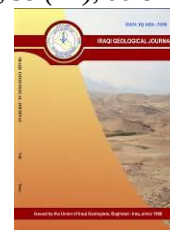




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Feasibility of Producing Conventional and Lightweight Insulating Bricks Using Water Treatment Plant Clay Residues and Local Waste Materials in Basra, Iraq

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Abstract

This study investigates the physical, chemical, and mineralogical properties of clay deposits in Basrah, southern Iraq, aiming to develop high-performance insulating and lightweight bricks. A total of three representative clay samples were collected from the major sites of the Great Basrah Project, Al-Harthah, and Umm Qaser, and were characterized using grain size distribution, Atterberg limits, X-ray diffraction, and X-ray fluorescence. Bricks were manufactured using different clay-based mixtures with additions of recycled glass (5–15%) and paper waste (2–5%), and the mixtures were fired at 950°C and 1050°C to evaluate the effect of each additive on the final brick properties. The results indicate that each clay source produced different physical and mechanical responses depending on the additive type and firing temperature. The addition of recycled glass, particularly at higher firing temperatures, enhanced density and compressive strength while reducing water absorption, producing Class A bricks in the Great Basrah Project. Al-Harthah mixtures showed satisfied the specification limits, whereas Umm Qaser mixtures showed comparatively lower performance. In contrast, the addition of paper waste increased porosity and reduced density, resulting in lightweight bricks with thermal insulation but lower mechanical strength. Efflorescence decreased at higher firing temperatures in most mixtures. Overall, the results suggest that the examined clay mixtures, when combined with suitable additives and firing conditions, can produce thermally efficient lightweight bricks that comply with Iraqi, American, and British standards.

Keywords: Basrah Clay; Lightweight Insulating Bricks; Glass and Paper Additives; Firing Temperature

1. Introduction

One of the first materials human civilizations used to build structures was bricks. Basic techniques of brickmaking were initially practiced in Mesopotamia. The oldest known unfired clay bricks originated in the ancient city of Ur and were dated to approximately 4000 B.C.E. The primary factor in the crafting of the earliest brick was the availability of clay. Clay is a naturally occurring sediment that can be moist, malleable, and can harden upon drying and firing. To this day, clay is the primary constituent in brickmaking (Al-Shafei, 1985). Of all Iraq's natural resources, clay is perhaps the most important. It is particularly key to the construction industry and brick manufacturing. Iraq's central and southern regions are known to host thick deposits of clay, which provide the locality with a vital and abundant raw material. The primary source of clay used in traditional brick factories in these regions the Quaternary deposits (Al-Khafaji et al., 2012). The local materials are known to be high in salt, impurities, and other unusable minerals. These factors, in turn, affect the physical and mechanical

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properties of the bricks. Such compositional flaws often lead to cracking and poor performance during drying and firing processes. These problems emphasize the need to study clays from Basrah Governorate physical, chemical, and mineralogical properties to assess the potential to be used for construction, specifically insulating bricks, which, for construction, need to exhibit high porosity, low thermal conductivity, sufficient mechanical strength, and stability under service conditions. Employing locally sourced industrial additives, enhanced brick performance and insulation, and, in addition, using waste materials, enhanced the eco-friendliness of brick production by reducing energy consumption and imported raw materials. Al-Saad (2006) showed that the presence of additives such as kaolin (15–25%) or sand (10–15%) improved brick attributes such as decreased water absorption, increased density and compressive strength, and, in some cases, less efflorescence, when fired at 1100 °C. Samples that had no additives or were fired at 1000 °C did not achieve the standard requirements. Hassan (2005) showed, after analyzing the physical, chemical, and mineralogical properties of selected Quaternary soils from the Thi-Qar Governorate, and using sand and corn-cobs in varying proportions, that bricks were successfully produced with the addition of 15% corn-cobs and firing at 900°C. Al-Rawi (1982) similarly reported that the resultant lighter bricks from the incorporation of agricultural residues, more specifically sugarcane bagasse and wood chips, improved thermal insulation in the bricks and reduced the thermal conductivity. Al-Khafaji et al. (2012) also noted that the addition of fine sand and the ideal firing temperature increased the properties of the southern Iraqi clays to be satisfactory for the national standards of building bricks.

Therefore, this study aims to assess the physical, chemical, and mineralogical properties of the local clay deposits found in Basrah Governorate while also producing lightweight and thermally insulating sustainable building bricks and incorporating various locally available waste materials by recycling the waste materials and reducing dependence on imported raw materials.

1.1. Study Area

The study area lies in Basrah Governorate, southern Iraq (47°15'–47°30' E; 30°03'–30°55' N), in the southeastern part of the Mesopotamian Plain (Fig. 1). The surface is flat with recent deposits dominated by clayey silt and silty clay with minor sand (Al-Saad, 2006).

Table 1. Geographic coordinates of the study samples

No	Sample location	Coordinates	
		Latitude (North)	Longitude (East)
1	The Great Basrah Project	30° 41' 36.05"	47° 44' 20.84"
2	Al-Hartha	30° 38' 55.87"	47° 45' 20.17"
	Umm Qaser		47° 55' 29.64"

1.2. Geologic Setting

The study area lies within the southeastern Mesopotamian Plain and is covered mainly by Quaternary deposits, formed by fluvial and marine processes during the Pliocene to Holocene (Al-Sayyab et al., 1982). These sediments, up to about 7 m thick, consist mostly of clay and silt brought by the Tigris, Euphrates, Shatt Al-Arab, and Karun rivers, with some aeolian influence in the east. Saline layers containing gypsum, calcite, and halite also occur locally (Mahmood, 1997; Al-Khayat, 2002).

