Fires Accidents and its Implication on Mechanical and Structural Properties of Different Construction Materials

Asad H. Aldefae¹*, Abbas S. Edan² and Abbas F. Essa²

¹Department of Civil Engineering, University of Wasit, Iraq, Wasit, Kut, Iraq.
²Department of Physics, College of Sciences, University of Wasit, Wasit, Kut, Iraq

* Corresponding author: asadaldefae@uowasit.edu.iq

Abstract. In this paper, numerous and comprehensive physical and mechanical tests were carried out on various building construction materials (i.e. different kinds of floor and wall tiles, steel bars and widely used metal plate of doors and windows) to investigate how the high level of temperatures significantly impact on these materials through the physical, structural and mechanical changes. Before exposing of materials to this heating level, tests are performed on materials to be as a reference. The physical and mechanical characterization includes; compression tests, tensile tests, X-Ray Diffraction (XRD) as well as Field Emission Scanning Electron Microscope (FESEM). It was observed that the high temperature led to make damages on the internal and external structure of the materials and this obviously effects on the durability of the building or may lead to its destruction. It was noticed also that this level of temperature reduced the compressive strength whereas the molecular structure is strongly influenced by this reduction. Slightly changes in tensile strength of rebar were also noticed. High temperatures level are significantly effect on the internal structure of the floor and wall tiles and fine and moderate cracks on the roofs of these tiles are appeared and reduction in the modulus of rupture of the floor and wall tiles.

Keywords: Accidental fires, X-Ray Diffraction, X-Ray Fluorescence, Durability, Construction materials.

1. Introduction

Construction materials are widely used in engineering infrastructures. Steel bars are the common used construction material in the construction projects because of its high tensile strength, durability, and fire resistance. Walls and floor tiles, steel bars and steel plate are the most widely used materials in the construction projects and any other infrastructures, multi-stories buildings as well as the domestic units [1, 2]. The properties of steel have direct relation with structural safety. The fire resistance of both the steel materials (in the reinforced concrete materials), and tiles are strongly influenced by increasing the temperature and fire accidents. Furthermore, it is very important to understand the fire resistance of the materials, how they behave when exposure to high temperature and how the structural and mechanical properties of such materials change after disasters when expose to such accident for a long while [3]. This is very important particularly during the rehabilitation stages and maintenance of the building. In the engineering of materials science, standard specimens of these materials are usually conducted to specific test procedure (i.e. standard codes should be followed) under different...
conditions and boundary limits of these specifications have to be considered correctly. However, during services, concrete and most of the construction materials may exposed to different external environmental conditions. Thus, the mechanical and structural properties of such materials are complicated as they are affected by these environmental conditions such as the effect of temperature [4, 5]. The fire safety requirements should be achieved and followed during the design and constructions of building and subsequently, identified in building codes [6, 7].

The resistance of steel and most of the tiles (i.e. Ceramic, Granite, Alabaster) are more complex comparing with other materials not because it contain different natural materials as the components have different properties, but its properties also depending on strength and the porosity. The fire resistance behavior under high temperatures level of the composite materials is play an essential role and this parameter should be considered because it can, in many cases, determine the threshold of the temperatures at which a material’s properties does not change dramatically (i.e. has suitable properties) [8].

In this paper, an extensive tests program are performed on different specimens of selected construction materials and tested to investigate the changes in the physical and mechanical properties. The test program divided to two main groups, the first one is for specimens before exposure to heating whereas the second group are for specimens when exposure to high heating level (i.e. 600°C). Reason of selecting this temperature is that this value represents the thresholds where degradation in the strength of materials is occur. The aim of this procedure of testing to investigate how the high temperature level effect on the physical and mechanical characterization. The test program includes; X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Field Emission Scanning Electron Microscope (FESEM), compressive strength and Tensile test.

