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MICROSTRUCTURAL AND MINERALOGICAL ASSESSMENT OF THERMALLY PRODUCED METAKAOLIN FROM GAARA FORMATION, WESTERN DESERT, IRAQ, AND ITS POZZOLANIC APPLICATION IN ENHANCING PORTLAND CEMENT PROPERTIES

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Abstract

Kaolin is an industrial raw material that, when subjected to heat, is converted to metakaolin, a very reactive pozzolanic admixture used in high-performance concrete. The use of locally sourced Iraqi kaolin would offer both environmental and economic advantages by decreasing reliance on imported materials, as well as lowering carbon emissions through partial substitution of Ordinary Portland Cement (OPC). This study aims to prepare metakaolin from white kaolin collected from the Ga'ra Formation at the Dweikhla mine situated in the Western Desert of Iraq (Governorate of Anbar). The present kaolin was milled into a fine powder and calcined for 3 h at 600°C to obtain the dehydroxylated and structurally transformed raw kaolin. The chemical composition of the obtained metakaolin showed high purity (54.31% SiO_2, 37.70% Al_2O_3, 1.96% Fe_2O_3, and 1.98% Loss on Ignition). The presence of 1.5% TiO_2 in the metakaolin indicates trace rutile impurity with small quantities of CaO, MgO, and SO_3. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) examination revealed that the material was amorphous and glassy and consisted of fine, platy, and irregular particles that were partially agglomerated. Most of the particle sizes were less than 10 microns, which was also responsible for high surface area and pozzolanic activity. These findings were further corroborated by EDX analysis, which showed a significant increase in silica and alumina. The produced metakaolin was tested on mortar mixes by replacing a certain mass of the OPC; 10% by weight was replaced with metakaolin. The mixes were typical 1:3 cement to sand ratios with water-to-cement ratios of 0.5. The mechanical characterization, via compressive strength tests realized after 2 and 28 days, demonstrated a clear improvement: strength increased from 18.1 MPa to 20.1 MPa at 2 days, and from 39.7 MPa to 44.5 MPa at 28 days. This enhancement is attributed to the pozzolanic reaction and improved microstructure, confirming the effectiveness of Iraqi metakaolin as a high-performance cementitious additive.

Keywords: kaolin; Metakaolin; Thermal Activity; Garaa; Portland Cement.

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1. Introduction

The usual formula for kaolin, an aqueous aluminum silicate mineral, is $Al_2Si_2O_5(OH)_4$. Feldspar and other alumino-silicate minerals naturally break down to produce this fine white clay (Tamar-Agha & Al-Hazaa, 2023). Kaolin is used extensively in the manufacturing of paper, textiles, porcelain, ceramics, and medicinal absorbents. Kaolinite, a soft, light sedimentary rock with a platy crystalline structure and an earthy smell, is its main mineral component. Kaolinite is roughly composed of $H_2O{\cdot}Al_2O_3{\cdot}2SiO_2$ (Karmma, 2025; Prasad et al., 1991)

Kaolin is found in Iraq in economically viable amounts in a number of formations, including the Ga'ra Formation (84 – 86% kaolinite), Husseini Formation (85%), and Amaj Formation (86 – 93%), particularly in the Al-Rutba region in western Anbar (Tamar-Agha et al., 2019). Ferruginous sandstones, kaolinitic claystone, and ironstones make up the majority of the bedrock geology in the Gaara Depression and Al Rutba subzone. The Gaara Formation also contains economically important minerals, including kaolin and trace amounts of iron. Quaternary deposits are frequently found on top of the Gaara Formation, which supports younger formations like the Rutba (Cretaceous). Its hydrogeological and geological importance has influenced the region's stratigraphy and the potential for mineral resources (Jassim & Goff, 2006a; Sissakian & Mohammed, 2007).

The study of (Wahab Al-Ajeel et al., 2012) demonstrated that both the calcination temperature and duration significantly affect the pozzolanic activity of the produced calcined claystone, with the pozzolana derived from Al-Amij red claystone exhibiting a higher activity index compared to that from Al-Hussainiyat red claystone" Because it can improve the performance of Portland cement, the conversion of kaolinite into metakaolin, a highly reactive pozzolanic substance, has substantial industrial potential. By eliminating the hydroxyl and creating "metakaoline" through heating between 550 and 700 degrees Celsius, kaolin can be thermally activated (MacKenzie, 1970; Ren et al., 2023).

The development of an amorphous aluminosilicate phase results from the dehydroxylation process, which starts at about 450°C and is usually finished by 600°C (Highley, 1984; Siddique & Klaus, 2009). To lessen reliance on imports and promote the development of high-performance, sustainable cementitious materials, metakaolin was produced locally using Iraqi kaolin from the Dweikhla deposit in the Western Desert (Anbar Governorate). The pozzolanic activity of metakaolin is due to its high content of reactive silica and alumina. In this study, Iraqi kaolin clay from the Dweikhla mine (Ga'ara Formation, Western Desert) was selected due to its local availability, low cost, and high kaolinite content, making it suitable for thermal activation and pozzolanic applications.