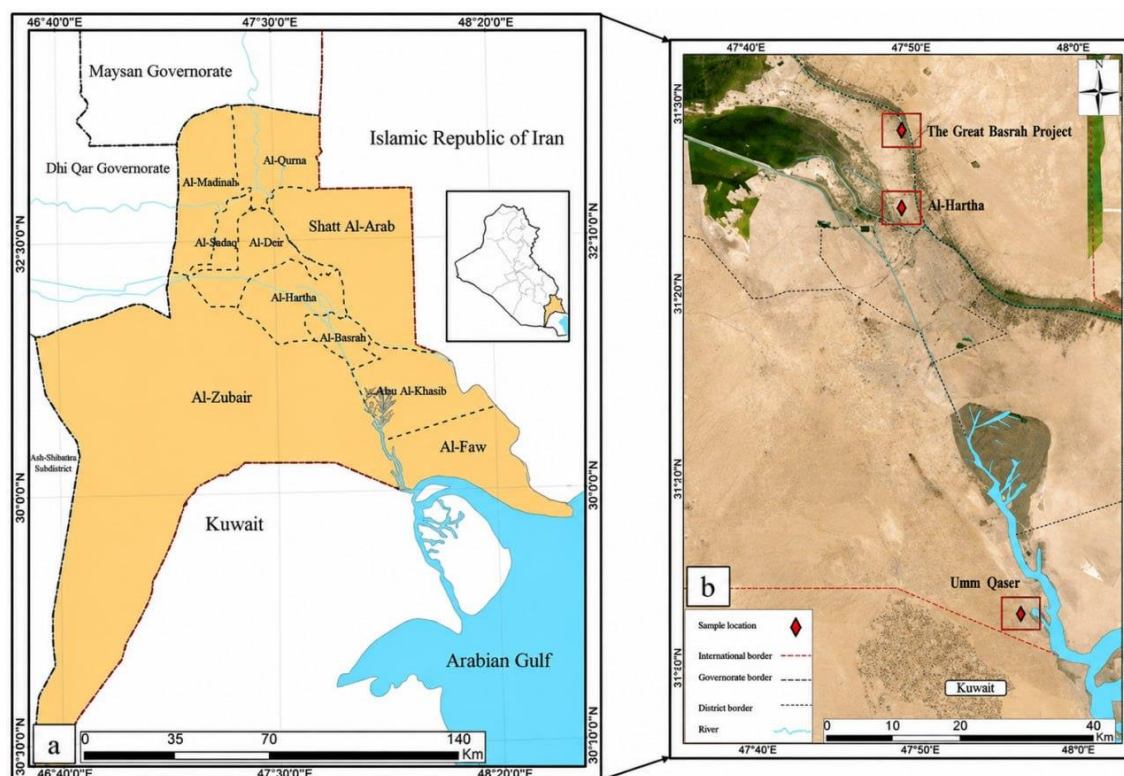


Fig. 1. a) General location of the study area and b) Location of sampling sites within the study area in southern Iraq

1.3. Geologic Setting

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2. Materials and Methods

Three clay samples (≈ 5 kg each) were collected by representative sampling from Umm Qasr (dredged sediments), the Basrah Mega Project (treatment plant), and Al-Hartha. The sites were selected due to the availability of large quantities of underutilized clay-rich sediments. Samples from Umm Qasr were obtained from dredging activities, Al-Hartha from ~ 2 m depth, and Basrah Mega Project from accumulated sediments within the treatment plant. Grain size analysis was performed using wet sieving ($63 \mu\text{m}$) and the hydrometer method (ASTM D422-63, 2002; Folk, 1980), along with Atterberg limits, XRD, and XRF.

2.1. Assessments, Pre-Firing, and Preparation of Bricks

2.1.1. Grain size analysis

Grain size distribution was determined using wet sieving techniques, where the sand fraction was separated from the other sample components using a 63-micron sieve mesh. The hydrometer method was also applied according to the American Standard ASTM D422-63 (2002) and based on Folk's

classification (1980) in the laboratory of the Department of Geology, University of Basra, using a 152H hydrometer manufactured in France.

2.1.2. Atterberg's limits

The liquid and plastic limits were examined using the Casagrande apparatus according to the American standard ASTM D4318(1986) in the laboratories of the College of Science, Department of Geology, University of Basra. In addition, the plasticity index and liquidity index were calculated. These parameters were used to evaluate the suitability of these sediments for shaping and their potential use in ceramic industries.

$$P.I = L.L - P.L \quad (1)$$

$$R.I = S.L - P.L \quad (2)$$

Where: P.I is Plasticity Index, L.L is Liquid Limit, P.L is Plastic Limit, R.I is Rieck Index, S.L is Shrinkage Limit.

2.1.3. X-ray diffraction technique (XRD)

X-ray diffraction (XRD) was employed to determine the mineralogical composition of the clay samples, as clay minerals cannot be accurately identified using optical methods due to their fine grain size. The analysis was conducted at the Department of Physics, College of Science, University of Basrah. The samples were prepared by grinding and passing them through a 63 μm sieve, then bulk samples were examined to identify non-clay minerals within a 2°– 40° angular range. Clay minerals were separated and prepared as oriented samples, divided into three groups: untreated, heated at 550°C, and treated with ethylene glycol vapor for 24 hours. These treatments improved the clarity of basal reflections and allowed more accurate identification of clay minerals within a 2°–20° angular range.

2.1.4. X-Ray Fluorescence technique (XRF)

Chemical analyses of the raw materials were conducted using X-ray fluorescence (XRF) in the Department of Geology at the University of Baghdad to determine the proportions of major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , K_2O , Na_2O , SO_3 , and CaO). Additionally, the loss on ignition (LOI) was determined by exposing the samples to 1000°C for two hours to quantify the percentage of material lost during firing.

2.2. Bricks Forming and Firing Processes

2.2.1. Preparation of mixtures

After collecting the raw materials from the field site, they were crushed and ground to obtain fine particle sizes. The samples were washed and then passed through a 425- μm sieve. Subsequently, different mixtures were prepared with specified weight ratios, and the specimens were compacted using the semi-dry method with a steel mold of 38.2 mm diameter. The samples were then dried and fired according to a specific firing program to be ready for the evaluation tests.

2.2.2. Mixing and forming

To prepare the samples, 50 grams of raw materials were weighed for each mixture, with glass and paper waste added in different proportions as main additives. Clay was utilized in weight percentages of

100%, 95%, 98%, and 85%, which correlate to additive percentages of 0%, 5%, 2%, and 15%, respectively (Table 2). Each 50 g mixture was dry-mixed, and then, the mixtures were manually formed after adding 7–8% water. To enhance the homogeneity of the mixture, it was sieved through a 1 mm sieve, then the mixture was stored in sealed nylon bags for 24 - 48 hours to allow for even moisture distribution before compaction.

Table 2. Proposed mixtures for brick manufacturing

Mix No.	Raw Material (%)	Additives (%)	
		Glass	Paper
1	100	-	-
2	95	5	-
3	85	15	-
4	98	-	2
5	95	-	5

2.2.3. Firing program

The shaped and dried samples were fired at temperatures of 950–1050 °C. The temperature was increased at a rate of 3 °C/min until the desired temperature was reached. After the samples were fired, they were cooled gradually for more than 24 hours to prevent cracking and allow newly formed mineral phases to stabilize and crystallize. Firing was done at the Geochemistry Laboratory, Department of Geology, University of Basrah, using a Gallenkamp Muffle Furnace (Model number 3) in normal atmospheric conditions.

2.3. After Firing Tests

2.3.1. Apparent porosity

Apparent porosity is defined as the ratio between the volume of voids within the solid mass and its total volume, and it is considered one of the fundamental properties that control the behavior of ceramic materials. Porosity depends on several factors, the most important of which are grain size and distribution, forming method, and compaction pressure. The apparent porosity of the fired specimens at different temperatures (950–1050 °C) was determined according to the standard specification.

$$V = W_s - W_h \quad (3)$$

$$A. P\% = \left(\frac{W_s - W_d}{W_s - W_h} \right) * 100 \quad (4)$$

Where: V is External volume, AP% is Apparent porosity percentage, W_s is Weight of the sample in air when saturated with water (g), W_d is Weight of the sample in air when dry (g), W_h is Weight of the sample when immersed in water and suspended (g).

