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# Improving the Physical and Mechanical Properties of Fireclay Refractory Bricks by Added Bauxite

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## ABSTRACT

In this study, the investigation of Local natural Iraqi rocks kaolin with the addition of different proportions of bauxite and its effect on the physical and mechanical properties of the produced refractories was conducted. Kaolin/bauxite mixture was milled and classified into various size fractions, the kaolin (less than 105 μm) and the bauxite (less than 70μm). The specimens were mixed from kaolin and bauxite in ranges B1 (95+5)%, B2 (90+10)%, B3(85+15)%, and B4 (80+20)% respectively. The green specimens were shaped by the semi-dry method using a hydraulic press and a molding pressure of 7 MPa with the addition of (9-12) %wt. of PVA ratio. After molding and drying, the specimens were fired at (1100, 1200 and 1300) °C. Physical properties (density, porosity, water absorption) and mechanical properties (indirect tensile strength and hardness) were measured for all the prepared samples. The results showed that the porosity was increased and the density was decreased, such increase and decrease affected on to the mechanical properties for refractory. The highest values of indirect tensile strength and hardness were obtained at 20% Bauxite at 1300 °C (0.85386 MPa, 1411Kg / mm$^2$) respectively.

**Keywords:** refractory bricks, kaolin, Iraqi bauxite.

# تحسين الخواص الفيزيائية والميكانيكية لطابوق الحراري بإضافة البوكسايت

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## الخلاصة

في هذا البحث تم فحص الكاولين كالصخور العراقية الطبيعية المحلية مع إضافة نسب مختلفة من البوكسايت و دراسة تأثيرها على الخواص الفيزيائية والميكانيكية للحراريات المنتجة ،تم طحن خليط الكاؤلين / البوكسايت بحجوم حبيبية معينه ،الكاؤلين (أقل من 105 ماكرون) والبوكسايت (أقل من 70) ماكرون . تم خلط العينات بنسب وزنيه معينه كالأتي B1 (95 + 5)٪وB2 (90 + 10)٪وB3 (85 + 15)٪ و B4 (80 + 20) ٪ على التوالي. وشكلت العينات بالطريقة شبه الجافة باستخدام المكبس الهيدروليكي بضغط 7 ميكا باسكال بإضافة محلول بوليمري بنسب وزنيه من(9-12)% من وزن العينة وتم تجفيف العينات لمده 9ساعات وتلبيد العينات بدرجات حرارية معينة (1100,1200,1300) م° . تم فحص الخواص الفيزيائية (الكثافة والمسامية وامتصاص الماء) والخصائص الميكانيكية

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(مقاومة الشد غير المباشرة والصلادة) لجميع العينات. وأظهرت النتائج زيادة المسامية الظاهرية ونقص الكثافة الحجمية يؤثر على خصائص الميكانيكية للحراريات. وتم حصول على اعلى قيم مقاومة الشد غير مباشرة والصلادة في العينة الحاوية على 20% بوكسايت عند درجة حرارة تلبيد 1300م°(0.85386 MPa، 1411Kg/mm²) على التوالي .

## 1- INTRODUCTION

Refractory materials may be defined as materials that retain their physical and chemical identity when subjected to high operating temperatures. These materials are non-metallic compounds that can withstand high temperatures fluctuations between (1100 and 1300) °C **Musa, et al., 2012** and **Ameh, et al., 2009,** with high resistance to fusion and withstand high temperature physically and chemically. They are also thermally good to be used in the metallurgical industry in the construction of all furnaces where they are used in the internal lining of furnaces for melting and heating before further processing, smelting in vessels for holding and transporting molten metals and slags, and in the flues or stacks through which hot gases are conducted, **Ewais, 2004.**

Bauxite is defined as a mixture of minerals which consists mainly of aluminum oxide bound to one or more water molecules (hydrated aluminum oxide). They are diaspore, boehmite and gibbsite **Ullmann, 1982,** with **a s**mall amount of impurities such as $SiO_2$, $k_2O$, $Fe_2O_3$, $TiO_2$, CaO, MgO and $Na_2O$, **Ullmann, 1982.** Bauxite is the primary source for industrial aluminum and alumina production by Bayer process, **Laming, 1971**.