Ordinary Portland Cement (OPC) was mixed with the resultant metakaolin at a weight replacement level of 10%. Tests of compressive strength showed a noticeable performance improvement when compared to control mixes devoid of metakaolin. This improvement is explained by the pozzolanic reaction that forms more calcium silicate hydrate (C-S-H) gel between the metakaolin and calcium hydroxide that is formed during cement hydration. The results demonstrate that Iraqi metakaolin is a suitable pozzolanic additive that enhances mechanical qualities and fosters economic and environmental sustainability in the building industry.

2. Location of Study Area

The raw kaolin samples used in this study came from the Dweikla mine, which is situated in the Western Desert of Iraq, some 80 kilometers north of the Rutba-Al-Anbar Governorate. According to (Figure 1), the study region is located between 33°30′N and 33°40′N latitudes, and between 40°05′E.and 40°25′E longitudes.

Tectonically, the research area is located in Iraq's Western Desert, which is a section of the Arabian Platform's Stable Shelf. From the Late Carboniferous to the Early Permian periods, when Hercynian motions uplifted the eastern and western edges of the Arabian Plate, this region underwent intense geological tectonic activity. These events led to the formation of the Rutba Basin, which later accumulated significant sedimentary deposit sequences.

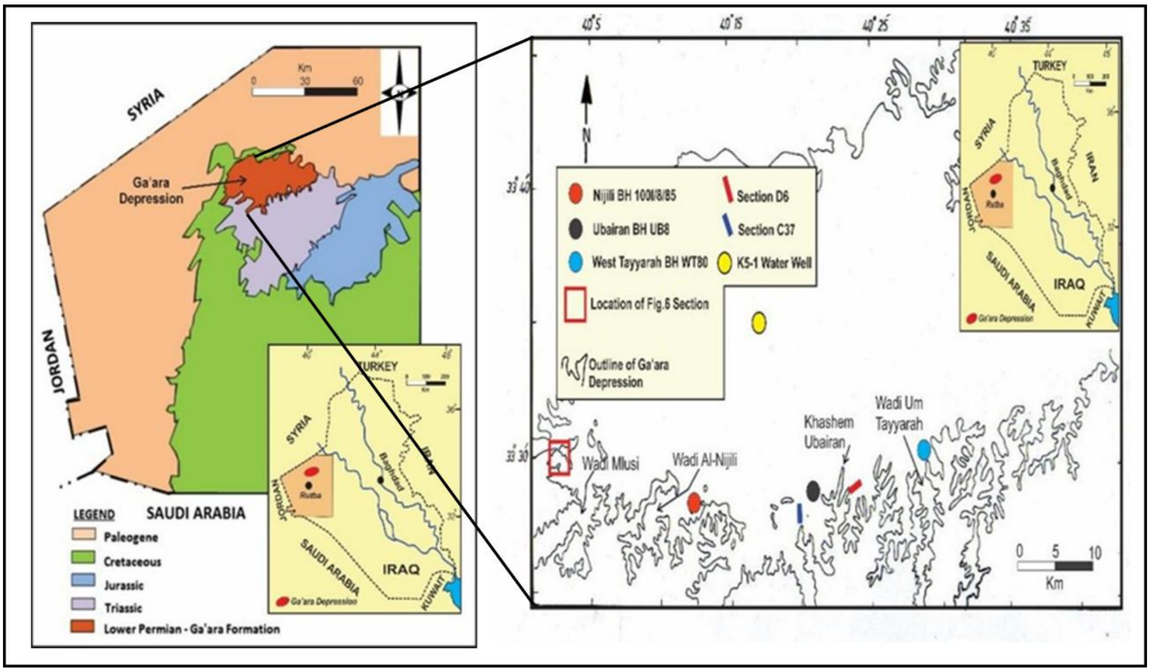

Figure 1: Geological and Location maps showing Dweikla Mine of the Ga′raa Formation (Tamar-Agha & Al-Hazaa, 2023).

3. Previous Studies

Many investigations have been conducted to determine the ideal conditions for producing metakaolin from kaolin and using it as a pozzolanic element in cement and concrete. Atta et al. (2007) stated that kaolin can be effectively converted to metakaolin by calcining it for three hours at 600°C. Similarly, kaolin was calcined for four hours at 600°C to create metakaolin

(Komnitsas et al., 2009). In a comprehensive study, Serbian kaolin was heated to 550, 600, 650, and 700°C for 30 to 180 minutes (Ilić et al., 2010). Their findings showed that cooling the calcined samples to room temperature prevented recrystallization and that the optimal temperature for producing high-interaction metakaolin was 600°C for 90 minutes.

The pozzolanic activity of metakaolin and its benefits in construction materials have been widely documented. People have been studying how metakaolin reacts with other materials and the benefits it brings to construction projects. Sinngu et al. (2023) demonstrated that metakaolin is more active as a pozzolan than most other additives, and is characterized by its environmental properties and high effectiveness. Velastegui et al. (2024) applied predictive and microscopic (SEM) tools to analyze the effect of metakaolin, confirming its success in reducing porosity, improving compaction, and increasing density up to 60 days.

Vejmelková et al. (2010) used 10% metakaolin, and high-performance concrete improved its strength, durability, resistance to chlorides and acids, such as HCl, after 28 days, confirming the effectiveness of the material. Later, Duan et al. (2012) investigated the partial replacement of Portland cement with varying percentages of metakaolin (5%, 10%, 15%, and 20%) in cementitious systems and found that incorporating metakaolin enhanced both compressive and flexural strengths of mortar, demonstrating its effectiveness in improving the mechanical performance of cement-based materials.