2. Materials and Methodology
The experimental program includes; testing and studying the mechanical and structural properties of different construction materials before and after exposing to high level of temperature (i.e. 600 °C for 2 hrs.). The tests program for the specimens includes different types of construction materials including; Granite tiles, Alabaster tiles, Porcelain tiles, Terrazzo tiles, floor/wall Ceramic Glaze tiles, steel bars and metal plate of doors and windows. The materials are selected carefully to represent three main supplier countries because most of the construction materials are imported from these countries. The tests conditions and the objective was to investigate the strength behavior and simulate construction materials under firing so the changes in the physical and mechanical properties of the structures exposed to specific limits of temperature must be determined. A variety of physical and mechanical tests were performed on these construction materials before and after exposure to heat. The physical and mechanical characterization includes; X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Field Emission Scanning Electron Microscope (FESEM), and tensile test. Similar procedure that was presented in details by [9-11] is followed. The experimental work program steps can be summarized as below;

2.1 Tensile test
The Tensile strength of both the steel bars and steel plates has been determined according to the specifications and limitations of the American Society for Testing and Materials (ASTM) for uniaxial Tension testing for construction materials, ASTM E8/E8M-16a [12]. Two types of specimens were used which are rebar with dimensions; (200 x 12)mm and a metal plate with dimension shown in figure 1. Steel bar’s specimens have been tested before and after firing.
The set-up of a tensile test is shown in figure 2, including placing a specimen between two fixtures called "grips" which clamp the specimen. After that, a load was conducted axially to one end (connected in such a way to be tensioned axially upward) of the specimen while the other end was fixed with the bottom jaw. The increasing in the tensile stress was recorded during the test. At the same time, the elongation of the specimen (axial strain) is recorded with time until failure occurs.

Figure 1. Steel plate specimen's dimensions.

Figure 2. Set up of Tensile Test on Rebar and metal plate.

2.2 X-Ray Diffraction (XRD)
XRD-System type Rigaku was used to inspect the crystal structure of Granite and Alabaster Tiles before and after firing. It is rotating the anode with high brilliance (RU-200BH) X-ray diffract meter. This system produces 1.54 Å (Cu-anode) wavelength (i.e. high intensity X-rays. It has 12 kW maximum powers (60 kV and 200 mA). The purpose of utilizing the XRD technique for inspecting the crystallization changes and re-arrangement of the molecular and atomic crystal structure. The crystalline structure causes handers of the incident X-rays that diffract into many specific directions. A three-dimensional picture of the density of electrons can be produced via the crystallographer within the crystal structure by measuring the intensities angles of diffracted rays.

2.3 X-Ray Fluorescence (XRF);
It was used for chemical analyses Granite Tiles and Alabaster Tiles before and after firing. Thermo Scientific Niton XL2 XRF Analyze with X-Ray Source (X-Ray Tube): Ag anode 38kV maximum, 80 μA maximum and dynamically adjustable current for optimal sensitivity on every analysis. X-ray fluorescence (XRF) includes production of characteristic "secondary" (or fluorescent) X-rays from the material that has been triggered by being directed to high energy X-rays. The purpose of this technique is to use for preliminary analysis, crystallization analysis and the crystal changes, particularly in the investigation of metal plates and glass ceramics. In fact, utilizing this technique is for knowing the elements changes of the material after fire accidental.
2.4 Field Emission Scanning Electron Microscope (FESEM)  
Nova NanoSEM 450 Field Emission Scanning Electron Microscope was used to study morphology, texture, surface features and measured the particle size of clay brick, Alabaster, and Granite before and after firing.

3. Results and Discussion  
Modulus of rupture, tensile strength, X-Ray Diffraction measurements (XRD), X-Ray Fluorescence (XRF) and Field Emission Scanning Electron Microscope (FESEM) are the main testing of this paper. Details of the outputs are shown as follow:

3.1 Modulus of Rupture  
Six specimens for each type of tiles are tested in loading machine to determine the modulus of rupture and they were numbered from A1 to A6 or B1 to B6. Figure 3 shows values of the modulus of rupture of Granite tiles, Alabaster tiles, Terrazzo Tiles, wall Ceramic glaze, floor Ceramic glaze and Porcelain tiles before and after firing, respectively. The modulus of rupture can be determined by dividing the breaking load that was measured from the load machine to the minimum thickness for the specimen along the broken line. It was observed that the modulus of rupture of specimen decreases at high firing temperatures. The results show that the modulus of rupture of post-firing specimens is lower than modulus of rupture of pre-firing specimens and this behavior is logic because the Granite has small longitudinal shrinkage ratio as it has minimum water content.

