Improvement of Gypsum Behaviour Using Glass Wool

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Abstract

This paper presents an experimental investigation to assess the behaviour of gypsum plasters containing glass wool. Two types of locally available gypsum powder Gypsum-1 and Gypsum-2 were used in this study. The addition of glass wool was done as a partial replacement by volume at five different ratios 5%, 10%, 15, 20% and 25%. A comprehensive experimental programme was designed to measure both mechanical and thermal characteristics using 122 samples with different size configuration. These include tests for setting time, compressive and flexural strengths, density at ambient and high temperatures, thermal conductivity and thermal resistance. In order to explore actual behaviour, the test results have been compared with relevant BS EN and Iraqi Standards.

The results obtained showed that both compressive and flexural strengths have consistent behaviour for all of the tested samples. The highest values of compressive and flexural strengths were 4.17 MPa and 2.11 MPa for modified gypsum mixtures of Gypsum-2 containing 20% and 25% glass wool respectively. The added amount of glass wool in addition to its distribution within the samples are the most critical parameters governing overall mechanical behaviour. The control gypsum mixtures of both Gypsum-1 and Gypsum-2 exhibited cracks at high temperatures, whereas modified mixtures seem to be durable at these conditions. Some improvements have been obtained in terms of thermal conductivity and thermal resistance for the modified gypsum mixtures.

Keywords: gypsum plaster, glass wool, mechanical behaviour, thermal properties

الخلاصة

يعرض هذا البحث دراسة عملية لتقييم تصرف خلطة الجبس الحاوية على الصوف الزجاجي. تم استخدام نوعين من الجبس المتوفر محلياً. عملية اضافة الصوف الزجاجي كانت بشكل بدليل جزئي كنسب حجمية من الجص مقدارها 5% ،10 % ، 15 % ، 20 % و 25 % . تم تصميم برنامج عملي واسع لقياس الخصائص الميكانيكية والحرارية باستخدام 122 نموذج وبمختلف الاحجام.أظهرت النتائج المستحصلة لفحوصات مقاومة الانضغاط والكسر تصرف متوافق لكل العينات المفحوصة. حيث كانت أعلى قيمة لمقاومةالانضغاط والكسر 4.17ميكاباسكال و 2.11ميكاباسكال لخلطة الجبس الثانية الحاوية على صوف زجاجي مقداره 20 % و 25 % على التوالي. العوامل الرئيسية التي تتحكم بالتصرف الميكانيكي هي كمية الصوف المُضاف وطريقة توزيعة داخل الخلطة. أظهرت الخلطات المرجعية (الغير حاوية على الصوف الزجاجي) ولكلا النموذجين العديد من التشققات في في درجات الحرارة العالية، بينما كانت الخلطات المطوّرة (الحاوية على الصوف الزجاجي) ذات ديمومة عالية في هذه الظروف. تم الحصول على بعض التحسينات في خصائص التوصيل الحراري والمقاومة الحرارية لخلطات الجبس المطوّرة.

الكلمات المفتاحية: الطلاء بالجص، الصوف الزجاجي، التصرف الميكانيكي، الخصائص الحرارية

1. Introduction

Gypsum material and its products have many applications in the construction field, mainly as a finish coating layer for the interior surfaces of walls and slabs. Some of the modern constructions fabricated using gypsum sheets as the inner leaf of the wall system [1]. This technique improves thermal insulation and comprising more energy saving. However, the brittle characteristics in addition to lower tensile and impact strengths prohibit the structural applications of gypsum. On this basis, several attempts have been made to improve the mechanical strength of gypsum; for instance, using glass, carbon and polypropylene fibers, polyvinyl acetate, furfural, calcium oxide and ferric oxide as additives to the gypsum mixture at different percentages. The mechanical strength of the hardened gypsum can be achieved through interlacement of the hydrated crystalline. If the additives are incorporated, the former interlacement will increase. [2 to 8].

The mechanism of hydration involves three processes: dissolution, diffusion and precipitation. These processes govern the overall behaviour of gypsum. In general, there are two types of gypsum plaster; the first is α-plaster which comes from the wet process and the second is β-plaster which is based on the dry process. Both of them have the capability of reacting with water in a sequence complying with the mechanism of hydration mentioned earlier. However, the resulting crystals of β-plaster products are shorter and stacked rather than entangled crystals of α-plaster [9].