According to the literature, metakaolin is a very useful supplemental cementitious material when it is generated under ideal calcination conditions. In addition to boosting durability and mechanical qualities, its usage in cementitious systems lowers the amount of calcium hydroxide in concrete, increasing its resistance to long-term deterioration and chemical assault.

4. Materials and Methods

The cement used in the experiment was ordinary Portland cement of type 32.5, produced by the Al-Tawsea Plant, with a compressive strength of 39.7 MPa. The durability of the cement mortar molds is determined after the hardening process, in accordance with Iraqi Standard No. 5 of 2019, referencing the EN 196-1 (2005) guideline.

The kaolinite-rich clay used in this study was obtained from the Dweikhla mine, which is part of the Ga'ara Formation in the western Iraqi desert (Anbar Province). The clay samples were brought to the laboratory in bulk for processing and thermal activation. Initially, the raw clay was crushed using a laboratory jaw crusher to a particle size of 1 – 3 cm (Figure 2a). The resulting fragments were then ground into fine powder using a planetary ball mill, which provides uniform and efficient grinding suitable for pozzolanic applications. The powder was subsequently sieved to ensure a uniform particle size fraction suitable for consistent thermal activation (Figure 2b).

The kaolin powder was thermally activated at 600 °C for three hours using a muffle furnace. These temperatures and durations were selected based on previous studies demonstrating that

600 °C is sufficient to induce complete dehydroxylation of kaolinite and transform it into amorphous metakaolin with high pozzolanic reactivity, while minimizing the formation of undesirable crystalline phases such as mullite or spinel.

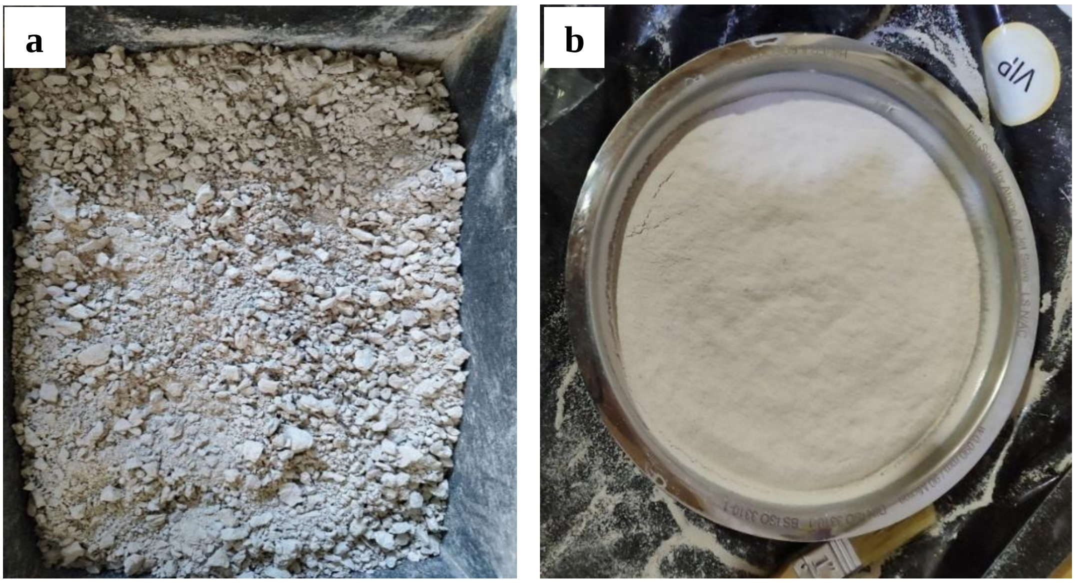

Figure 2: a) Metakaolin after cracking. b) Metakaolin after grinding.

Although higher calcination temperatures (650 – 800 °C) have been used in other studies to accelerate activation, the selection of 600 °C in this study was also driven by economic considerations, as it reduces energy consumption while still achieving the desired structural and reactivity characteristics. This approach is supported by several recent studies (Dubey & Gupta, 2020; Huang et al., 2025; Velastegui et al., 2024), which confirmed that calcination at 600 °C for 2 to 3 hours is optimal for producing highly reactive metakaolin suitable for cement enhancement. This process was carried out in the laboratories of the Chemistry Department at the College of Science, Tikrit University. Kaolinite underwent dehydroxylation as a result of the heat treatment, which caused the following reaction to change it into amorphous metakaolin: according to the following equation:

$$Al_2Si_2O_5\,(OH)_4 \rightarrow Al_2Si_2O_7 + 2H_2O$$

This reaction represents the dehydroxylation of kaolinite upon thermal treatment, resulting in the formation of amorphous metakaolin with high pozzolanic activity.

As bound hydroxyl ions are released during this process, about 14% of the mass is lost (He et al., 1994). Metakaolin ($Al_2O_3 \cdot 2SiO_2$) is produced as a highly reactive amorphous phase that can be used in pozzolanic processes (Huang et al., 2025; Pera et al., 1998; Sayanam et al., 1989)

X-ray Diffraction (XRD) analysis has been implemented on both raw kaolin and metakaolin to examine changes in crystalline structure. The morphology of the surface was shown utilizing

SEM, while Energy Dispersive X-ray Spectroscopy (EDX) provided data on elemental composition. All advanced characterizations were conducted at Al-Khwarah Company laboratories in Baghdad.