2.3.2. Water absorption

Water absorption is defined as the percentage of water that enters the voids of a ceramic material, which significantly influences the mechanical strength of fired bricks. A low absorption percentage suggests that a material is denser and structurally stronger, as it means that less water is absorbed.

Testing was conducted according to ASTM C20-00 (2010) and the Iraqi standard specifications at the Geochemistry Laboratory, University of Basra. The testing procedure involved drying samples in an oven at 110 °C for 24 hours to obtain a constant dry weight. The samples were then immersed in water for 24 hours, surface-dried, and weighed again in their saturated state. Water absorption was calculated using the following formula:

$$W.A\% = \left(\frac{W_s - W_d}{W_d} \right) * 100 \quad (5)$$

Where: W.A%: Water absorption percentage. W_s : Saturated weight of the sample (g). W_d : Dry weight of the sample (g).

2.3.3. Bulk density

Bulk density is the weight of the sample in relation to the total sample volume, solid and pore spaces included. It is directly related to porosity, water absorption, and compressive strength. A reduction in porosity generally increases density and compressive strength while decreasing water absorption. For this research, bulk density was calculated according to the American Standard (ASTM C20-00, 2010) and the standard calculation formula.

$$D = \frac{W_d}{V} \quad (6)$$

Where D is bulk density (g/cm³), W_d is sample weight when dry (g), and V is external volume of the sample ($W_s - W_h$).

2.3.4. Compressive strength

As per the American standards (ASTM C773-88, 2006), compressive strength testing was conducted at the College of Engineering, University of Basrah, using a uniaxial hydraulic press (Maruto Tokyo, Japan), with a 20 tons maximum capacity. The samples were placed centrally positioned between the press plates, and the surface of the samples was maintained at the same level. The device was monitored and the reading was taken at a standstill; this was the indicator of the sample's breaking point. After taking these readings, the compressive strength was determined by the standard formula.

$$C.S = \frac{P}{A} \quad (7)$$

Where: C.S is Compressive strength (kg/cm²), P is Load imposed by the press (kg), A is Area of the specimen that was loaded (cm²).

2.3.5. Efflorescence

Efflorescence occurs repeated wetting and drying cycles on the surface of the brick. This can lead to surface deteriorating and flaking, and impacts the structure's overall durability. The efflorescence test was conducted following two efflorescence testing standards, the British Standard (BS 3921, 1985) and the Iraqi Standard (IQS 25, 1988). The sample was placed on its small base in a shallow container with 1 cm of water for 7 days. The sample was then left to dry in the container, and the degree of efflorescence was recorded.

3. Results and Discussion

3.1. Grain Size Analysis

The results indicate that the analyzed deposits contain 36–46% clay, 48–51% silt, and 5–13% sand (Table 3). Using Folk's standard classification (1974), these deposits can be described as sandy mud to mud, indicating suitable particle-size characteristics and a favorable particle-size distribution for brick production. In addition, the grain size conforms with the Iraqi Standard Specification (25, 1988) and the American Standard Specification (ASTM C62-10, 2010), validating the appropriateness of these materials for use as primary materials in clay-based products.

Table 3. Grain Size distribution of clay samples from Basrah, The results were compared with the Iraqi Standard Specification (25, 1988)

No	Sample	Grain size analysis			Texture Classification
		Sand	Silt	Clay	
1	Al-hartha	13	51	36	Sandy mud
2	Great Basrah Project	9	48	43	Mud
3	Umm Qaser	5	49	46	Mud
	Rang	5-13	48-51	36-46	
	Average	9	49.3	41.6	

3.2. Atterberg's limits

According to Kingery et al. (1976), plasticity is one of the fundamental properties of clay, which, when used to make ceramics, provides them with the necessary toughness and strength during the drying and firing stages. The studied samples were classified as ranging from medium to super plastic, as indicated in Budnikov's (1964) (Tables 4 and 5). Plasticity, as described by Grim (1968), is associated with the percentages of clay and silt present; the more plastic a material is, the higher its clay content, and conversely, the higher its silt content, the less plasticity it possesses (Fig. 2). The data on the Plasticity Index (PI) suggests that the studied samples are appropriate for producing clay bricks. The Riecke index results for the studied samples are within the range of 4 to 13, which is deemed acceptable for the needed qualifications of clay for the ceramics industry. As stated in Grim (1962), a value below 10 is indicative of more suitable clay for the industry.

Table 4. Atterberg Limits and Plasticity Indices of clays from Basrah Governorate Samples Based on Budnikov (1964)

No	Sample	LL	PL	PI	SL	RI
1	Al-hartha	31	22	9	26	4
2	Great Basrah	64	48	16	55	7
3	Umm Qaser	56	29	27	42	13

Table 5. Classification of the studied sample based on the plasticity Index

Plasticity Index (P.I)	Plasticity (P.)	Samples
>25	Super Plastic	Umm Qaser
15-25	Plastic	Great Basrah Project
7-15	Moderately Plastic	Al-hartha