Bauxite is also used to produce refractory bricks, during firing below 1200°C. Its structure is transformed into dense granules containning mainly Corandom (∝-Al2O3). At temperatures within the range (1250–1350)°C the mullite phase is formed as a result of the reaction between silica and alumina, **Laming, 1971**.

Gibbsite is its hydrate at (290–340)°C and transforms to boehmite, and at less than (1200–1300)°C it is transformed to corundum as shown in the following equation, **Ullmann, 1982.**

$$Al_2O_3.\,3H_2O \xrightarrow{290\text{-}340} Al_2O_3.\,H_2O \xrightarrow{490\text{-}550^{\circ}C} \gamma Al_2O_3 \xrightarrow{\text{below } 1200\text{-}1300^{\circ}C} Al_2O_3$$

Mullite phase is formed at a temperature (1250–1350)°C, according to the following equation, **Musa, et al., 2012.**

$$3\,Al_2O_3 + 2SiO_2 \xrightarrow{1250\text{-}1300^{\circ}C} 3Al_2O_3.\,2SiO_2.$$

Mullite is considered as a binding phase in most of the refractory brick and it has a high resistance to melting and minimum thermal expansion as well as low thermal conductivity. Mullite is also characterized by its chemical and thermal stability, **Shackelford, and Doremus, 2008**

The aim of this research is to manufacture porous refractory bricks as thermal insulators for lining the furnaces by adding locally raw materials (Bauxite to Dwaikhla Kaolinite clays).

## 2- EXPERIMENTAL WORK

### 2-1 The Preparation of Specimens

Iraqi bauxite rocks were washed, crushed, ground and sieved. Also, Iraqi kaolin rocks were crushed, ground and sieved. Iraqi kaolin clay used is characterized by its good plasticity. The particle size of milled kaolin was (>125)μm and the particle size of milled Bauxite was

(>75)µm. Iraqi bauxite and kaolin were produced from the Iraqi State Company of Mining Industry.

The chemical composition of bauxite and kaolin raw materials were investigated by chemical analysis and shown in **Table 1.**

The specimens were mixed from kaolin and bauxite in range B1 (95+5)%, B2 (90+10)%, B3(85+15)%, and B4(80+20)% respectively. The green specimens were shaped by the semi-dry method using a hydraulic press and a molding pressure of 7MPa with the addition of (9-12)%wt. of PVA solution ratio. The specimens had a cylindrical shape (30 mm diameter and 30 mm high) according to **DIN 51053**. After molding and drying, the specimens were fired at (1100, 1200 and 1300) °C. The fired bricks important physical and mechanical properties were investigated.

## 2.2 THE INVESTIGATIONS

2-2-1 The Physical Investigations

2-2-1-1 Apparent Porosity (P %), Water Absorption (W %), and Bulk Density (B).

The procedure involved at first measuring the dry weight (D) in (g). The specimen is boiled in water for 5hr and allowed to cool in water for 24 hr. The saturated weight (W) in (g) and the suspended weight in water (S) in (g) are calculated according to ASTMC20-2005. The apparent porosity (P%) is expressed as the percentage of the volume of the open pores penetrated by the immersion liquid with respect to the total volume of the material. It can be calculated using formula, **Mehdi, 2007.**

$$P\%=\left(\frac{W-D}{V}\right)*100 \tag{1}$$

Where

P%: apparent porosity, V: volume of pores in ($cm^3$) =W-S

Water absorption can be indicative of open pores due to the weight of moisture in pores compared to the weight of the sintered body and it depends on the properties of the raw materials, grain size, and the conditions of shaping process and firing temperatures, while water absorption is calculated as follows **ASTM-C20-00.2005.**

$$A\%=\left(\frac{W-D}{D}\right)*100 \tag{2}$$

Where:

A%: water absorption, W: saturated weight in (g), D: dry weight in (g) **ASTM-C20-00.2005.** And the bulk density (B) can be defined as the ratio of the mass of materials to its bulk volume. Where the volume involves the volume of solid components, pores, and seal pores, **Laming, 1971.** The bulk density of the components and the simplest method involves measuring dry weight divided by the exterior volume, including pores can be calculated as follows:

$$B=\frac{D}{V} \tag{3}$$

Where

B: bulk density in ($\frac{g}{cm3}$)

**2.3 The Mechanical investigation**

The mechanical investigation includes:

2-3-1 The indirect tensile strength

The indirect tensile strength of the sintered models has been calculated using a hydraulic piston designed for this purpose. The diameter of the model was pressed to the extent that the model appears to fail. The pressure strength at which the model begins to fail was measured by the thickness of the model and its diameter. Following the relationship, indirect tensile strength is calculated, **Laming, 1971.**

$$\sigma_f = \frac{2F}{\pi h d} \quad (4)$$

Whereas:

$\sigma_f$= indirect tensile strength (N / mm$^2$).