Chemical analysis of major oxides in both raw and calcined samples was conducted to identify the effects of thermal treatment on chemical composition. The results are displayed in Table 1.

Table 1. Comparative Chemical Analysis of Kaolin and Metakaolin

Oxide	Kaolin (%)	Metakaolin (%)
SiO_2	50.13	54.31
Al_2O_3	31.89	37.70
Fe_2O_3	1.91	1.96
CaO	1.34	1.65
MgO	0.72	0.80
SO_3	0.61	0.72
L.O.I	13.24	1.98
Total	99.84	99.12

The thermally activated metakaolin was further ground to achieve a particle size distribution comparable to that of ordinary Portland cement (OPC). A sieve analysis was performed to ensure that the majority of particles passed through the 75 µm (No. 200) sieve, indicating adequate fineness for pozzolanic reactivity. Subsequently, 10% by weight of the cement was replaced with metakaolin. Mortar mixtures were prepared using a conventional mix proportion of 1 part cement, 3 parts sand, and 0.5 part water (by weight). A control mortar sample without metakaolin was also prepared for comparison.

The compressive strength of the prepared mortar specimens was evaluated following the Iraqi Standard No. 5 (2019), which specifies strength testing at 2 and 28 days rather than at 3 or 7 days, as required by ASTM or DIN standards. Standard graded sand conforming to Iraqi Specification No. 15 (Type I) was used in the mortar mixture, with a cement:sand: water ratio of 1:3:0.5 by weight. Cement mortar was made with 40x40x160 mm prisms, and compressive strength was calculated as the applied load divided by the cross-sectional area of the specimen, expressed in megapascals (MPa). All mortar cubes were cured by immersion in water for the designated periods of 2 and 28 days before testing.

After curing, the mortar specimens were removed from water and subjected to compressive strength testing using a calibrated compression testing machine. The load was applied continuously until failure, and the maximum load at failure was recorded. Based on these measurements, the compressive strength of the mortar was calculated, and the cement type was classified accordingly. All compressive strength tests were performed in the laboratories of Al-Rafidain Cement Factory, located in Nineveh Governorate.

5. Result and Discussion

5.1. Chemical Analysis

The chemical analysis of the kaolin and metakaolin samples (Table 1) indicates a noticeable increase in the relative proportions of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) following calcination. This apparent increase is primarily due to the reduction in mass resulting from the loss of chemically bound water during dehydroxylation, rather than an actual increase in these oxides. Furthermore, the Loss on Ignition (L.O.I.) value dropped significantly from 13.24% in raw kaolin to 1.98% in the resulting metakaolin, indicating the removal of structurally bound water (dehydroxylation), which is a key indicator of thermal activation. Minor changes were observed in oxides such as SO_3, CaO, MgO, and Fe_2O_3, but these did not substantially alter the overall pozzolanic composition. These results are consistent with the expected chemical behavior of kaolinite-rich clays upon calcination and confirm the suitability of the produced metakaolin for use in cementitious applications.

5.2. XRD Examination of Metakaolin and Kaolin

To verify the conversion of kaolin to metakaolin, X-ray diffraction (XRD) analysis was conducted on the samples before and after thermal activation at 600 °C for three hours (Figures 3 and 4). In the raw kaolin sample (Figure 3), clear diffraction peaks characteristic of kaolinite are observed, particularly the most prominent one at $2\theta = 12.4°$, corresponding to a basal spacing (d-spacing) of 7.2 Å. This peak is a key diagnostic feature of kaolinite. However, the second common kaolinite peak at $2\theta = 24.9°$ (d =3.57 Å) is not clearly visible in Figure 4, possibly due to overlapping or low intensity. Additionally, a peak at $2\theta = 26.6°$, corresponding to quartz (SiO_2), is present, confirming the presence of quartz in the raw clay.

X-ray diffraction (XRD) analysis was conducted to assess the structural transformation of kaolinite to metakaolin following calcination at 600 °C for 3 hours. As shown in Figure 4, the XRD pattern reveals the absence of characteristic kaolinite peaks, particularly the basal reflection at $2\theta = 12.4°$, which confirms the breakdown of the kaolinite crystalline structure due to dehydroxylation. While a broad amorphous hump between 20° and 30° 2θ-typically associated with metakaolin, was not clearly visible, the significant reduction in kaolinite peaks and the dominance of quartz reflections (e.g., the sharp peak at $2\theta = 26.6°$, corresponding to quartz) suggest a successful transition to an amorphous pozzolanic material.

The absence of additional crystalline impurities also confirms the purity of the resulting metakaolin. This structural transformation is consistent with observations reported in similar studies (Dubey & Gupta, 2020; Onyelowe et al., 2023; Wahab Al-Ajeel et al., 2012), where thermal activation of kaolinite produced a largely amorphous phase suitable for cementitious applications even in cases where the amorphous hump was subtle or masked by residual quartz.