<7
Non forming plastic mass

Poorly Plastic
Non - Plastic

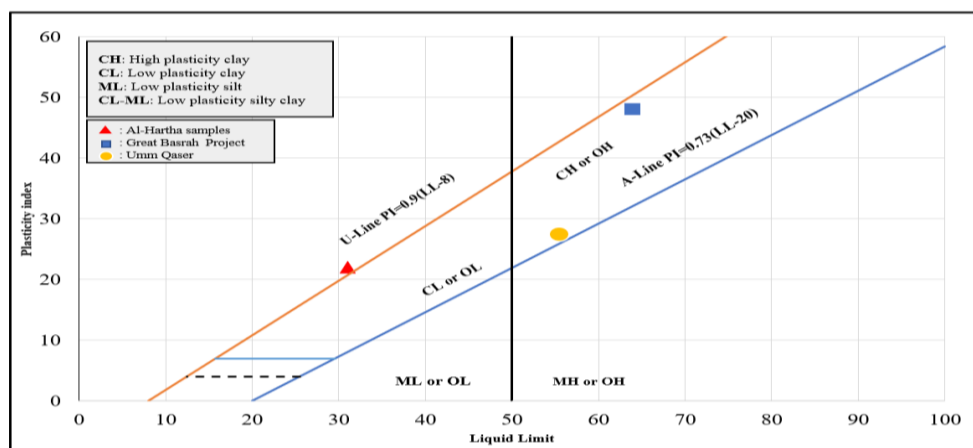


Fig. 2. Plasticity chart of the studied samples

3.3. Mineralogical Analysis

X-ray diffraction (XRD) patterns (Figs. 3 and 4) show that quartz was identified as the dominant non-clay mineral in all studied samples. Calcite is another non-clay mineral that is present in all samples. It functions as a fluxing oxide that speeds chemical reactions during the firing process and lowers the melting temperature of the ceramic body. The firing process decomposes carbonate minerals, increasing a sample's water absorption and porosity while decreasing the sample's density, which may cause bricks to crack. However, excessive amounts of these components may negatively affect the properties of the final product (Al-Khafaji, 2001). The samples also contain gypsum, feldspar and small amounts of dolomite, which is consistent with the results of the chemical analysis that showed a high percentage of magnesium oxide (MgO), especially in the samples from the Hartha area. This indicates that the increased MgO content contributed to the formation of dolomite. Identified clay minerals are made up of kaolinite, montmorillonite, illite, chlorite, palygorskite, and montmorillonite with chlorite mixed-layer. Among these minerals, kaolinite is an important component in the mixture due to its contribution to plasticity and shaping properties. This is due to high drying capacity and plasticity during the formation, which is a result of the mineral containing a substantial volume of aluminum oxide (Al_2O_3) (Al-Ejandre et al., 2009). Illite is a non-expansive mineral with interlayer space that contains potassium as well as strong interlayer bonding (Christie, 2007).

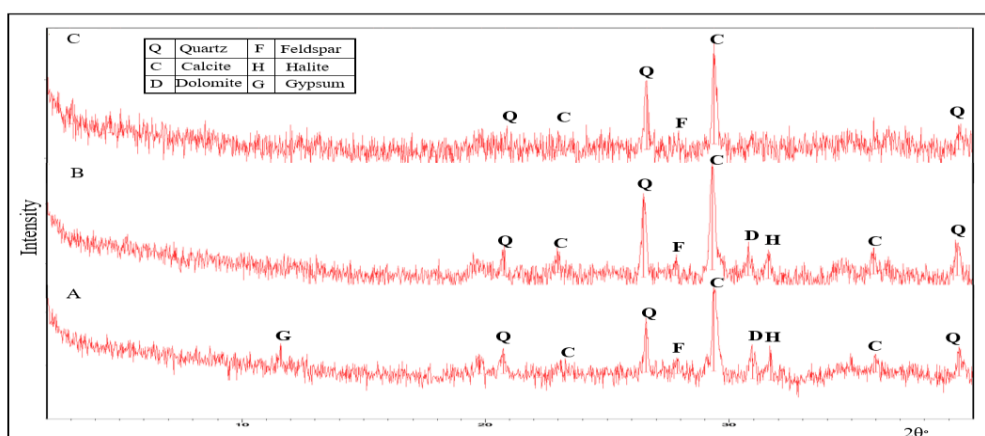


Fig. 3. X-ray diffraction of bulk sample, where A: Al-Hartha and B: Great Basrah Project, and C: Umm Qaser

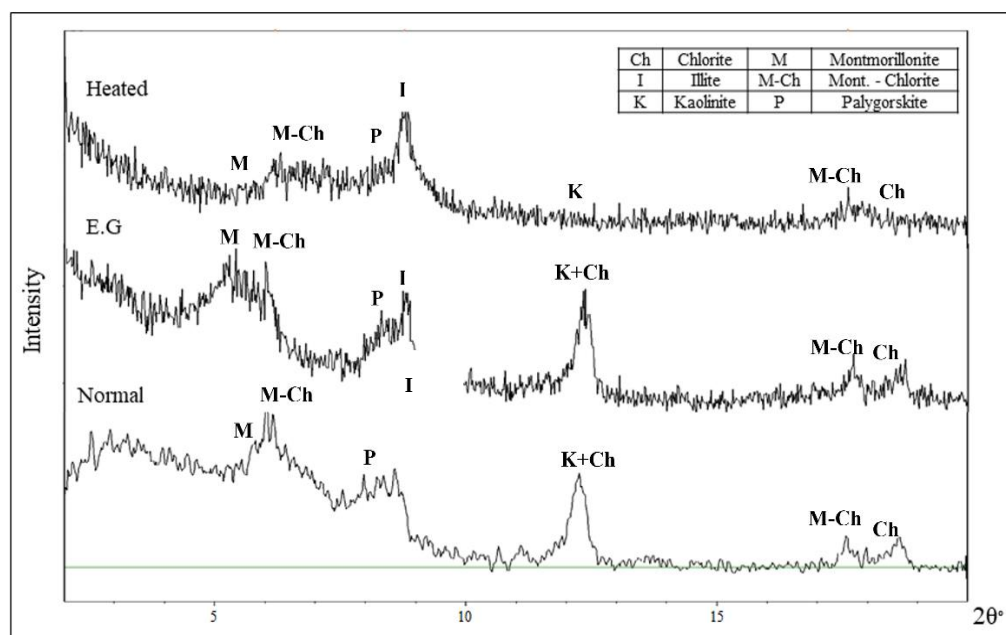


Fig. 4. X-ray diffraction of an oriented sample

3.4. Chemical Analysis

To determine the chemical properties of the clay deposits from the study areas and their potential for clay brick production, chemical analysis was done to quantify the major oxide constituents (Table 6; Fig. 5). Results indicate that among the various oxide constituents in all the samples, silicon dioxide (SiO_2) was the most prevalent, having a concentration of 32.74% in the Al-Hartha deposits, 30.17% in the Greater Basra Project deposits, and 37.61% in Umm Qaser deposits. The relatively higher silica content in the Umm Qaser deposits can be attributed to the increased proportion of silt fraction within these sediments. Silica is an important component of ceramic bodies, reducing plasticity and the amount of shrinkage that occurs during firing. This contributes to better dimensional stability and less deformation during firing (Cultrone et al., 2005). The content of aluminum oxide (Al_2O_3) is between 5.41 and 11.37%. Alumina is a constituent of matrix clay minerals and acts as a refractor oxide in improving the thermal and mechanical strength of the fired bricks by raising the temperature for vitrification and formation of glassy phases (Ryan, 1978). The range of iron oxide (Fe_2O_3) is between 4.57–11.84 %, with greater values in Greater Basra Project samples. Iron oxide acts as both a fluxing agent and coloring oxide that provides a red to brown color to the fired products, especially for firing temperatures below 900°C (Al-Saad, 2006). The higher values of magnesium oxide (MgO) and calcium oxide (CaO) showed ranges of 21.15–25.33% for CaO and 3.04–8.86% for MgO , respectively. Such high values point to the existence of carbonate phases, mainly calcite and dolomite, as non-clay minerals. High values of CaO and MgO could have a negative effect on the firing process by enhancing the liberation of CO_2 which reduce physical strength if the degassing is not well controlled (Cultrone et al., 2005). Na_2O and K_2O along with CaO , Fe_2O_3 , act as fluxing agents, decreasing the melting point of the clay body, especially above 900°C. When the clay is fired within the 900–1100°C range, it develops a continuous glassy phase. This increases the interparticle bonding and enhances the physical and mechanical properties of the fired bricks (Hibbard, 2002; Karaman et al., 2006). The sulfate content is between 0.98–3.18%, which indicates that some of the calcium is in a sulfate form rather than a

carbonate. This compositional characteristic could affect firing reactions and should be considered when adjusting firing conditions.