F = maximum weighted load after which the model starts with failure (N).

d = model diameter (mm).

h = model thickness (mm).

2-3-2 Hardness

The method of Vickers microscopy (HV) was used to measure the hardness of the models by shedding a load of 9.8 N at a time of 20 sec. Three hardness readings were taken rate for each sample calculated from Equation.

$$HV = \frac{2fSIN\frac{136^{\circ}}{2}}{d^2} = 1.854\frac{F}{d^2} \quad (5)$$

*Where:-*

*F*= Load in kg, *d* = Arithmetic mean of the two diagonals, *d1*, and *d2* in mm HV = Vickers hardness.

**3- RESULTS and DISCUSSION:**

**3-1 Chemical Analysis:**

It can be indicated from the results of chemical composition analysis, as shown in **Table 1** that kaolinite has a high percentage of silica 49.01% and 34.97% $Al_2O_3$, 1.51% $Fe_2O_3$, 0.93 % $TiO_2$, with a small amount of impurities percentage. The results showed that kaolinite is suitable for manufacturing refractory bricks that were in agreement with the reference and the bauxite has a high percentage of alumina 54.94% and 22.40% $SiO_2$and 1.47%$Fe_2O_3$and 2.59%$TiO_2$ with a small amount of impurities percentage**.**

**3-2 The Physical properties**

3-2-1 The Apparent Porosity (P %)

**Table 2** shows the effect of firing temperatures (110 0-1300) °C on the apparent porosity of the fired specimens. The K codes specimens and presented apparent porosity between (13.4236 - 5.628041) % and for the B codes was (13.1996-18.5220) % to (10.3495-14.4262) %. It is observed that the apparent porosity of the mixtures increased with decreeing temperature due to the increased amount of the liquid phase formed, which closed the pores at the high-temperature levels. In cooling, the liquid phase solidifies to form the glass phase. **Fig. 1** showed the effect of additives on the apparent porosity, where the apparent porosity was increased with increasing the bauxite ratio at different temperatures of sintering. The apparent porosity for bauxite was higher than that for kaolin which could be attributed to the air pockets contained in it**, Lee and Yeh, 2008.** This is explained by the high-progressive porosity of container samples on the ratios of bauxite, B4 codes (22, 022, 18, 522, 14, 4262), at temperatures of (1100-1200-1300) ˚C When adding 20% bauxite.