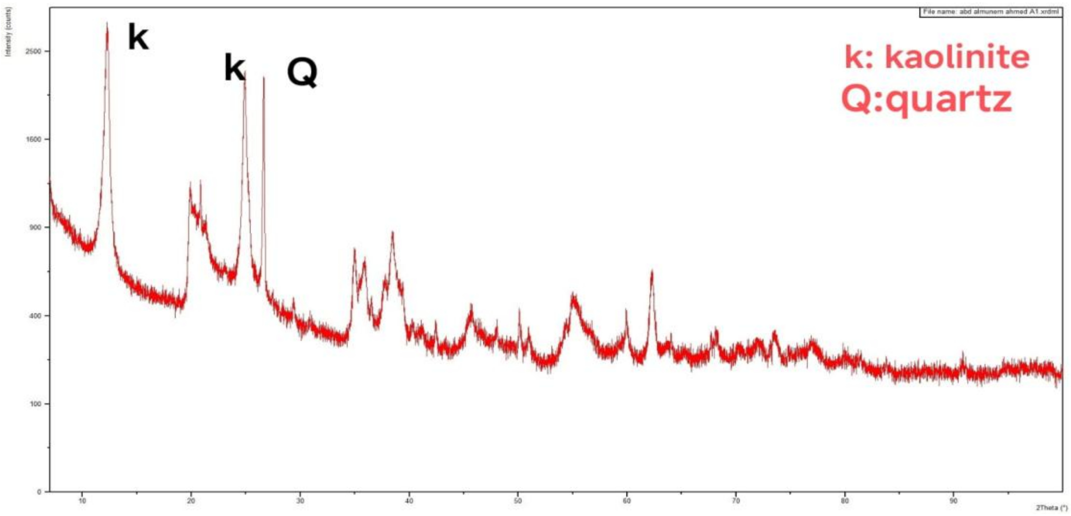

Figure 3. X-ray diffraction diffractogram of the kaolin sample from the Dweikha mine in western Iraq.

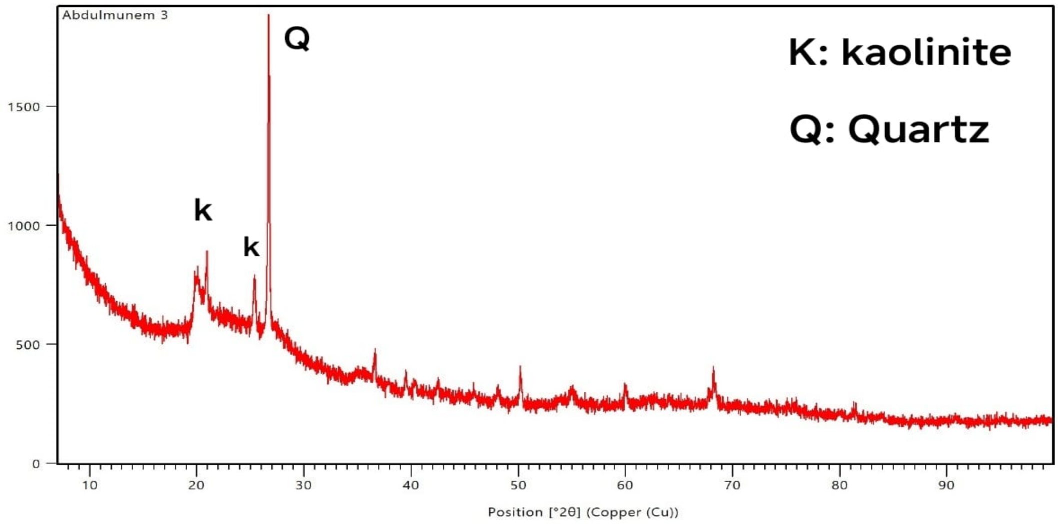

Figure 4. X-ray diffraction diffractogram of thermally activated metakaolin.

5.3. SEM Analysis of Metakaolin

Scanning Electron Microscopy (SEM) was used to examine the morphology and particle size of the thermally activated metakaolin. As shown in Figures 5 and 6, the micrographs revealed irregular, flaky particles with rough surfaces and no visible crystallinity, confirming the successful dehydroxylation of kaolinite at 600 °C. The particles appeared as nanostructured granules, with an estimated size range of 50 – 200 nm, and were loosely packed with dispersed edges and small interstitial voids measuring 1 – 5 µm.

These microstructural characteristics, fine particle size, porous texture, and absence of agglomeration reflect the effectiveness of the grinding process and contribute to an increased specific surface area, which enhances pozzolanic reactivity through improved interaction with calcium hydroxide in cementitious systems. This morphology is consistent with the literature that describes thermally activated metakaolin as a highly amorphous material with high surface area and reactivity (Al-Salami, 2025; Bachirat et al., 2024).

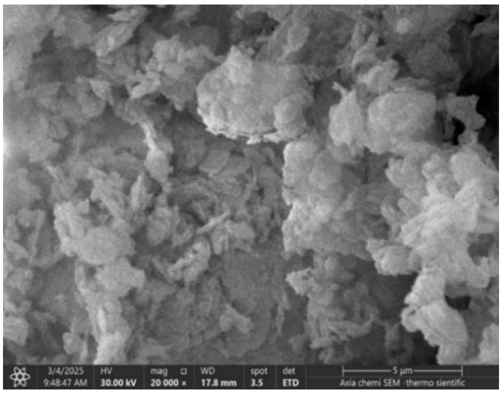

Figure 5. Metakaolin granules.