Table 6. Chemical Composition of Basra Clay Samples (Major Oxides, %)

N o	Sample	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	TiO ₂	L.O.I%
1	Al-hartha	32.74	4.57	7.25	21.87	8.86	3.12	1.39	3.18	0.60	16.42
2	Great Basrah Project	30.17	11.84	5.41	25.33	3.04	1.55	0.96	0.89	0.47	20.34
3	Wafaa Umm Qaser	37.61	5.96	11.37	21.15	3.74	2.50	1.48	1.08	0.94	14.17
	Rang	30.17-37.61	4.57-11.84	5.41-11.37	21.15-25.33	3.04-8.86	1.55-3.12	0.96-1.39	0.89-3.18	0.47-0.60	14.17-20.34
	Average	33.50	7.45	8.01	22.78	5.21	2.39	1.27	1.71	0.68	16.97

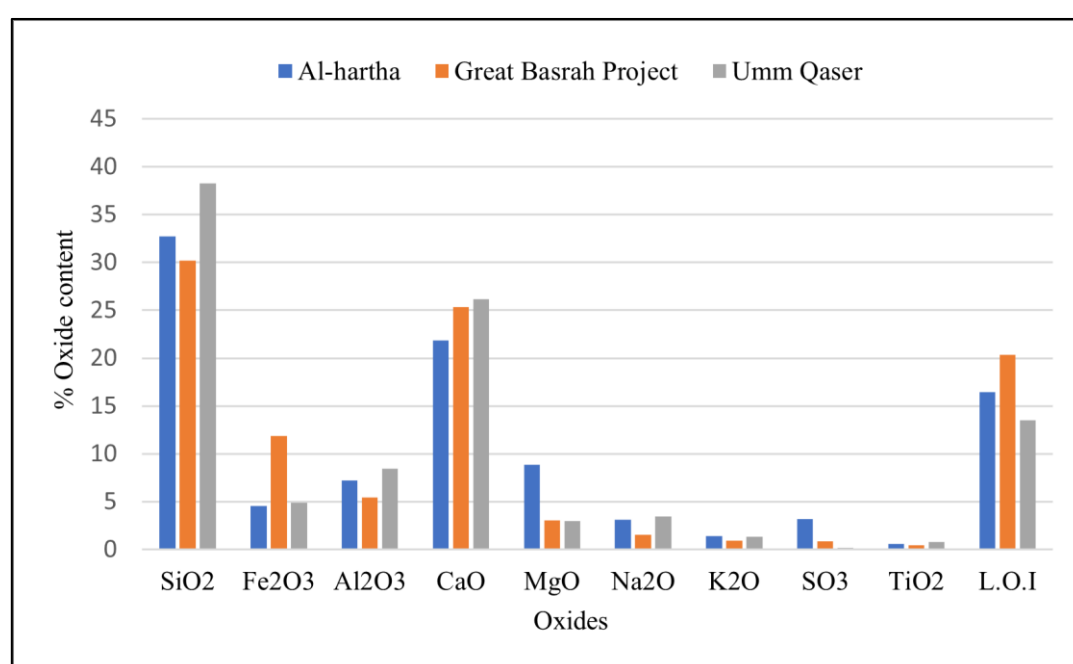


Fig. 5. Distribution of major oxides in the studied samples

3.5. Apparent Porosity

The apparent porosity values for firing temperatures of 950°C and 1050 °C ranged between 26.01-57.68% and 12.89-55.68%, respectively (Table 7). It was observed that the apparent porosity decreased with increasing firing temperature for all mixes. This reduction is attributed to the sintering process, in which particles fuse together, reducing pore space and consequently lowering both apparent porosity and water absorption (Fig. 6). Worrier et al. (1989) noted that apparent porosity and water absorption are directly related, and that both decrease with increasing firing temperature. The significantly reduced apparent porosity in the mixes containing 5% and 15% glass, particularly at 1050°C. This improvement is mainly due to the high silica content in the glass reacting with CaO and alkalis to form new calcium silicate and calcium aluminosilicate phases, such as wollastonite, gehlenite, diopside, and anorthite, as well as partial filling of pores by the resulting glassy phase (Maciulaitis and Malaikiene, 2010). Conversely, in mixes 3 and 4, the addition of paper caused an increase in porosity.

This is due to the combustion of organic fibers during firing, which releases gases and creates additional voids within the sample body, contributing to the total porosity (Al-Marahleh, 2005; Al-Saad, 2014).

Table 7. Results of the main mixture tests

Location	Sample	Mix	Temp.	App.	Water	Bulk	Compressive	Efflo.
Al-Harthah	A	0	950	27.39	18.41	1.48	7.37	M
			1050	23.96	15.17	1.57	8.33	S
		1	950	26.30	17.23	1.52	8.16	M - S
			1050	24.2	15.12	1.59	8.55	N
		2	950	26.01	17.19	1.51	8.14	M - S
			1050	22.48	13.93	1.61	10.78	S - N
		3	950	32.58	24.07	1.35	4.42	M - S
			1050	36.81	28.43	1.29	5.46	M
		4	950	44	38.28	1.14	1.71	M - S
			1050	41.11	33.76	1.21	1.90	S
		Range	950	26.01-	17.19-	1.14-	1.71-	M-S
		Average		31.26	23.04	1.40	5.96	M
		Range		22.48-	13.93-	1.21-	1.90-	N-M
		Average	1050	29.71	21.28	1.45	7	S
		0	950	51.82	37.75	1.37	9.44	M - S
Great Basrah Project	B		1050	32.12	16.85	2.18	60.71	S
		1	950	48.56	34.81	1.39	9.50	M
			1050	19.93	8.94	2.22	64.06	M - S
		2	950	45.30	30.97	1.46	13.58	M
			1050	12.89	5.40	2.38	137.86	S - N
		3	950	56.63	43.49	1.30	5.49	M - S
			1050	35.18	17.54	2	46.27	S - N
		4	950	57.68	47.38	1.17	2.41	M - S
			1050	43.34	25.30	1.22	24.00	S
		Range		45.30-	30.97-	1.17-	2.41-	M-S
		Average	950	51	38.88	1.34	8.08	M
		Range		12.89-	5.40-	1.22-	24-	S-N
		Average	1050	28.69	14.81	2	66.58	S
		0	950	46.96	35.50	1.32	7.62	M
			1050	42.57	26.56	1.60	17.20	M - S
Umm Qaser	C	1	950	48.18	35.32	1.36	8.88	M
			1050	42.20	26.73	1.57	13.76	M - S
		2	950	44.13	30.96	1.42	8.71	S
			1050	40.84	27.41	1.48	14.99	M - S
		3	950	54.57	42.08	1.29	5.41	S
			1050	55.51	42.30	1.31	7.53	M - S
		4	950	56.86	47.46	1.19	1.72	S
			1050	55.68	45.26	1.23	6.70	M - S
		Range		44.13-	30.96-	1.19-	1.72-	M-S
		Average	950	50.14	38.26	1.32	6.47	S
		Range		40.84-	26.56-	1.23-	6.70-	M-S
		Average	1050	33.65	33.65	1.44	12.44	M-S