![Figure 3. Values of modulus of rupture of Granite tiles, Alabaster tiles, Terrazzo tiles, wall Ceramic glaze, floor Ceramic glaze and Porcelain tiles before and after firing.](image)

The main excited finding here is that the spacing between particles is getting bigger when high water content ratio used, subsequently, leads to reduction in the modulus of rupture for
post-firing specimens. Furthermore, cracks are governed as a side effect of the increasing of longitudinal shrinkage which results to reduce modulus of rupture of fired specimens.

3.2 Tensile test
The measured values for the stress-strain relationship for pre-fired and post-fired steel bars specimens that were exposed to 600 °C temperature are given in figure 4 for Iraqi, Iranian, and Ukrainian steel bar’s specimens, respectively (see table 1). The aim of this test is to investigate how the high temperature level effects on the steel component for the reinforced concrete materials and in this case, simulation is achieved for a building that had a many hours of firing and obviously this leads to changes in the mechanical properties of reinforcing steels that are used widely in structures. It was observed that the maximum stress and yield stress decreased after firing. As well as, the Maximum Strain and Elongation % was increased. Basically, when the building exposed to accidental firing, there is high possibility that the steel elements suffer from reduction in the strength particularly when a structure is subjected to a huge fire. Figure 5 shows the relationship of the stress-strain for both pre-fired and post-fired steel plate specimens of different manufactured kinds (i.e. Iranian, and Turkish, see table 1) Metal Plate, respectively. The main goal of this test is to simulate the element manufactured from steel plate as parts of building when exposed to fire and investigating the changes in the stress and strain properties of both the steel bars and steel plate that are widely used in structures. After firing, it was observed the maximum stress, yield stress, maximum strain and elongation percentage are slightly influenced by the firing. Actually, this result is not surprising as the It is axiomatic that the steel materials are manufactured under high level of temperature reaches to 1000 °C. These results demonstrate that the Turkish plate specimens are less affected than Iranian metal plate under similar temperatures level.

![Figure 4](image1.png)

**Figure 4.** Stress-Elongation diagram for determination of Yield Stress and Maximum Stress of Iraqi, Iranian and Ukrainian steel bars, respectively from left to right for pre-fired and post-fired specimens.

![Figure 5](image2.png)

**Figure 5.** Stress-Elongation diagram for determination of yield stress and maximum stress of Iranian and Turkish metal plate, respectively for pre-fired and post-fired specimens.
Table 1. Measurements of elongation, yield stress, maximum strain and maximum stress of steel bars before and after firing.

| Sample | Cros. Area (mm²) | Max. Load (kN) | Max. Stress N/mm² | Yield Load (kN) | Yield Stress N/mm² | Max. Strain | L₀ (mm) | L₄ (mm) | AL % |
|--------|-----------------|----------------|-------------------|-----------------|-------------------|-------------|--------|--------|------|
| Before firing |
| Iraqi Rebar | A1 113.10 | 72.99 | 645.38 | 61.40 | 542.92 | 0.095 | 200 | 219.00 | 9.50 |
| Rebar | A2 113.10 | 72.99 | 645.38 | 60.20 | 532.28 | 0.106 | 200 | 221.20 | 10.60 |
| A3 113.10 | 72.69 | 642.72 | 60.50 | 534.94 | 0.095 | 200 | 219.00 | 9.50 |
| Iranian Rebar | B1 113.10 | 74.50 | 658.69 | 56.14 | 496.35 | 0.151 | 200 | 230.20 | 15.10 |
| Rebar | B2 113.10 | 74.20 | 656.03 | 56.44 | 499.01 | 0.146 | 200 | 229.20 | 14.60 |
| B3 113.10 | 76.00 | 672.00 | 57.64 | 509.65 | 0.141 | 200 | 228.20 | 14.10 |
| Ukrainian Rebar | C1 113.10 | 71.49 | 632.08 | 52.68 | 465.74 | 0.183 | 200 | 236.60 | 18.30 |
| Rebar | C2 113.10 | 71.49 | 632.08 | 53.73 | 475.06 | 0.181 | 200 | 236.20 | 18.10 |
| C3 113.10 | 72.99 | 645.38 | 54.48 | 481.71 | 0.177 | 200 | 235.30 | 17.65 |
| After firing |
| Iraqi Rebar | A1 113.10 | 57.94 | 512.32 | 48.91 | 432.47 | 0.152 | 200 | 230.4 | 15.20 |
| Rebar | A2 113.10 | 59.45 | 525.62 | 49.36 | 436.47 | 0.157 | 200 | 231.30 | 15.65 |
| A3 113.10 | 56.44 | 499.01 | 48.01 | 424.49 | 0.148 | 200 | 229.50 | 14.75 |
| Iranian Rebar | B1 113.10 | 66.97 | 592.16 | 50.12 | 443.12 | 0.157 | 200 | 231.30 | 15.65 |
| Rebar | B2 113.10 | 66.97 | 592.16 | 51.17 | 452.43 | 0.161 | 200 | 232.10 | 16.05 |
| B3 113.10 | 65.47 | 578.85 | 48.91 | 432.47 | 0.156 | 200 | 231.20 | 15.60 |
| Ukrainian Rebar | C1 113.10 | 66.97 | 592.16 | 51.92 | 459.09 | 0.185 | 200 | 236.90 | 18.45 |
| Rebar | C2 113.10 | 67.27 | 594.82 | 51.92 | 459.09 | 0.187 | 200 | 237.40 | 18.70 |
| C3 113.10 | 66.97 | 592.16 | 52.37 | 463.08 | 0.184 | 200 | 236.80 | 18.40 |