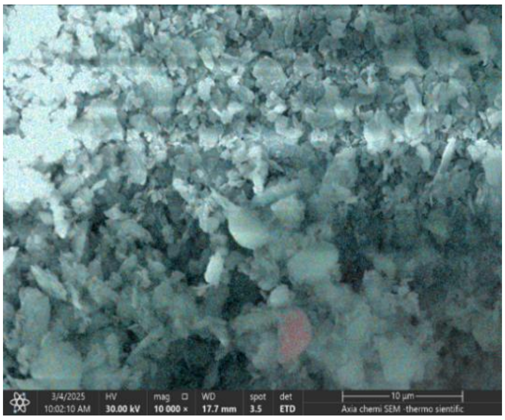

Figure 6. Red Rutile granules in metakaolin

Such a morphology is consistent with previous findings, which describe metakaolin as consisting of non-crystalline, plate-like particles that enhance pozzolanic reactivity by providing a higher specific surface area for reaction with calcium hydroxide (Al-Salami, 2025; Bachirat et al., 2024). This microstructure is favorable for forming additional C-S-H and C-A-H gels, thus improving the mechanical strength and durability of the cementitious matrix.

5.4. EDX Analysis of Metakaolin

Energy Dispersive X-ray Spectroscopy (EDX) analysis of the metakaolin sample confirmed that the material is predominantly composed of oxygen (44.4 wt%), silicon (31.5 wt%), and aluminum (22.3 wt%), with a minor percentage of titanium (1.8 wt%), indicating the presence of trace impurities such as rutile. These elements are also reflected in the atomic composition, where oxygen represents 58.3%, followed by silicon 23.5%, aluminum 17.3%, and titanium 0.8%. This composition confirms the typical structure of anhydrous aluminum silicate and supports the successful transformation of kaolin into high-purity metakaolin, can be seen in Figure 7 of a-e, the proportions of the elements in the metakaolin, where we note the prevalence of aluminum and silica.

The EDX spectrum presented in Figure 8, along with the data summarized in Table 2, revealed clear peaks corresponding to the key components of the sample. A strong aluminum peak appears around 1.5 keV, confirming the abundance of this element. A well-defined silicon peak is observed near 1.75 keV, reflecting the substantial silicon content. Additionally, a prominent oxygen peak appears below 1 keV, which is consistent with the aluminosilicate structure of metakaolin. A small but distinct peak at approximately 4.5 keV confirms the presence of titanium as a trace element.

Overall, the EDX analysis confirms that the metakaolin derived from Iraqi kaolin exhibits chemical homogeneity, structural uniformity, and acceptable purity, supporting its suitability for use in pozzolanic and cementitious systems.