Range	950	26.01	17.19	1.14	1.71	M - S
Average		44.46	33.39	1.35	6.84	M
Range	1050	12.89	5.40	1.21	1.90	M - N
Average		35.25	23.25	1.63	28.54	S

3.6. Water Absorption

Water absorption is one of the key parameters used to classify brick suitability and grade in many international standards. WA values is directly related to porosity, which represents the percentage of interconnected open pores within the brick body (Karaman et al., 2006). Table 7 presents the results of conventional brick mixtures designated as Mixes 0–4 fired at different temperatures, fired at 950 and 1050 °C. At a firing temperature of 950 °C, water absorption values ranged from 17.19% to 47.38%, with an average of 33.39%. In contrast, at 1050 °C, the values ranged between 5.40% and 45.26%, with an average value of 23.25%. Sample C4, containing 5% paper waste, had the maximum value for water absorption after being fired at 950 °C. The lowest absorption value was observed in sample B2 containing 15% glass and fired at 1050 °C (Fig. 6). The results show that water absorption and porosity decrease with increasing firing temperature, especially in mixtures (1) and (2) with glass additions of 5% and 15%, respectively. Fine glass particles fill pore structures and simultaneously enhance the chemical reaction between the mixture and its silica, which improves the sintering process and decreases water absorption (Hasan et al., 2021). This was supported by the chemical analysis results (Table 6), which revealed high levels of fluxing oxides in the raw materials. Clay brick mixtures (0, 1, and 2) achieved the best results for water absorption enabling their classification as Class A bricks. These results indicate that the produced bricks can be classified according to ASTM C62; however, the relatively higher water absorption values are related to the use of pore-forming additives intended for lightweight insulating applications.. Additionally, the samples from the Basrah Great Project site had the lowest water absorption at a firing temperature of 1050 °C. On the other hand, greater amounts of paper waste additives in mixtures (3) and (4) resulted in increased levels of water absorption. The reason for this is that the paper waste burned away during the firing process, resulting in more empty spaces in the body of the brick, which increased the porosity and, as a result, the water absorption.

3.7. Bulk Density

Density is considered one of the important physical properties of ceramic bodies, as it is directly related to mechanical properties, porosity, and thermal characteristics. Table 7 presents the results of the bulk density test for insulating and lightweight brick mixtures fired at different temperatures (950 and 1050 °C), respectively. The bulk density values at a firing temperature of 950 °C ranged between 1.14 and 1.52 g/cm³, with an average value of 1.35 g/cm³, whereas at 1050 °C the values ranged between 1.21 and 2.38 g/cm³, with an average of 1.63 g/cm³. Density is impacted by the firing temperature, with recorded density values being lower at 950 °C than at 1050 °C. A lower shrinkage ratio at 950 °C, compared to 1050 °C, is responsible, along with the loss on ignition which reduces sample weight and releases gases, leading to pore expansion and an increase in specimen volume. The modification of mixtures 1 and 2 with glass increased the bulk density values, with the increased values being attributed to reduced apparent porosity and water absorption from the silica addition. Manufactured bricks' bulk density values correlate directly with the porosity values, as inversely related (Al-Khafaji et al., 2012). The bulk density values in 1050 °C improved when compared to its values at 950 °C. The presence of fluxing oxides in the raw materials causes liquid phase formation. This triggers the closure of the pores in the specimen body after cooling, thus diminishing the porosity, which in turn causes an increase in the bulk density (Rud et al., 1981). Additionally, the firing temperature of 1050 °C promoted

the formation of mineral phases (Anorthite and Wollastonite), which increased the specimen density. (Mason and Berry, 1968; Read, 1970). Significant changes in the bulk density values were also identified in mixtures 3 and 4 (Fig. 7). The decrease in values is due to the fact that there was a significant combustion and volatilization of paper waste during the firing, which in turn caused more voids in the body of the brick, the overall density of the body of the brick increased (Al-Marhaleh, 2005).

3.8. Compressive Strength

Table 7 shows the results of compressive strength test at 950 and 1050 °C for the samples from the two study sites are presented. At 950 °C, compressive strength for all mixtures from both sites were between 1.71 and 13.58 N/mm² with an average of about 6.84 N/mm². At 1050 °C, the compressive strength test values ranged from 1.90 to 137.86 N/mm² with an average compressive strength of 28.54 N/mm². The high compressive strength observed at 1050°C can be attributed to enhanced sintering and the presence of Fe₂O₃ as a fluxing oxide, which promotes liquid phase formation at relatively lower temperatures and improves particle bonding. In addition, the incorporation of silica-rich glass contributes to further densification and reduction in porosity, resulting in improved mechanical performance. The compressive strength result achieved for all mixtures from the great Basrah Project site fired at 1050 °C qualified for Class A as per the international standards. This classification is based on the compressive strength values, which fall within the limits specified for Class A bricks according to ASTM C62 with average compressive strength of 28.54 N/mm². Mixture 2 with 15% glass addition achieved the highest compressive strength of 137.86 N/mm² (Fig. 7). The increased compressive strength can be attributed to the greater glass content since glass contributes to more rapid thermal reactions and the creation of binding glassy melts. This can be linked to regulate the viscosity of the intergranular glassy phase. As solidification occurs during the sintering process, the glassy phase fully transforms, increasing the strength and rigidity of the samples leading to even higher compressive strength (Manfredini and Hanuskova, 2000). Moreover, the examined site's deposits contain high quantities of fluxing oxides that assist in lowering the melting and glassy phase formation temperature. This led to increased compressive strength at relatively lower firing temperatures (Budnikov, 1964). Although mixture 0 exhibited the lowest compressive strength across all sites, strength improved after additive incorporation. In addition, mixtures 3 and 4 had the lowest compressive strength values, which agrees with the findings from the previously discussed physical tests. The increase in organic material content (paper waste) reduced the resistance of the product to compressive loading, owing to its combustion during firing and the formation of internal voids. These voids contributed to an increase in apparent porosity and a reduction in bulk density (Chan, 2011).