Currently, the applications of gypsum are restricted by coating aspect and thermal purposes[1]. So, many researches emphasized upon enhancement the surface texture, color and thermal resistance especially at elevated temperatures [10].

One of the most effective materials in thermal insulation performance is glass wool. This material is usually produced from glass fibres with a configuration similar to the wool texture, so it is so called "glass wool". The inner structure contains small pockets of air between the glass fibres. This technique allows for high potential of thermal insulation. It is available in the forms of blanket or rolls and can be produced as sprayed material then applied in place over the surface intended to be insulated. Also, it can be used for soundproofing [11].

The manufacture procedure of glass wool consists of mixing certain proportions of the natural sand and recycled glass at 1450 °C. The glass undergoes into the fibres and is pressed through a fine mesh by centripetal force, cooling on contact with the air. This manner produces structure with a lower density. Normally, resin binder is used to paste the fibres together In order to obtain the mechanical strength [11].

Despite much attention being paid to improve the thermo-mechanical behaviour of gypsum plaster at ambient and high temperatures, there was no scientific research that seemed to have been conducted in investigation the addition of glass wool to the gypsum mixture. In this study, a new fabrication of gypsum plaster using glass wool was experimentally evaluated in terms of both mechanical and thermal characteristics. The results obtained have also been compared with the relevant BS EN and Iraqi Standards.

2. Details of the experimental programme

An experimental investigation was carried out on a new type of gypsum plaster to evaluate its mechanical and thermal behaviour. In order to explore variation of gypsum material, two types of locally available gypsum were used in this study. They were provided from different quarries at the city of Najaf-Iraq. Glass wool was used as a partial replacement for both types of gypsum at five ratios 0%, 5%, 10%, 15, 20% and 25% by volume. In this paper, the term "modified mixtures" refers to the gypsum mixtures containing glass wool, and "control mixture" was used to refer for a mixture without any addition of glass wool. Figure 1 shows the materials used in this study, whilst Table 1 presents their technical properties.

The preparation of specimen moulds, casting of the gypsum samples and finishing operations were performed according to BS EN12390-1, 2 [12, 13]. The glass wool was added to the gypsum powder before the mixing process as a crumb with a well distribution manner, as shown in Figure 2. This technique was followed in order to prevent the agglomeration of the glass wool within a specified zone of the gypsum mixture. After 24 hours the samples were taken out of their moulds, marked and covered in a nylon sheet at a temperature of 20 ± 2 ˚C until the date of the test, as shown in Figure 2.

To meet the objective of the study, the experimental programme consisted of two phases, namely mechanical and thermal. The mechanical phase involved conducting the setting time, compressive and flexural strength tests, while the thermal phase involved running the tests of density at ambient and elevated temperatures, in addition to computing the value of thermal conductivity and thermal resistance based upon the models suggested by BS EN Standards.

Figure 1. Gypsum powder and glass wool

Table 1. Properties of the gypsum and glass wool materials used in this study

<table>
<tr><th colspan="5">Gypsum material</th></tr>
<tr><th rowspan="2">No.</th><th rowspan="2" colspan="2">Property</th><th colspan="2">Result</th></tr>
<tr><td>Gypsum sample-1</td><td>Gypsum sample-2</td></tr>
<tr><td>1</td><td colspan="2">Fineness of particles</td><td>12% (retained)</td><td>13% (retained)</td></tr>
<tr><td>2</td><td colspan="2">SO_3 content</td><td>1.715</td><td>1.257</td></tr>
<tr><th colspan="5">Glass wool material*</th></tr>
<tr><td>Change its properties with time</td><td>Resistance to fire</td><td>Thermal resistance ($m^2.K/W$)</td><td>Thickness (cm)</td><td>Density (kg/m^3)</td></tr>
<tr><td>Stable</td><td>Non-combustible</td><td>1.326</td><td>5</td><td>95</td></tr>
</table>

*According to the Aryana Pars technical sheet.