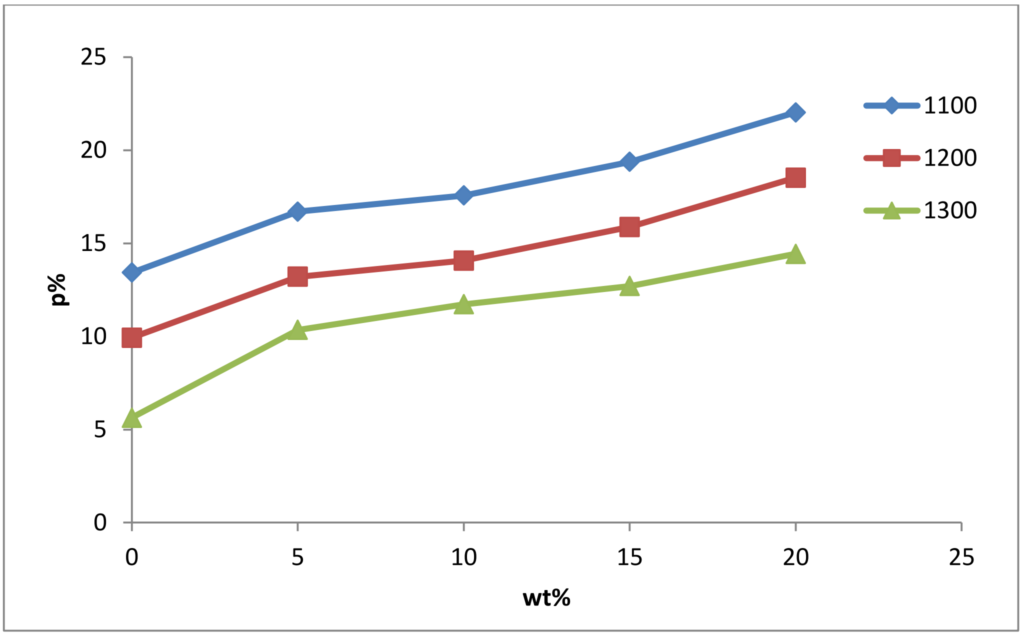


**Figure1.** The relationship between porosity and the ratio of adding Bauxite for different temperature**.**

3-2-2- Water Absorption (A %)

**Table 3** shows the effect of firing temperatures on water absorption for the range of (1100-1300°) C. It showed the water absorption between (6.369518-10.0117) percent to (2.272328-6.18251) % respectively. The B codes specimens displayed the lowest values of water absorption, because as the porosity decreases the water absorption decreases. Also, it can be noticed from the results that the percentage of water absorption continuously decreases as temperature increases. This was in agreement with **Dhanapandian, and Gnanavel, 2010**, **and Aiyedun, et al., 2012**. This is due to the extent of densification in the fired body which is a measure of the water absorption and is also used as an expression to open pores. In addition to that, increasing in firing temperature leads to a reduction in the percentage of porosity in the component as results of shrinking of them. This consequently leads to the disappearing of many pores which will reduce the percentage of water absorption that was in agreement with **Onche, 2007**. The results are shown in **Fig.2**.

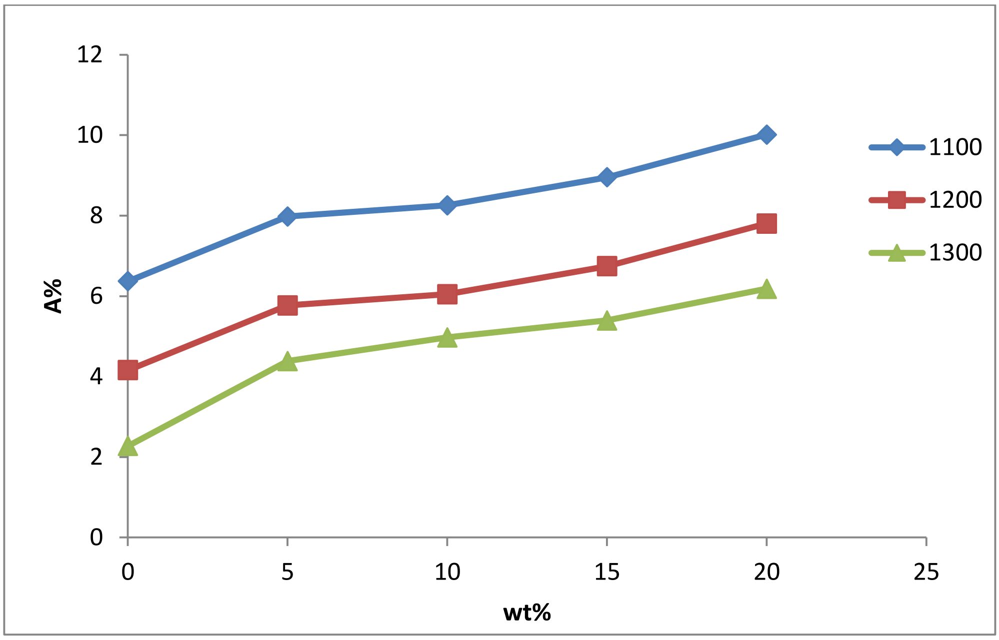


**Figure 2.** The relationship between water absorption and the ratio of adding for different temperature**.**

3-2-3 The bulk density (B)