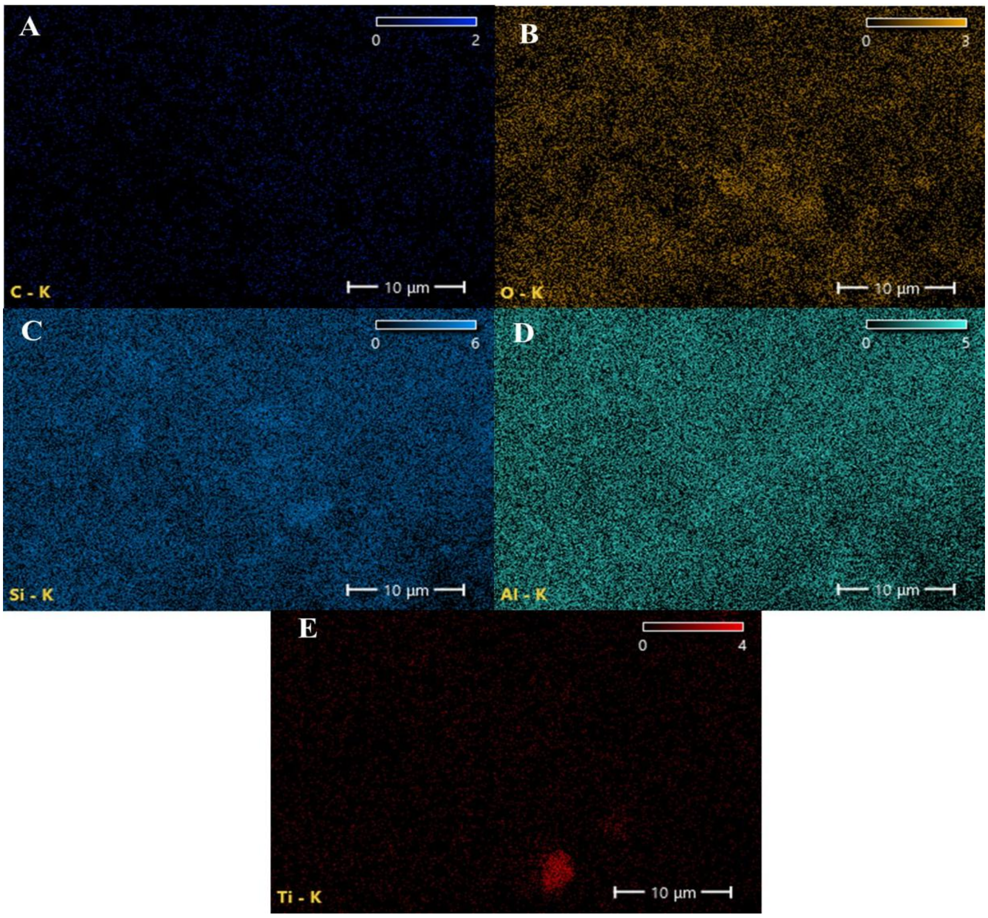

Figure 7. Distribution of the proportions of members in a dotted form in the metakaolin, A: Carbon, B: Oxygen, C: Silicone, D: Aluminum, E: Titanium.

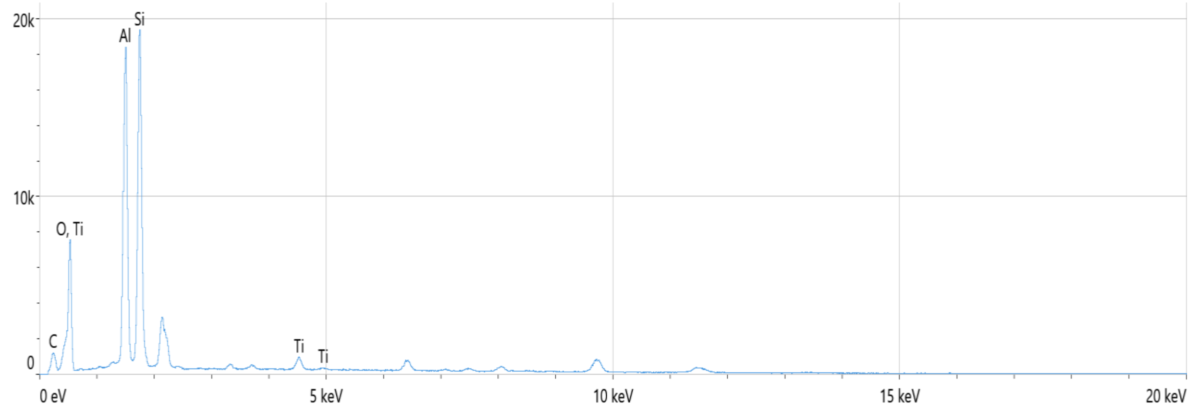

Figure 8: The EDX chart of the metakaolin sample shows the proportions of the members in the sample.

Table 2: Ratios of elements to metakaolin and their weights according to EDX analysis.

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
O	58.34	0.5	44.41	0.5
Al	17.33	0.1	22.27	0.1
Si	23.53	0.1	31.50	0.1
Ti	0.83	0.0	1.82	0.0
Total	**100.00**		**100.00**	

5.5. Compressive Strength and Pozzolanic Activity Index (SAI)

The strength`s compressive results of mortar samples with and without. Metakaolin additions are presented in Table 3. A notable enhancement in compressive strength was found with the incorporation of 10% metakaolin by weight of cement. At 2 days of curing, the reference sample (Cement+0%MK) exhibited a compressive strength of 18.1 MPa, whereas the metakaolin-enhanced sample (Cement+10%MK) reached 20.1 MPa. This improvement was more pronounced at 28 days, with the strength increasing from 39.7 MPa in the control sample to 44.5 MPa in the modified mixture. These results are consistent with recent research showing that 5% to 15% of the weight of cementitious materials should be replaced with metakaolin to better compressive strength. This kind of addition not only increases the concrete's strength but also adds durability to the concrete (Li, 2024).

The compressive strength activity index (SAI) of the metakaolin was evaluated based on ASTM C311 and compared against the criteria defined in ASTM C618. Mortar mixtures with 10% metakaolin replacement were tested alongside a control mixture (100% OPC). At 2 days, the metakaolin mix exhibited a compressive strength of 20.1 MPa compared to 18.1 MPa for the control, and at 28 days, 44.5 MPa versus 39.7 MPa. Metakaolin at a 10% replacement level achieved an SAI of 112% at 28 days according to ASTM C311, exceeding the requirements of

ASTM C618 (≥ 75%). Therefore, it can be considered an effective pozzolanic material that enhances the compressive strength in this mortar mix.

Table 3. Compressive Strength Results for Mortar Samples with and without Metakaolin.

Samples	Compressive strength	
	2 Days	28 Days
Cement+0%Mk	18.1 Mpa	39.7 Mpa
Cement+10%Mk	20.1 Mpa	44.5 Mpa

These findings confirm the high pozzolanic reactivity of the thermally activated metakaolin produced from Iraqi kaolin. A full comparison across various replacement levels (10%, 15%, 20%, and 25%) is presented in a separate study currently under review.

This increase in strength is attributed to the pozzolanic reaction between the amorphous metakaolin and the calcium hydroxide ($Ca(OH)_2$) formed during cement hydration. This reaction leads to the formation of additional calcium silicate hydrate (C–S–H), which is the main binding product responsible for strength development in cementitious systems.