Figure 2. The processes of adding glass wool to the gypsum mixture and curing of the gypsum samples

2.1 Mechanical phase

2.1.1. Water/ plaster ratio and setting time

In these tests, the optimal mass of the gypsum binder in grams which can be saturated when it is sprinkled into 100 g of water as well as the initial setting time of the gypsum mixtures were determined. The procedure described in BS EN 13279-2:2014 [14] using cylindrical glass container with 66 mm internal diameter and 66 mm height was followed in obtaining water/plaster ratio (R). On the other hand, Vicat apparatus was used to find the initial setting time (T_i) in minutes. These tests were only conducted for the control gypsum mixtures based upon the following expressions:

$$R = \frac{100}{m_1 - m_0}$$
Eq. 1

$$T_i = t_1 - t_0$$
Eq.2

where

R is water/plaster ratio
m_0 is mass of glass container + mass of water, in g;
m_1 is mass of glass container + mass of water + mass of plaster, in g;
T_i is the initial setting time in minutes;
t_1 is the time at which the depth of penetration (22 ± 2) mm above the glass plate is achieved, in minutes;
t_0 is the time at which the plaster is first added to the water, in minutes.

2.1.2. Compressive strength

The compressive strengths of both control and modified gypsum mixtures were measured corresponding to BS EN 13279-2:2014 [14] using a digitally controlled compression machine with a maximum load capacity of 2000kN. The testing machine was calibrated so that the maximum permissible mean error of forces as percentage of indicated force did not exceed ±2 as per in the standards. A constant loading rate of 0.15 MPa/s was used throughout the tests. Load was monitored until specimen failed and the maximum load in kN was recorded. This test was carried out at the sample age of 7 days and average result of three samples was considered for each test.

2.1.3. Flexural strength

This test was performed in accordance with the BS EN 13279-2:2014 [14] using prism specimens with dimensions of (50× 50× 150) mm supported at 100 mm centres. One point load flexural machine was used in this test with maximum load capacity of 2000kN. The specimen was placed on the supporting rollers of the bending device and the maximum load in Newton was recorded. The flexural strength ($F_{\downarrow}P$) was determined using the following formula:

$$F_P = \frac{3PL}{2\,bh^2}$$
Eq.3

where

F_P is the flexural strength, in N/mm^2 (MPa);

P is the average breaking load in N at least three obtained values;

b is the width dimension of the prism in mm;

h is the height dimension of the prism in mm.

2.2 . Thermal phase

2.2.1. Density

This test was performed according to BS EN 12390-7 [15]. The average density of three cubic samples with dimensions of 75 mm was determined. The samples were removed from their place, wiped and left to dry in the laboratory for about one hour and then weighed using a scale with an accuracy of 1 gram. Both control and modified gypsum mixtures were tested at ambient and five different temperatures. The latter temperatures were 100 ˚C, 200 ˚C, 300 ˚C, 400 ˚C and 500 ˚C**,** and the samples were kept for a period of two hours at each temperature level.

2.2.1. Thermal properties

The thermal conductivity and thermal resistance of the gypsum samples were determined according to BS EN 13279-1:2008 [16]. Tabulated design values for thermal conductivity were adopted based upon the values of the net dry densities. The suggested expression for the thermal resistance described in EN BS 1745 [17] was used to predict the effect of gypsum plaster on the composition of masonry wall constructed with clay units.

3. Results and discussion

3.1. Water/ plaster ratio and setting time

The results obtained for the optimal water/plaster ratios and setting times for both types of gypsum powder are shown in Table 2.

Table 2. Test results for the water/plaster ratios and setting times of gypsum powder

Property	**Symbol**	**Test result**		
water/plaster ratio	Gypsum-1	52%	45%	48.5% (Average)
	Gypsum-2	40%	38%	39% (Average)
setting time (minutes)	Gypsum-1	8		
	Gypsum-2	12		

It can be seen from Table 2 that the water/plaster ratios for the samples of Gypsum-1 were higher than those recorded for samples of Gypsum-2. This may be due to the higher fineness for the particles of Gypsum-1, as shown in Table 1; consequently, the required amount of gypsum to saturate 100 grams of water is lower. In order to identify the actual water/plaster ratio, the test was conducted for each dispatching and the average value was taken in consideration.