3.3 X-Ray Diffraction Measurements (XRD)

XRD was used for identification of the particle crystal structure, the distance between the crystalline levels, and the crystallite size of Ceramic tiles, Granite tiles and Alabaster tiles before and after firing temperature and to know the effect of firing temperature on growing of clay bricks particles. The crystalline size and of the particles specimens before and after firing was determined by using Debye Scherrer formula:

\[ D = \frac{K\lambda}{\beta \cos \theta} \]  
(1)

Where: D is the size of crystallite (in nm), K is a dimensionless shape factor (its value approximately unity). The rang of the shape factor has an optimal value around 0.9, but it changes with the actual shape of the crystallite, \( \lambda \) is the length of the X-ray (0.15406 nm), \( \theta \) is expressed as Bragg diffraction angle (degree), and \( \beta \) is the Full Width at Half Maximum (FWHM) of the chosen peak (Radian) [13]. The distance between the crystalline levels was determined using the formula:

\[ n \lambda = 2d_{hkl} \sin \theta \]  
(2)

In the equation above, the factor \( d \) is the distance or space between atomic layers in a single crystal whereas lambda (\( \lambda \)) is the wavelength of the incident x-ray waves, and \( n \) is an integer number represents the order of the diffraction peak [14]. XRD measurements of the tested specimens have close result that obtained from the water absorption of clay bricks test [15] in which the water absorption of particles clay bricks decreased after firing temperature.

Table 2 summarizes the structural characteristics of Granite and Alabaster tiles before and after firing, it was observed after firing; decreasing the crystallite size and decreasing the inter-planar distance in crystals of specimen particles. This can be attributed to the fact that the higher temperature
level affected on (increases) the evaporation rate of the solvent. XRD of Granite and Alabaster tiles confirms the result that we get from the water absorption of the specimens test, it was noted that the water absorption of specimen particles increased after firing temperature. Figures 6 show XRD patterns of Granite and Alabaster specimens before and after firing, respectively.

Table 2. Crystal structure characteristics of Granite and Alabaster tiles specimens before and after firing.

| Specimen            | 2θ (Deg.) | FWHM (Deg) | d_{hkl} (Å) | Crystallite size (nm) | 2θ (Deg.) | FWHM (Deg) | d_{hkl} (Å) | Crystallite size (nm) |
|---------------------|-----------|------------|-------------|-----------------------|-----------|------------|-------------|-----------------------|
| Pre-fired specimens |           |            |             |                       |           |            |             |                       |
| Indian Granite      | 21.9906   | 0.0960     | 4.03872     | 88.01                 | 8.9183    | 0.1200     | 3.90762     | 69.33                 |
| Chinese Granite     | 8.8785    | 0.1200     | 9.95190     | 69.33                 | 26.7451   | 0.1920     | 3.33056     | 44.40                 |
| Post-fired specimens|           |            |             |                       |           |            |             |                       |
| Pre-fired specimens |           |            |             |                       |           |            |             |                       |
| Turkish Alabaster   | 29.485    | 0.1920     | 3.02698     | 44.67                 | 29.5021   | 0.1840     | 3.02530     | 46.61                 |
| Iranian Alabaster   | 29.527    | 0.1440     | 3.02279     | 59.57                 | 29.5038   | 0.1680     | 3.02512     | 51.05                 |