The SEM micrograph illustrates (Figure 9) the refined and denser microstructure of the cement matrix incorporating thermally activated metakaolin compared to the control mix. Although the metakaolin is no longer identifiable in its original form due to its pozzolanic reaction with calcium hydroxide ($Ca(OH)_2$), the microstructure reveals the presence of additional calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels. These reaction products are responsible for the enhanced strength and reduced porosity of the hardened cement paste.

This improvement is further attributed to the fine particle size of metakaolin, which enhances the packing effect, reduces pore connectivity, and accelerates the pozzolanic reaction rate. Based on the SEM micrograph (Figure 9), the particle size of the metakaolin appears to range between 0.5 and 3 µm, supporting its role as a micro-filler. Although no direct BET (Brunauer–Emmett–Teller) surface area measurement was conducted, the observed fineness suggests a high surface area, which is generally associated with enhanced pozzolanic reactivity and improved long-term performance of concrete (Al-Salami, 2025; Huang et al., 2025).

Interestingly, the partial presence of unreacted metakaolin particles in some regions can be interpreted as evidence that the pozzolanic reaction is still ongoing. This behavior suggests that the initial reaction formed a dense layer of hydration products, which decreased the matrix permeability and, consequently, limited the further diffusion of calcium hydroxide into the remaining metakaolin particles. As a result, the later stages of the pozzolanic reaction proceed at a slower rate, characteristic of low-permeability cement systems.

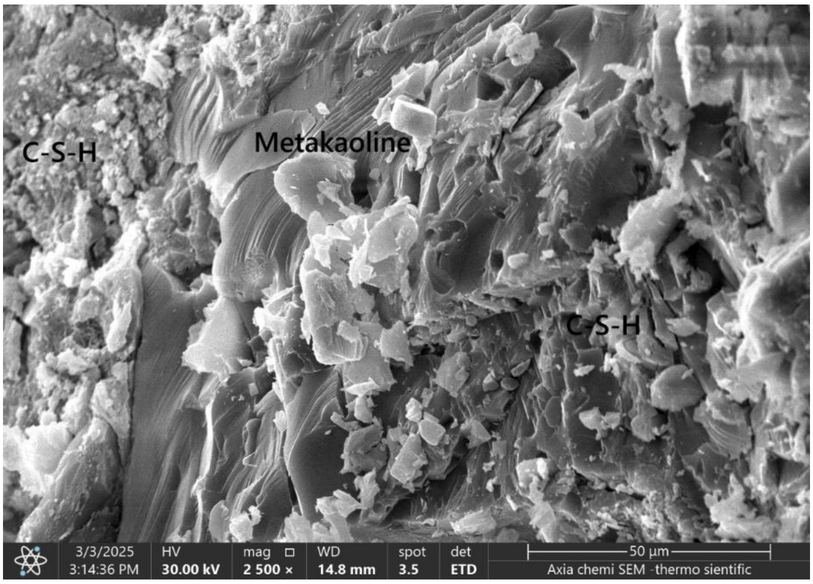

Figure 9. SEM image (at 2500× magnification) of mortar containing 10% metakaolin, showing the interaction between metakaolin particles and cement Products for hydration.

This microstructural observation not only supports the improved compressive strength values obtained at various curing ages but also indicates the long-term reactivity and durability potential of the metakaolin-modified cement. These findings are consistent with previous studies, e.g., Huang et al. (2025) and Sharma (2024), that highlight the dual role of metakaolin as both a pozzolanic reactive material and a micro-filler enhancing structural densification.

The image highlights the formation of a dense (C-S-H) gel around metakaolin surfaces, indicating strong pozzolanic activity and contributing to improved microstructure and compressive strength. In conclusion, the compressive strength of mortar is considerably increased at early as well as later curing ages when 10% metakaolin by weight of cement is added. These outcomes support the potential of metakaolin as an additional cementitious material to enhance the performance and sturdiness of cement-based composites and are in line with current study findings (Al-Salami, 2025; Li, 2024; Sharma, 2024).

6. Conclusions

Metakaolin was effectively produced through thermal activation of Iraqi kaolinite clay at 600 °C for 3 hours. This process led to complete dehydroxylation and the formation of an amorphous, pozzolanic material with high reactivity. The chosen calcination conditions proved sufficient to initiate the pozzolanic reaction and enhance the microstructure of the cement matrix, while also offering a practical and energy-efficient alternative suitable for industrial applications.

Chemical analysis confirmed that the resulting metakaolin is rich in silicon, aluminum, and oxygen, indicative of an anhydrous aluminosilicate composition. Complementary morphological and structural analyses using XRD, SEM, and EDX validated the transformation process and confirmed the high pozzolanic reactivity of the produced material.

Replacing 10% of cement with metakaolin increased the 28-day compressive strength from 39.7 to 44.5 MPa and achieved a compressive strength activity index of 112% according to ASTM C311, exceeding ASTM C618 requirements. This confirms its effectiveness as a pozzolanic material for strength enhancement, despite not fully meeting the Iraqi standard.

Beyond mechanical performance, using locally produced metakaolin provides a cost-effective and sustainable strategy to reduce dependence on Portland cement, addressing both environmental and economic challenges in Iraq's construction sector. Thus, metakaolin derived from Iraqi kaolinitic clay represents a viable, eco-friendly solution for enhancing cement quality and promoting sustainable infrastructure development in the region.

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