The results obtained showed that the samples of Gypsum-1 exhibited a lower setting time than that for samples of Gypsum-2. This is consistent with the higher particles fineness of these samples. Since, it represents the available surface area for the hydration processes, so the setting time decreases with an increase in the fineness of gypsum particles. It should be mentioned that the presented values of fineness in Table 1 represent the weight of gypsum retained on the sieve 100 µm. According to BS EN 13279-1:2008 [16], the setting times for gypsum plasters of manual and projection machine applications should not be less than 20 minutes and 50 minutes respectively. The Iraqi Standards No 28-1988 [18] specified the setting time for gypsum plaster between 8 to 25 minutes. Based upon the former limitations, both of gypsum plasters (Gypsum-1 and Gypsum-2) are only satisfying the Iraqi Standards No 28-1988.

3.2. Compressive strength

The results obtained of compressive strength test for both control and modified gypsum plaster mixtures are illustrated in Figure 3.

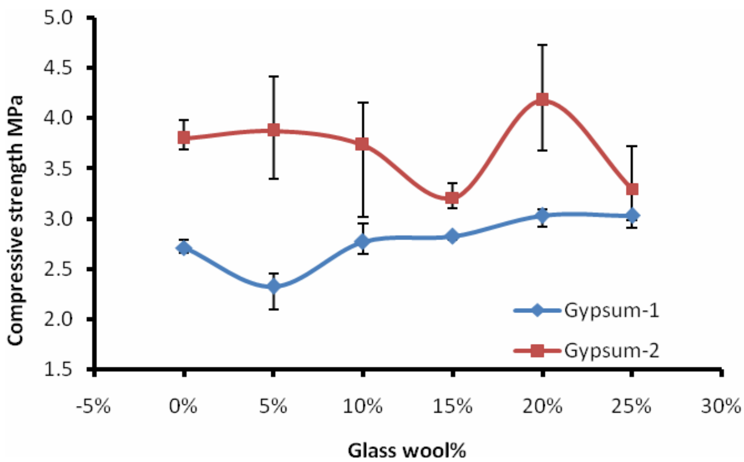


Figure 3. Compressive strength of various gypsum mixtures

From Figure 3, it is apparent that the values of compressive strength for both control and modified gypsum mixture of Gypsum-2 were higher than those of Gypsum-1. This behaviour related to the process turns powdery hemihydrates (CaSO4.0.5H2O) into the solid mass which influenced strongly by water and the properties of hemihydrates itself. The transfer to the solid mass is normally occurred due to formation of entangled needles of gypsum crystals as given the following reaction [9]:

$$CaSO_4.0.5H_2O+1.5H_2O \longrightarrow CaSO_4.2H_20 \qquad \text{Eq.4}$$

Except for mixture of 5% glass wool, all of the modified mixtures of Gypsum-1 exhibited higher values of compressive strength compared with those of the control mixture. The same cannot be said for the modified mixtures of Gypsum-2 where a fluctuate behaviour between decreasing and increasing in the value of compressive strength was noted.

In general, the higher value of compressive strength was recorded at the modified mixture containing 20% glass wool for both gypsum samples (Gypsum-1 and Gypsum-2). The percentage increases in compressive strength were 11.8% and 10% for the mixtures samples of Gypsum-1 and Gypsum-2 respectively. This behaviour may be explained by the re-arrange process of the inner structure so that more interlock between glass wool and solid hydration products at this level of addition (20%) is permitted. The aforementioned interlock did not obtain for the other modified gypsum mixtures.

The BS EN 13279-1:2008 [16] specified the minimum compressive strength for most applications of gypsum plaster as 2 MPa, while the Iraqi Standards No 28-1988 set out it as 3 MPa. On this basis, all of the test results comply with the BS EN 13279-1:2008 [16], whereas both control and modified mixtures of Gypsum-2 and only mixtures containing 20% and 25% glass wool of Gypsum-1 comply with the Iraqi Standards No 28-1988 [18].

3.3. Flexural strength

The results obtained of flexural strength for all of the tested samples are presented in Figure4.