Figure 6. XRD pattern of Granite and Alabaster specimens for pre-fired and post-fired specimens.

3.4 X-Ray Fluorescence (XRF)
The X-Ray fluorescence results are obtained using special apparatus that was found in the laboratories of Ministry of Technology and Sciences, Baghdad, Iraq. The result indicates that the Granite and Alabaster specimens have the highest amount of Ti (Titanium), followed by V (Vanadium), Fe (Iron), Cr (Chromium), Mn (Manganese), and Co (Cobalt). These chemical elements are frequently found as oxides in clay bricks by forming chemical compounds such as; SiO₂, Al₂O₃, Fe₂O₃, MgO, etc....
element that contributes to the colour of Ceramic glaze tiles is an iron oxide (Fe2O3). The color is not controlled as the other materials inside raw materials has different organic matters that produced stuff of grey, black, or dark brown depending on the quantity present. However, the color is changed after the firing process due to oxidization that occurs due to carbonaceous material and iron compounds. Figure 7 shows the chemical elements of Granite and Alabaster specimens before and after firing, it was observed that some of these elements were influenced by firing temperature by decreasing or increasing in (LOQ).

Figure 7. Chemical elements percentage (LOQ) of Granite and Alabaster specimens before and after firing (A-F).

3.5 FESEM
Morphological, crystallographic and microstructural information of Ceramic glaze, Terrazzo Tiles and Porcelain Tiles specimens for both pre-fired specimens and post-firing specimens were investigated using Field Emission Scanning Electron Microscope (FESEM). This technique is commonly used to inspect small area less than nm. Figure 8 shows the surface morphology of ceramic tiles specimens before and after firing. It is observed that different sizes of particles of tiles, the reason for this is due to the presence of different chemical elements specimens, and this is confirmed by XRD and XRF measurements. It was observed that the particle size of specimens increased after firing and this consistent with the results of XRD measurements.

Figure 8. Surface morphology of pre-fired and post-fired Ceramic glaze, Terrazzo tiles and Porcelain specimens.
Figure 9 shows the surface morphology images that obtained from FESEM of Granite and Alabaster tiles specimens before and after firing. The diffractogram of the materials is generated after a 120 minutes of heating. Before firing, it was observed different sizes of particles of Granite and Alabaster, the reason for this is due to the presence of different chemical elements in the Granite and Alabaster. After firing, it was observed that the particle size of the minerals of Granite and Alabaster decreased, and this consistent with the results of XRD measurements. Actually, the crystallization phenomenon started at the beginning along the surface of the specimens and then, crystallization shell around the particles is formed as well as shattering of the bonds between grains of the minerals particularly for Granite tiles.

4. Conclusions

1- The chemical elements percentage (LOQ %) of the Ceramic, Granite and Alabaster tiles were diagnosed before and after firing by using XRD and XRF technique. It was observed that some of these elements were influenced by firing temperature by decreasing or increasing (LOQ %). After firing, XRD measurements indicated an increase in the crystallite size and decrease the inter-planar distance in crystals of specimen particles. This is because a higher temperature increases the rate of evaporation of the solvent; thereby speeding up the rate of growth of crystals and this explains why the compressive strength of the specimens decreases after the firing process. It was observed from FESEM measurements the particle size of tested specimens are increased after firing and this consistent with the results of XRD measurements.

2- The modulus of rupture of Granite and Alabaster decreases and the water absorption increases after firing temperature. The reason for this is that the high temperature of the sample caused cracks on the surface of the sample and therefore the water will permeate these cracks.

3- The (XRD) and (FESEM) measurements confirm the mechanical result. Also, from (XRD) and (XRF) measurements, observed a change in chemical elements percentage and compositions (LOQ %) before and after firing.