The effects of firing temperatures in the range of (1100-1300) °C on the bulk density in **Table 3.** The B codes specimens displayed the bulk density between (2.2627 -2.2511)$\frac{g}{cm3}$ to (2.4767-2.3343)$\frac{g}{cm3}$ respectively. It can be seen that the values of bulk density increases with increasing firing temperatures for a given composition as shown in **Fig.3**. The variation in the bulk density between the specimens is due to the fact that density of fired brick depends on several factors such as the specific gravity of clay, method of manufacture, and degree of firing **Phonphuak, and Thiansem, 2011.** The increase in temperature leads to a continuous reaction of phase crystal formation specially mullite crystal. This interpenetrates with each other due to liquid sintering mullite in high temperatures causing to reduce the porosity of the refractory production and increase the values of bulk density. It can be observed that the bulk density decreases with the increases in apparent porosity that was in agreement with the reference**, Estani, et al., 2005.**

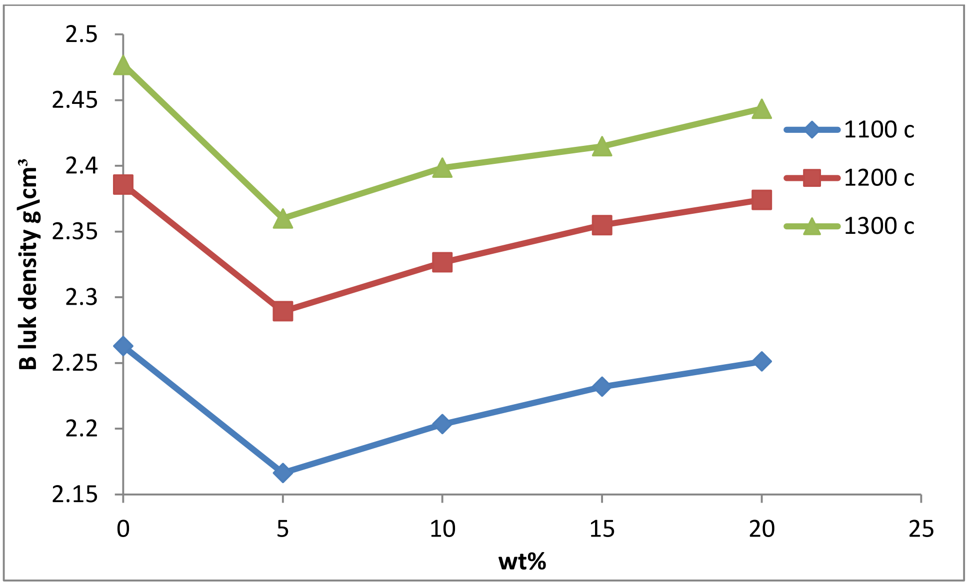


**Figure 3.** The relationship between bulk density and the ratio of adding Bauxite for different temperature**.**

### 3-3 Mechanical Properties

3-3-1 Indirect Tensile Strength

The results of indirect tensile strength were shown in **Table 5** in the range of (1100-1300) °C. It can be seen from the results of indirect tensile strength for the ratio of B codes specimens ranged from (0.135905 - 0.17693) MPa to (0.462558 -0.853857) MPa respectively. Indirect tensile strength can indicate the engineering quality of refractories as building materials for lining the furnaces**, Duggal, 2008 and Al-Marahleh, et al., 2012**. The indirect tensile strength of the specimen is remarkably improved by firing at a higher temperature. This is due to that the increasing of densities with increasing firing temperature causes an increase in indirect tensile strength with an increase in bulk density due to a decrease in porosity with raising in fired temperatures. It can be noticed from **Fig.4** that reduction in the indirect tensile strength with an increase of the apparent porosity means that the increase in additives percentage of insulating additives materials to the kaolinite in the ratio mixture of specimens, besides, the mechanical properties are influenced by the chemical composition of the raw materials and porosity of the produced refractories which was in agreement with **Al-Marahleh, et al., 2012**, and **Othman, 2010**.