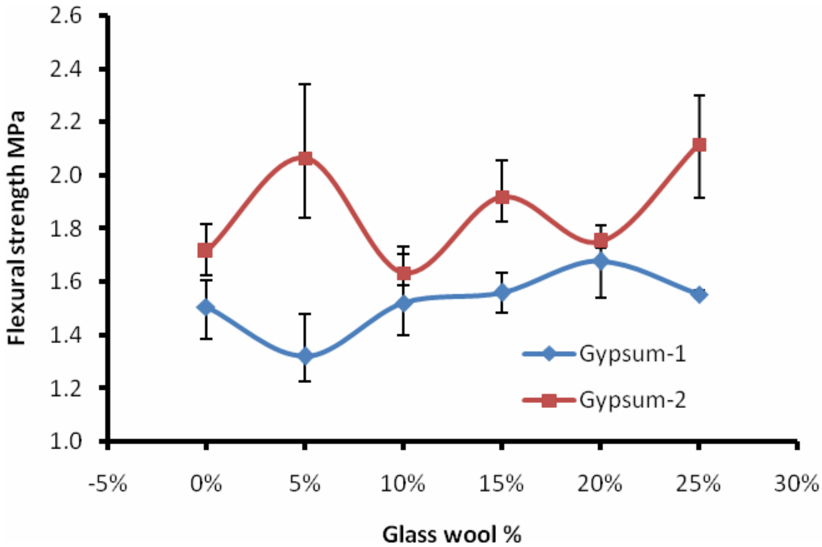
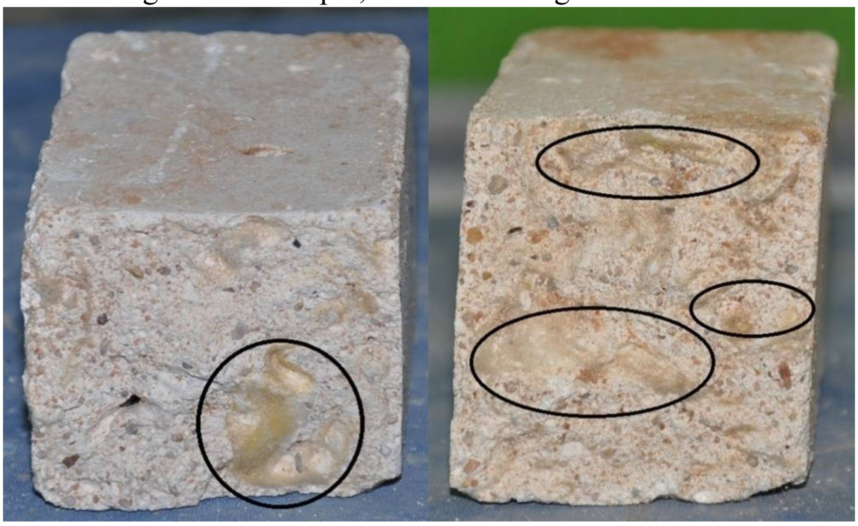


Figure 4. Flexural strength of various gypsum mixtures

In general, there was consistency between the results of flexural strength test and those obtained for the compressive strength test. All of the tested samples of Gypsum-2 showed higher values of flexural strength than those for samples of Gypsum-1. The values of flexural strength of the modified gypsum mixtures were governed by both ratio of glass wool added and method of its distribution within the gypsum sample. In case of small amount of addition with a bad distribution, the fibres of glass wool form ganglions inside the sample. When the load is applied, the path of the bending load will pass through these weak ganglions and the failure will occur quickly at a low value of flexural strength. This mechanism was noted for the failure mode of these samples, as shown in Figure 5-a. If the added amount is sufficient with an adequate distribution, the fibres of glass wool form uniform layers and absorb the bending load, hence increase the flexural strength of the sample, as shown in Figure 5-b.



(a) (b)

Figure 5. Failure mode of the tested samples due to the flexural load: a. low ratio of glass wool added with bad distribution; b. high ratio of glass wool added with an adequate distribution.

Using the results obtained for compressive strength (f_c) test, the values of flexural strength (F_P) for mixture of Gypsum- 1 and Gypsum-2 can be derived as per in Equations 5 and 6 respectively.

$F_P = 0.54\, f_c$

Eq.5

$F_P = (0.4 - 0.6) f_c$

Eq.6

The value of flexural strength according to BS EN 13279-1:2008 [16] for general application gypsum plaster should be more than 1 MPa, while there was no mention value in the Iraqi Standards No 28-1988 [18]. All of the tested samples satisfy the requirements of the former standards.

