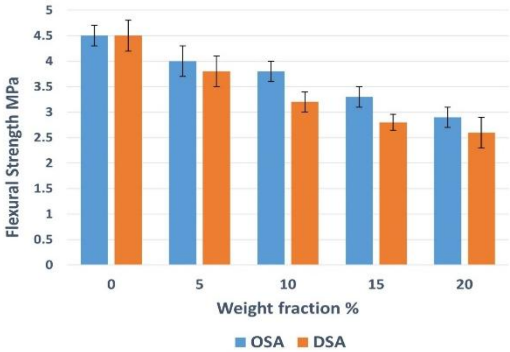

Figure 5. Flexural strength of OSA and DSA samples.

For each mix proportion (RM, X, and A), three independent specimens were prepared and tested. The reported results represent the average of three measurements (n = 3), and the standard deviation was calculated accordingly. When fly ash was partially replaced with additional Olive Seed Ash (OSA) and Date Seed Ash (DSA), the density of the geopolymer mortar gradually dropped. Specifically, the maximum density reduction was observed for the mix X4 (20% OSA), reaching 1.36984 g/cm³, while a similar reduction to 1.36984 g/cm³ was recorded for the mix A4 (20% DSA). Waste ashes such as DSA and OSA generally exhibit lower bulk densities compared to conventional fly ash. Biomass-derived ashes tend to be lighter due to their higher organic content and more porous microstructure. The addition of these waste ashes increases the porosity of the geopolymer matrix, as the irregular and less dense particles characteristic of biomass ashes introduce more voids within the material. Consequently, this increased porosity results in an overall reduction in the density of the geopolymer mortar (Kalkan & Gündüz, 2024). Figure 6 presents the results of the density tests.

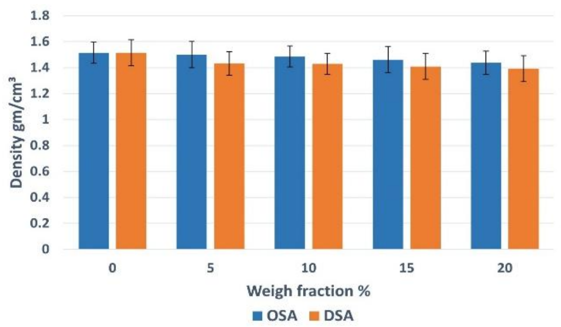

Figure 6. Density of DSA and OSA samples.

Thermal conductivity measurements were conducted on specimens cured for 28 days. The results obtained for geopolymer mortars containing varying weight fractions of Date Seed Ash (DSA) and Olive Seed Ash (OSA) are presented in Figure 7. The addition of higher proportions of waste ash resulted in lower thermal conductivity in the mortars. The 20% replacement mixes recorded the lowest thermal conductivity values: 0.471 W/m·K for OSA (X4) and 0.441 W/m·K for DSA (A4). The incorporation of olive seed ash contributes to increased porosity within the composite matrix. The higher porosity introduces more air voids, and since air is an excellent thermal insulator, this results in a reduction of the overall thermal conductivity of the material (Zeyad et al., 2025).

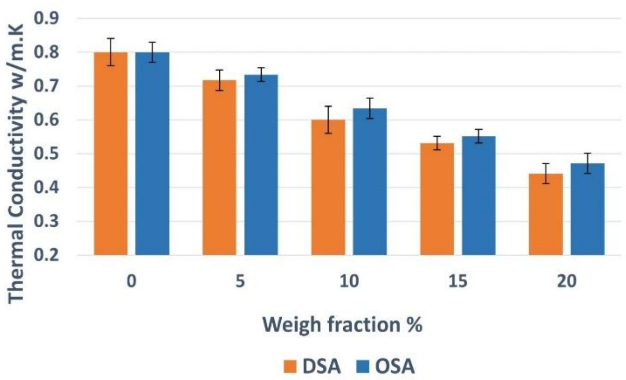

Figure 7. Thermal conductivity of DSA and OSA samples

4. Conclusions

When Date Seed Ash (DSA) and Olive Seed Ash (OSA) were partially substituted in geopolymer mortar, the compressive and flexural strengths decreased as the replacement ratio increased. The main causes of this decrease are the reduced degree of geopolymerization and increased porosity in comparison to regular fly ash. The density of the mortar gradually declined as the proportions of DSA and OSA increased, which can be ascribed to the lower bulk density and higher porosity of these agricultural ashes compared to conventional fly ash Thermal insulation properties were enhanced by the addition of DSA and OSA, as the increased porosity contributed to a notable decrease in thermal conductivity, indicating improved suitability for thermally efficient construction applications. Overall, this study demonstrates the feasibility of utilizing agricultural waste ashes, such as date seed and olive seed ash, in the fabrication of sustainable and cost-effective geopolymer mortars. However, careful optimization of replacement levels is necessary to maintain a balance between mechanical performance and environmental benefits.

Acknowledgements

The authors would like to sincerely thank Mustansiriyah University's laboratory workers for their invaluable assistance.

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