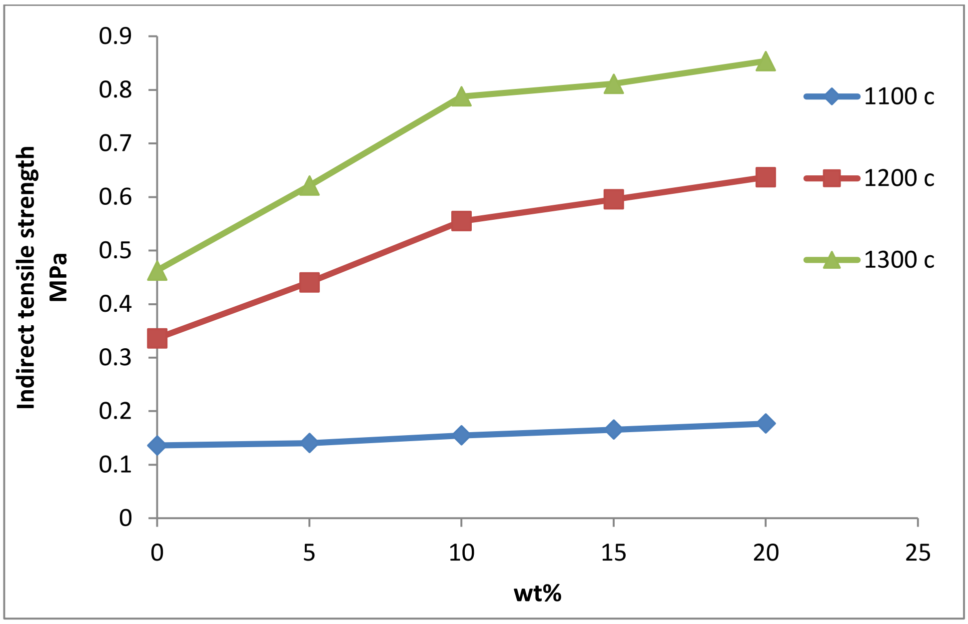


**Figure 4.** The relationship between indirect tensile strength and the ratio of adding Bauxite for different temperature**.**

3-3-2 Hardness

The results of hardness were shown in **Table 6** at the range of (1100-1300) °C. It can be seen from the results of hardness for the ratio of B codes specimens ranged from (840-1002) Kg/mm² to (1306-1411) Kg/mm² respectively. It was observed in the **Fig. 5,** that the hardness increased with increasing temperature. This is due to increasing the amount of glass phase which increases the bond between the grain of the specimen and also reduces the porosity, And also because of the increased content of the Mullite phase in the installation of these specimens, which has good mechanical properties **Al-Marahleh, et al., 2012** and **Kassim, et al., 2011**.

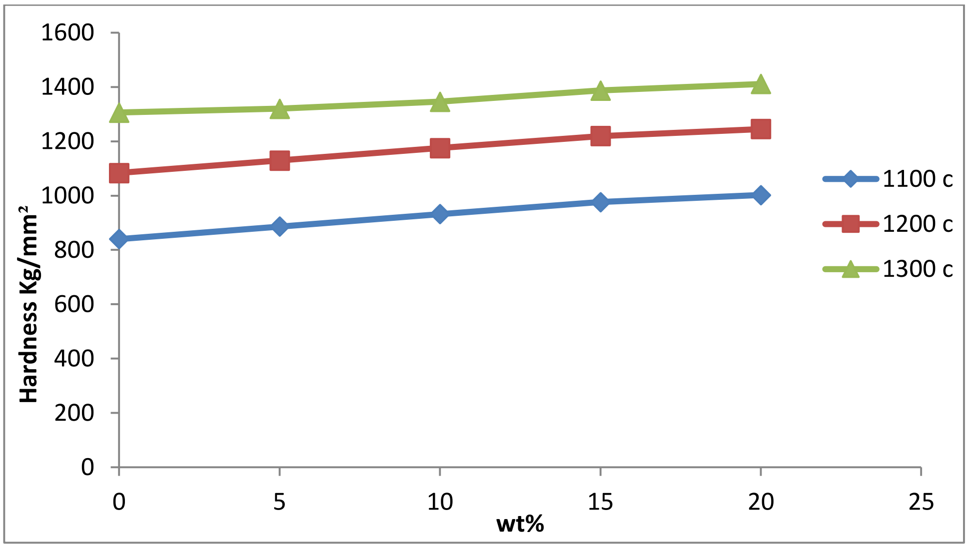


**Figure 5.** The relationship between hardness and the ratio of adding Bauxite for different temperature**.**

## 4- CONCLUSIONS

The following conclusions can be drawn from the results of the investigations and from the raw materials results. In this study, it was found the economic benefits from used local Iraqi raw materials to produce (lightweight and ordinary) ceramic refractories that have properties within international standards. The kaolinite clay from Dwaikhla deposit is suitable for producing refractories due to the high alumina content 34.21%. Optimum firing temperature was found 1300℃, which displayed the required properties and fit within international specifications with high indirect tensile strength, physical properties, and thermal properties.