3.4. Density

Figures 6 and 7 show the results obtained for the density measurements at ambient and high temperatures. In general, the modified gypsum specimens exhibited lower densities than those of control specimens. This behaviour can be attributed to the lower density of glass wool (95 kg/m^3). Since the replacement process was made by volume, so the resulting density of gypsum mixture decreases with an increase in the percentage of the added glass wool.

There was a trend of decreasing the density of all tested samples with an increase in temperature. This behaviour is due to the elimination of the free water from the capillary pores by evaporation, in addition to the loss of chemically bound water [19 and 20]. The decrease in density at 500 ˚C compared to that at 25 ˚C were about 13.5% for mixtures of Gypsum-1 and 18% for mixtures of Gypsum-2.

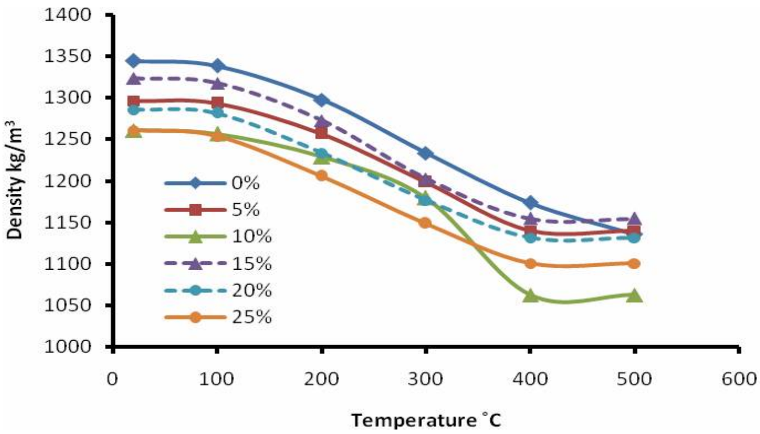


Figure 6. Temperature-density relationship for various mixtures of gypsum-1

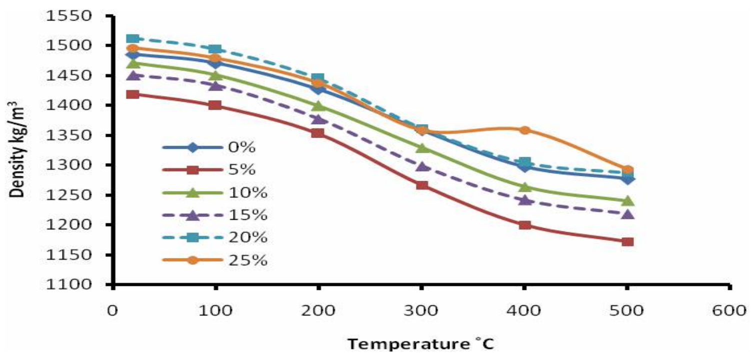


Figure 7. Temperature-density relationship for various mixtures of gypsum-2

Visual inspection of the control samples of both Gypsum-1 and Gypsum-2 revealed several cracks at higher temperatures. Conversely, adequate behaviour was noted for modified gypsum mixtures against high temperatures. It seems likely that this behaviour was due to the large temperature variation between the outer and inner surfaces of control samples, associated with a higher heating rate. These factors combined to produce a higher internal pressure exceeding the tensile strength of the gypsum sample [21]. According to the BS EN 13501-1[22], all of the tested samples classified as Class A1 where no contribution to the development of a fire has been observed during the test, so no need for additional protection when these products react with the fire. Iraqi Standards No 28-1988 set out the percentage decrease in weight after heating to a temperature of 230 ˚C should be not more than 9%. The results of this test are shown in Figure 8. It can be seen that all of gypsum plaster mixtures exhibited reduction in weight less than 9%