4- The modulus of rupture of the post-fired specimens of Ceramic, Terrazo and Porcelain tiles are lower than modulus of rupture for pre-fired specimens and this can be attributed to the low longitudinal shrinkage ratio and low water content for specimens. The main finding here can be attributed to the high water content ratio which causes increasing the spacing between the particles, then leads to lower modulus of rupture after firing as well as sharply increasing of longitudinal shrinkage that leads to appearance of cracks which leads to decrease the modulus
of rupture after firing. Also observed, the water absorption of fired samples was increased. The reason for this increase is that the high temperature of the Porcelain and ceramic glaze caused cracks on the surface of the sample and therefore the water will permeate these cracks. Also, the firing temperature caused a growth in the Porcelain and ceramic glaze particles.

5- It was observed that the maximum stress and yield stress decreased after firing. Also, maximum strain and elongation % was increased. While from metal steel plate tension measurements observed that the maximum stress, yield stress, maximum strain and elongation percentage was increased. However, this behavior reflected the possibility of the tensile strength drop of both the steel bars and steel plate at high temperatures when a structure exposed to high temperature level.

Acknowledgement
The authors would like to express their truthful thanks to the technical staff of the engineering laboratories at the University of Wasit and the technical institute of the middle technical university for their assistance in performing all the experimental tests. The second author would also like to acknowledge the partial financial support of the students from the University of Wasit, Engineering faculty, 200 kM south of the Capital: Baghdad, Republic of Iraq.

5. References

[1] Memon F A, Nuruddin M F, Khan S, Shafiq NA and Ayub T 2013 Effect of sodium hydroxide concentration on fresh properties and compressive strength of self-compacting geopolymer concrete Journal of Engineering Science and Technology 8 44-56

[2] Karaman S, Ersahin S and Gunal H 2017 Firing temperature and firing time influence on mechanical and physical properties of clay bricks American Journal of Civil Engineering 5 21-26

[3] Johari I, Said S, Hisham S, Bakar A and Ahmed Z A 2010 Effect of the change of firing temperature on microstructure and physical properties of clay bricks from beruas Malaysia Science of Sintering 1 245-54

[4] Biolzi L, Di Luzio G and Labuz J F 2013 Mechanical properties of photocatalytic white concrete subjected to high temperatures Cem. Concr. Compos. 39 73–81

[5] Khaliq W and Kodur V 2011 Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures Cem. Concr. Res. 41 1112–1122

[6] EN. 1992 Design of concrete structures. Part 1–2: General rules—structural fire design. Brussels, Belgium: European Standards (EN)

[7] ACI 2014 Building code requirements for structural concrete (ACI 318-14) and commentary (ACI 318-14R) American Concrete Institute (ACI): Farmington Hills, MI

[8] Letsch R 1987 Durability of construction materials: from materials science to construction materials engineering. In Proceedings of First International Congress of RILEM 1107–1114.

[9] Martín M I, López F A, Alguacil F J and Romero M 2014 Development of crystalline phases in sintered glass-ceramics from residual E-glass fibres Ceram. Int. 40 2769-2776

[10] Karamanov A and Pelino M 2008 Induced crystallization porosity and properties of sintereds diopside and wollastonite glass-ceramics J. Eur. Ceram. Soc. 28 555-562

[11] ASTM I 2016 ASTM E8/E8M-16a: Standard Test Methods for Tension Testing of Metallic Materials West Conshohocken, PA, USA: ASTM International

[12] Kaushik H B, Rai D C and Jai S K 2007 Stress-strain characteristics of clay brick masonry under uniaxial compression J. Mater. Civ. Eng. 19 728-739

[13] Monshi A, Foroughi M R and Monshi M R 2012 Modified Scherrer equation to estimate more accurately nano-crystallite size using XRD World journal of nano science and engineering 2 154-160
[14] Moore Z 2008. Application of x-ray diffraction methods and molecular mechanics simulations to structure determination and cotton fiber analysis (Doctoral dissertation, University of New Orleans)

[15] Aldefae A H H, Essa AF and Edan A S 2020 Fire resistance of selected construction materials In *AIP Conference Proceedings* **2213** 020008