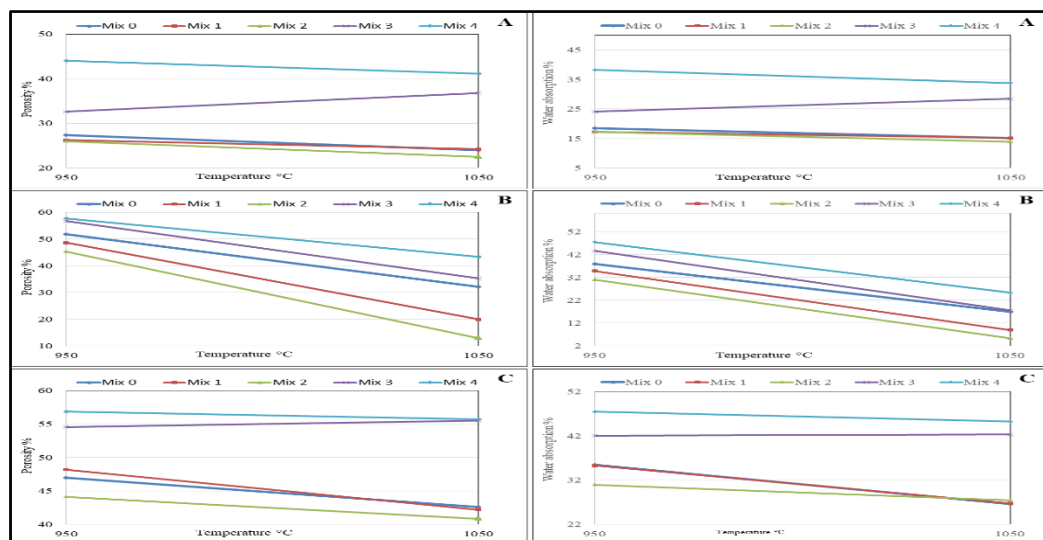


Fig. 6. The relationship between the porosity, water absorption, and firing temperatures for ordinary bricks, where A: Al-Hartha and B: Great Basrah Project

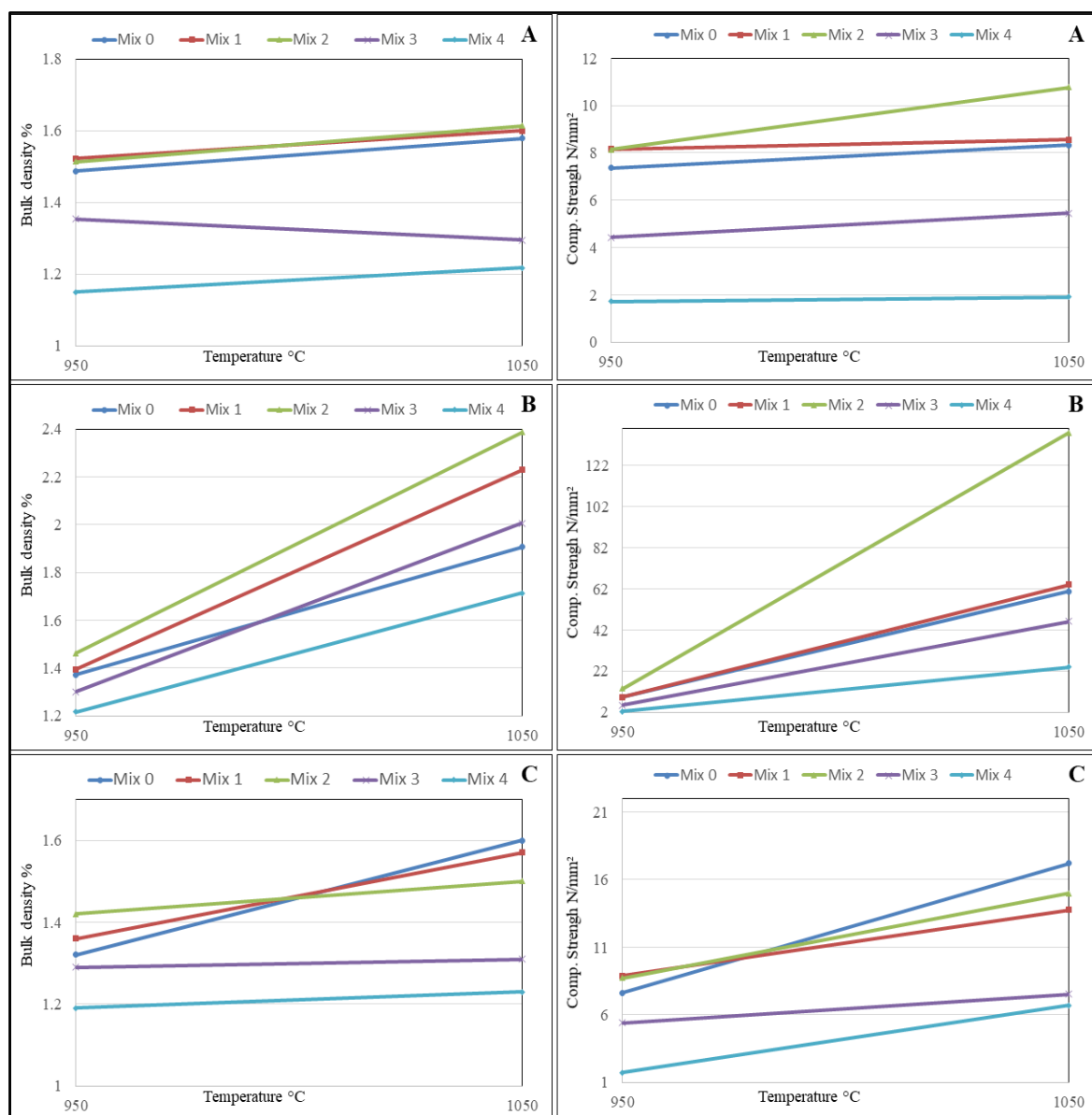


Fig. 7. The relationship between the bulk density, compressive strength, and firing temperatures for ordinary bricks, where A: Al-hartha and B: Great Basrah Project)

3.9. Efflorescences

Table 7 details the efflorescence testing results of the insulating brick samples fired at 950 °C and 1050 °C. The results show increasing firing temperature corresponds to a reduction in the degree of efflorescence across all investigated samples. The degree of efflorescence for 950 °C was characterized as moderate to low; at 1050 °C, it was low to negligible (Fig. 8). The addition of 15% glass also contributed to reducing efflorescence due to the increased silica content, particularly iron oxide (Fe_2O_3), alumina (Al_2O_3), and magnesia (MgO), to produce chemically stable mineral phases such as wollastonite, gehlenite, and anorthite, especially at higher firing temperatures (1050 °C) (Brownell, 1958). Oxides that do not react encourage the development of sodium, potassium, and calcium salts, which include carbonates, sulfates, and chlorides. When salts are exposed to moisture, they migrate through the pore channels until they reach the surface of the brick, where they can crystallize to cause scaling, or under the surface, causing expansion. Both factors negatively affect the mechanical properties of the brick.