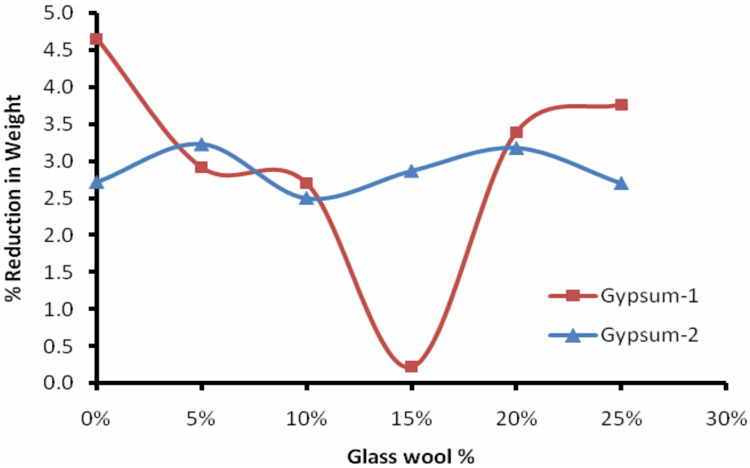


Figure 8.Reduction in sample weight of various gypsum plaster mixtures after exposed to 230˚C

3.5. Thermal properties

The calculated values of thermal conductivity for both control and modified gypsum plaster mixtures are shown in Figures 9.

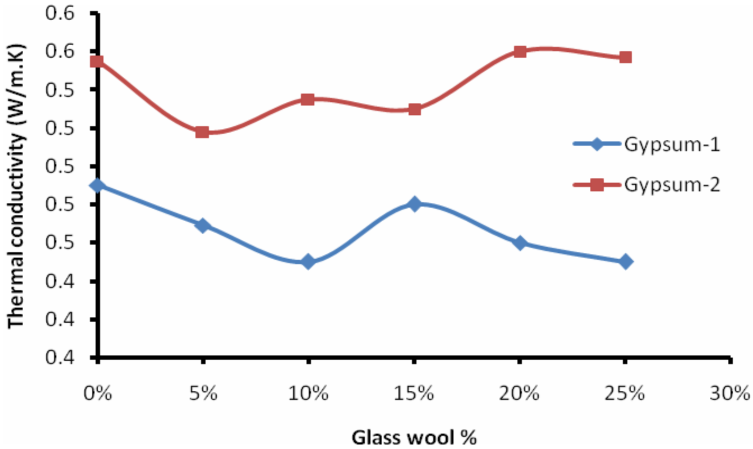


Figure 9. Thermal conductivity for various gypsum plaster mixtures at temperature of 25 ˚C

In general, lower values of thermal conductivity than those for mixtures of Gypsum-2 were observed for the mixtures of Gypsum-1. This behaviour was expected due to the lower density values of these mixtures.

Except for the gypsum mixture of 15% glass wool, the modified mixtures of Gypsum-1 showed continuous decrease in thermal conductivity with increasing the ratio of glass wool. This attitude can be attributed to the lower thermal conductivity value of glass wool and its ability to resist the thermal action. However, the behaviour of the modified mixtures of Gypsum-2 was unclear where higher thermal conductivity values were observed at ratios of 20% and 25% glass wool addition. The values of thermal resistances of the masonry walls produced from clay brick units coated with gypsum plaster can be determined from the following equations [17].

$$R_{design,mass} = \frac{d}{\lambda_{design,mass}}$$
Eq. 7

$$\lambda_{design,mass} = \lambda_{design,gypsum} + \lambda_{design,unit,mortar}$$
Eq. 8

Where
$R_{design,mass}$ is the thermal resistances of the masonry wall;
d is the thickness of the masonry in m;
$\lambda_{design,mass}$ is the design thermal value;
$\lambda_{design,gypsum}$ is the thermal conductivity of gypsum plaster;
$\lambda_{design,unit,morer}$ is the design thermal conductivity of the unit with mortar.

Using tabulated value for the composite wall (clay brick unit+ cement mortar) (0.582 W/m.K) with the calculated values for mixtures of 10% glass wool of Gypsum-1 and 5% glass wool for Gypsum-2, the design thermal values are 1.03 W/m.K and 1.1 W/m.K respectively. Applying Eq.7, the corresponding thermal resistances of masonry walls with 240 mm thick are 0.23 m^2.K/W and 0.21 m^2.K/W respectively.