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**Table 1.** Chemical analysis for kaolin and bauxite.

| **chemical composition** | **kaolin** | **Bauxite** |
|---|---|---|
| $AL_2O3$ | 34.97% | 54.94% |
| $SiO_2$ | 49.01% | 22.40% |
| $Fe_2O_3$ | 1.51% | 1.47% |
| $TiO_2$ | 0.93% | 2.59% |
| CaO | 0.29% | 1.69% |
| MgO | 0.18% | 0.06% |
| $Na_2O$ | 0.03% | 0.03% |
| $K_2O$ | 0.45% | 0.06% |
| L.O.I | 12.6 | 16.6 |

**Table 2.** The values of the porosity of the five samples at different temperatures.

| **mixture code** | **wt%** | **Porosity at 1100 º C** | **Porosity at 1200ºC** | **Porosity at 1300ºC** |
|---|---|---|---|---|
| K1 | 0 | 13.4237 | 9.923664 | 5.62804 |
| B2 | 5 | 16.6997 | 13.19968 | 10.3495 |
| B3 | 10 | 17.5685 | 14.06851 | 11.7245 |
| B4 | 15 | 19.3739 | 15.87391 | 12.6986 |
| B5 | 20 | 22.0221 | 18.52207 | 14.4262 |

**Table 3.** The values of the water absorption of the five samples at different temperatures.

| mixture code | wt% | water absorption at 1100 $^o$ C | water absorption at 1200 $^o$ C | water absorption at 1300 $^o$ C |
|---|---|---|---|---|
| K1 | 0 | 6.36952 | 4.159518 | 2.27233 |
| B2 | 5 | 7.97576 | 5.765761 | 4.38532 |
| B3 | 10 | 8.25708 | 6.047077 | 4.97101 |
| B4 | 15 | 8.95082 | 6.740815 | 5.39244 |
| B5 | 20 | 10.0117 | 7.801705 | 6.18251 |

**Table 4.** Shows the values of the Density of the five samples at different temperatures.

| mixture code | wt% | Density at 1100 $^o$ C | Density at 1200 $^o$ C | Density at 1300 $^o$ C |
|---|---|---|---|---|
| K1 | 0 | 2.26277 | 2.385773 | 2.47677 |
| B2 | 5 | 2.16632 | 2.289322 | 2.36004 |
| B3 | 10 | 2.2035 | 2.326498 | 2.35857 |
| B4 | 15 | 2.2319 | 2.354895 | 2.35489 |
| B5 | 20 | 2.25111 | 2.374105 | 2.33434 |

**Table 5.** The values of the indirect tensile strength of the five samples at different temperatures.

| mixture code | wt% | Indirect tensile strength at 1100 $^o$c | Indirect tensile strength at 1200 $^o$c | Indirect tensile strength at 1300 $^o$c |
|---|---|---|---|---|
| K1 | 0 | 0.13591 | 0.335905 | 0.46256 |
| B2 | 5 | 0.14036 | 0.440356 | 0.62119 |
| B3 | 10 | 0.15478 | 0.554777 | 0.78777 |
| B4 | 15 | 0.16539 | 0.595393 | 0.81137 |
| B5 | 20 | 0.17693 | 0.636932 | 0.85386 |

**Table 6.** The values of the Hardness of the five samples at different temperatures.

| mixture code | wt% | Hardness at 1100 $^o$c | Hardness at 1200 $^o$c | Hardness at 1300 $^o$c |
|---|---|---|---|---|
| K1 | 0 | 840 | 1083 | 1306 |
| B2 | 5 | 886 | 1129 | 1320 |
| B3 | 10 | 932 | 1175 | 1346 |
| B4 | 15 | 976 | 1219 | 1387 |
| B5 | 20 | 1002 | 1245 | 1411 |