Fig. 8. Variation in the degree of efflorescence in brick samples at different firing temperatures

3.10. Assessment of Brick Performance

Umm Qasr specimens fired at 950 °C and 1050 °C fall within the typical range of insulating refractory bricks. Similarly, the Great Basrah Project specimens fired at 950 °C exhibit identical characteristics. In contrast, samples fired at 1050°C, particularly those from the Great Basrah Project and Al-Hartha, exhibit characteristics consistent with dense refractory bricks. This behavior is mainly attributed to the increase in firing temperature, which enhances sintering, promotes pore closure, and leads to improved densification. Consequently, the reduction in porosity and the increase in density and mechanical strength at 1050°C result in a transition from insulating to dense refractory behavior. Although the primary objective of this study is to produce insulating bricks, the results demonstrate that some samples can also exhibit characteristics comparable to dense refractory bricks under higher firing conditions (Table 8).

Furthermore, a comparison with Iraqi, American (ASTM C62), and British standards for conventional clay bricks indicates that several samples, particularly those from the Great Basrah Project fired at 1050°C, satisfy the requirements of Class A in terms of compressive strength. This suggests that the studied materials may be suitable for both insulating and conventional brick production, depending on the firing conditions (Table 9).

Table 8. Comparison between standard properties of insulating and dense refractory bricks and the results of the present study

Requirements	Insulating refractory brick (ASTM C155-20)	Refractory brick (Ajala et al., 2017)	Al-Hartha		Great Basrah Project		Umm Qasr	
			950	1050	950	1050	950	1050
Apparent porosity	40-80 %	10-30%	31.26	29.71	51	28.69	50.14	47.36
Compressive strength N/mm ²	1-10 MPa	15-59 MPa	5.96	7	8.08	66.58	6.47	12.04
Density g/cm ³	0.3-1.2 g/cm ³	1.8-2.5 g/cm ³	1.40	1.45	1.34	2	1.32	1.44

Table 9. Comparison of clay brick sample properties with Iraqi and international standards

Requirements	Iraqi standards (25,1993)			American standards (C62-10, 2010)			British standards (3921, 1985)	Al-Hartha		Great Basrah Project		Umm Qasr	
Glass	A	B	C	A	B	C		950	1050	950	1050	950	1050
Water absorption%	22	26	28	20	25	-	No limit	23.04	21.28	38.88	14.81	38.26	33.65
Compressive strength N/mm ²	16	11	7	17	15	9	>5	5.96	7	8.08	66.58	6.47	12.04
Efflorescence	S	M	H	-	-	-	N-M	M-S	S-N	M-S	S-N	M-S	M

4. Conclusions

The present study evaluated the potential of clay deposits obtained from water treatment plants in three key areas in southern Iraq (Al-Hartha, the Great Basrah Project, and Umm Qaser) for the production of lightweight thermal insulating bricks. The results indicate that the physical, chemical, and mineralogical characteristics of these materials are suitable for brick manufacturing, particularly for applications requiring lightweight and thermally insulating properties. The incorporation of industrial additives significantly affected on the properties of the produced bricks. Paper waste (2–5%) increased the apparent porosity during firing, which contributed to improved thermal insulation performance, while causing only a slight reduction in compressive strength. In contrast, glass waste (5–15%) enhanced densification and mechanical strength due to improved sintering behavior.

The classification of the produced bricks was found to be influenced by multiple factors, including firing temperature, chemical composition, and the type and proportion of additives. Based on comparison with standard ranges, Umm Qasr samples at both firing temperatures (950°C and 1050°C), as well as the Great Basrah Project samples at 950°C, fall within the range of insulating refractory bricks. In contrast, samples fired at 1050°C, particularly those from the Great Basrah Project and Al-Hartha, exhibit characteristics consistent with dense refractory bricks due to reduced porosity and enhanced densification.

Furthermore, comparison with Iraqi, American (ASTM C62), and British standards for conventional clay bricks indicates that some samples, particularly those from the Great Basrah Project at 1050°C, satisfy the requirements of Class A in terms of compressive strength. This suggests that the studied materials can be utilized for both insulating brick production and conventional building bricks, depending on processing conditions.

Overall, the results demonstrate the feasibility of utilizing clay deposits from water treatment plants, combined with suitable industrial additives, to produce thermally insulating and mechanically acceptable bricks.

Author contributions: CRediT

- **Conceptualization:** The research concept and overall study design were developed by Zainab H. Al-Salihi and Harith A. Al-Saad.
- **Data Curation:** Clay and brick samples were collected, prepared, and organized by Zainab H. Al-Salihi and Harith A. Al-Saad, with samples obtained from the Great Basra Project and Al-Hartha Project.
- **Formal Analysis:** Laboratory analyses, including pre-firing grain size distribution, Atterberg limits, X-ray diffraction (XRD), X-ray fluorescence (XRF), brick forming and firing processes,

and post-firing testing (apparent porosity, water absorption, bulk density, compressive strength, efflorescence), were performed by Zainab H. Al-Salihi, with guidance and supervision from Harith A. Al-Saad. Analyses were conducted at the Physics Department, Basrah University, in Basrah, Geology Department, Baghdad University.

- **Funding Acquisition:** The research was self-funded by Zainab H. Al-Salihi, with no external financial support.

Investigation: Experimental investigation, including sample collection, preparation, characterization, and brick manufacturing, was carried out collaboratively by Zainab H. Al-Salihi and Harith A. Al-Saad.

Methodology: The experimental methodology, including pre-firing characterization, brick production, firing procedures, and post-firing testing, was developed and applied collaboratively by Zainab H. Al-Salehi and Harith A. Al-Saad.

Project Administration: Project administration and coordination were undertaken by Harith A. Al-Saad.

Resources: Clay and brick samples were provided by the Great Basra Project and Al-Hartha. Laboratory facilities were provided by Basra University.

Software: Data analysis, figure preparation, and documentation were performed using Microsoft Excel, Word, and other standard Microsoft Office tools.

Supervision: Scientific supervision and academic guidance were provided by Harith A. Al-Saad.

Validation: The findings were validated through comparison with previous studies on clay and brick preparation, including Al-Saad (2006), Hassan (2005), Al-Rawi (1982), and Al-Khafaji (2012). Comparable results were obtained regarding the effects of additives and firing conditions on brick properties, supporting the reliability of the study.

Visualization: Figures and visual materials, including images of XRD patterns, brick samples, and graphs showing relationships between porosity, water absorption, bulk density, compressive strength, and firing temperatures, were prepared by Zainab H. Al-Salihi. XRD images were obtained at the Physics Department, Basrah University, and brick images were produced at the Engineering College, Basrah University.

Writing – Original Draft: The original manuscript was written by Zainab H. Al-Salihi.

Writing – Review & Editing: The manuscript was reviewed and edited by Harith A. Al-Saad, with final revisions completed by Zainab H. Al-Salihi.

Declaration of Competing Interest

The authors, Zainab H. Al-Salihi and Harith A. Al-Saad, declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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Data Availability

The data supporting the findings of this study are not publicly available due to confidentiality agreements with the Great Basra Project and Al-Hartha area. Access to the data can be requested from the corresponding author under appropriate conditions.

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