4. Conclusions

This study was undertaken to evaluate the behaviour of two types of gypsum plasters containing some additions of glass wool based upon the experimental approach. The main significant findings of this study can be summarised as follows:

1. The compressive strengths for all of the mixtures of Gypsum-2 comply with the Iraqi Standards No 28-1988, whilst only modified mixtures containing 20% and 25% glass wool of Gypsum-1 satisfying the above requirements.
2. The most important parameters governing the mechanical strength of gypsum mixtures are the amount of added glass wool and the method its distribution within the sample. The mechanical strength improves when the glass wool is added in a sufficient amount combined with a well manner of distribution for the fibres.
3. Approximately, liner relationship was observed for the reduction in density of the gypsum mixtures with temperature.
4. The control gypsum mixtures of both Gypsum-1 and Gypsum-2 showed sever cracks at high temperatures, whereas modified mixtures exhibited durable behaviour.
5. Notable improvement in thermal conductivity and thermal resistance was observed for the modified gypsum mixture compared with those for the control ones. Nevertheless, some of the modified gypsum mixture of Gypsum-2 showed unclear behaviour.

5. References

[1] M. A. Ali and F. J. Grimer. Mechanical properties of glass fibre- reinforced gypsum. Journal of Materials Science, 1969; 4:389-395.
[2] Z. A. M. Raouf , et al. Improving the properties of gypsum by using additives. Journal of Engineering, 2012; 18(1): 1-18.

[3] Alia Al-Baghdady. Improvement of mechanical properties for juss mortar using vegetable and their plants fibers. Technical Journal, 2010; 23(1): 1-14.
[4] N. A. Hatim, I.K. Al–Khayat, M.A. Abdullah. Modification of gypsum products (Part I): physical and mechanical properties of adding some additives on different types of gypsum products Al–Rafidain Dent J. 2007; 7(2): 206–212.
[5] V. B. Petropavlovskaya, et al. Application of mathematical and computer modeling methods to manufacture high-strength unfired gypsum materials. Procedia Engineering, 2013, 57; 906 – 913.
[6]F.Asdrubali. A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies, 2015; 4:1–17.
[7] M. Carvalho. Microstructure and Mechanical Properties of Gypsum Composites Reinforced with Recycled Cellulose Pulp. Materials Research, 2008; 11(4): 391-397.
[8] Marcos Lanzón, P.A. García-Ruiz. Effect of citric acid on setting inhibition and mechanical properties of gypsum building plasters. Construction and Building Materials, 2012; 28: 506–511.
[9] S. S. Bobby and SaratSingamneni. Influence of moisture in the Gypsum moulds made by 3D Printing. Procedia Engineering, 2014, 97: 1618 – 1625.
[10] S. Karaman, et al. Use of sunflower stalk an pumice in gypsum composites to improve thermal properties. Journal of Applied Sciences, 2006; 6(6):1322-1326.
[11] https://en.wikipedia.org/wiki/Glass_wool
[12] BS EN 12390-1.Testing hardened concrete, Part 1: Shape, dimensions and other requirements for specimens and moulds. British Standards; 2000.
[13] BS EN 12390-2. Making and curing specimens for strength test. British Standards; 2009.
[14] BS EN 13279-2.Gypsum binders and gypsum plasters Part 2: Test methods. British Standards; 2014.
[15] BS EN 12390-7. Testing hardened concrete, Part 7: Density of hardened concrete. British Standards, 2009.
[16] BS EN 13279-1:2008. Gypsum binders and gypsum plasters; Part 1: Definitions and requirements. British Standards; 2008.
[17] EN 13501-1. Fire classification of construction products and building elements, Part 1: Classification using data from reaction to fire tests. British Standards, 2009.
[18] I.R.Q . No. 28-1988. Gypsum for building. The Iraqi Standards, 1988.
[19] Othuman MA, Wang YC. Elevated-temperature thermal properties of lightweight foamed concrete. Construction and Building Materials, 2011; 25:705–16.
[20] Hertz KD. Concrete strength for fire safety design. Magazine of Concrete Researches, 2005; 25(8):445–53.
[21] Liu C-T, Huang J-S. Fire performance of highly flowable reactive powder concrete. Construction and Building Materials, 2009;23(5):2072–9.
[22] EN BS 1745. Masonry and masonry products: Methods for determining thermal properties. British Standards; 2012