Investigations on the Reinforcement of Mechanical Properties of Gypsum Composites Containing E-glass Woven Fabrics

Azam Salimian, Mohsen Hadizadeh, and Masaood Zeini

***Abstract*— Glass fiber reinforced gypsum composites are new building materials that have been used in covering interior walls. Reinforcement by means of woven fabrics as a three dimensional material is an alternative to the use of short fibers. The application of appropriate fabrics can improve mechanical properties of gypsum composites. The aim of this research article is to investigate the effect of the application of mesh fabrics on mechanical properties of gypsum composites. To do so, three types of fabrics made of E-glass yarns with leno texture - to strengthen the warp and weft of the fabric in the gypsum mixture- were used. Bending, tensile and compression tests were carried out on them, and then statistical analyses were performed on the data. The results showed that the bearing capacity of compressive load in gypsum composites strongly depends on the joint between the layers of fabrics and mortar. The strength of the fabric plays an important role in the bending behavior of composites and the joint between the yarns of the fabric and mortar is the effective factor in the tensional load capacity.**

***Keywords*: Gypsum mortar, reinforcement, mechanical properties, direction of warp and weft**

I. Introduction

Gypsum is one of the unique construction materials because of its low price, abundance, ease of application, good ductility and excellent appearance. Gypsum is a quick mortar in terms of setting, and its increased volume after it is applied and before the hardening fills all the pores and fissures. The Gypsum's heat transfer coefficient is low and it is rather resistant to fire. According to its properties and thickness it could prevent the spread of fire for a certain period of time [1]. But gypsum has a brittle nature and a low elastic modulus. Therefore, it is very prone to cracking and has low bending strength. The process of gypsum hydration and setting depends on multiple factors: the temperature during the preparation of gypsum paste, the ratio between gypsum and water, the method of gypsum mixing, the intensity and duration of mixing, the size of the gypsum particles, and their purity [2].

Many studies have focused on the properties of gypsum reinforced with various additives. Glass fiber has a special place in various industries due to its special characteristics such as flexibility, heat and sound insulation, moisture resistance, high tensile strength, and resistance to chemicals and corrosion [3]. The application of glass fiber improves the mechanical properties of gypsum mortar under loading [4]. Variations in length and ratio of glass fibers influence the mechanical properties of the gypsum composite. Using 4 % of glass fiber with the length of 50 mm yields the best results in terms of enhancing the mechanical properties of gypsum composites [5]. The mechanical properties of gypsum composites vary with different particles of resin, and the high density of the particles in the composite improves the strength of the composite as well as its density [6]. The random mixture of other short fibers, such as PP and PPTA, improves the tensile properties of gypsum significantly [7].

Although all of the mentioned factors have improved the mechanical properties of gypsum mortar to some extent, adding additives to gypsum mortar have been unable to protect it adequately against the impact of loads resulting from natural disasters such as earthquakes.

Fabrics are light and flexible surfaces that can be used to strengthen and reinforce building materials. Fabrics have been used in various materials such as cement and concrete and have shown good performance. Glass fiber mesh fabrics with weft knitting weave can be a suitable alternative to metal meshes which provides strength and integrity for the cement plaster. The advantages of this glass fiber over lath include improvements in various aspects such as the speed and ease of application and handling, corrosion resistance, and safety during application [8]. The glass fabrics can be used in the reconstruction and strengthening of concrete structures as well. In fabrics with higher values of cover factor and yarn fineness, the effect of fabric reinforcement is more and the fabric strength is not considered to be the critical criterion [9]. The number of fabric layers influences the results of impact test in cement composites. With an increase in the number of fabric layers, the amount of shear stress and the amount of damage to the specimen in impact tests increase [10].

Moreover, the method of preparing fabric–matrix interface influences the mechanical performance of cement composites. Usually three different methods, which are casting, pultrusion and vacuum processing roller, are used for the preparation of composites. The process of producing cement composites with fabrics should be

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coordinated with the fabric structure and its yarn to optimize the bond efficiency. The pultrusion process is effective and causes stronger bonds and better utilization of the filaments which maximizes their efficiency, resulting in a stronger connection between the fabric and mortar. But this method for glass yarns that are coated with a resin is not very effective because there is no space between the filaments for impregnation [11]. Performing dynamic tensile tests at different speeds on composites are effective on test results and the differences in the tensile behavior of various fabric composites indicate the role of each fabric under high rate loading. There is a direct correlation between the properties of the composites and fabric individual properties (not in cement). Among glass, PE and carbon; the carbon fabric with the highest performance provides the best composite behavior in the high rate tensile tests [12]. The thickness of the fabric should be in harmony with the mortar thickness. For a mortar with higher thickness, thicker fabrics should be applied to protect and maintain finishing materials [13].

To improve the mechanical properties of materials such as concrete, they are usually compounded with other materials such as steel, staple fibers, and fabrics. A major reason for growing interest in utilizing fibers or fabrics in cement based composites is to increase the toughness and tensile properties of the basic matrix. Fibers such as nylon, polypropylene, glass, and carbon with a tensile modulus lower or higher than that of the cement matrix can be used to enhance cement composites properties. Woven fabrics can be used to improve the mechanical properties of concrete beams [14].

Composite materials are one of the most widely used and newest construction materials used for reinforcing construction materials. The most important fabric which is widely used in composites is the fabric made from glass fiber which was first used in the Soviet Union, England and the United States in 1950. In recent decades, the use of glass fiber and its products has prospered in the building industry because of its advantages including enhanced speed and ease of application and handling, safety during application, resistance to corrosion and moist, low weight and high tensile strength [15]. Different fibers have been used to improve the mechanical properties of gypsum [16-18].

In this research, woven E-glass fabrics have been used to improve the mechanical properties of gypsum under bending, tensile and compressive forces. In addition, the effect of the directions of warp and weft of the woven glass fabric on the mechanical properties of the gypsum composite is investigated.

TABLE I
CHARACTERISTICS OF THE YARNS

Sample code	Yarn linear density (tex)		Yarn diameter (mm)	Yarn wide (mm)	Load at break of yarn (N)	
	Warp	Weft	Warp	Weft	Warp	Weft
F1	450	800	1.2	2.1	143	269
F2	140	200	0.6	1	49	50
F3	70	35	0.3	0.3	12	17

II. MATERIALS AND METHODS

A. Fabric

Three types of woven fabrics of E-glass yarns were used in our investigations. These fabrics were produced from flat weft yarns (the thickness of weft yarns were 0.3, 0.1 and 0.07 for fabrics 1, 2, and 3, respectively). The characteristics of the yarns are shown in Table I. In order to exemplify the textile product structure, the fabrics are denoted as F1, F2 and F3. The weave design of each three fabrics was Leno in which the weft yarns lie between two groups of warp yarns, as the structure of woven fabrics shown in Fig. 1. Surfaces of all three fabrics were coated with vinyl acetate resin. The properties of the fabrics such as weight of fabric, fabric thickness, fabric strength and fabric cover factor values were measured considering ASTM standard test procedures. The weight of fabric per unit area was determined according to standard ASTM D3776. The thickness of fabrics was measured under a constant pressure (50 gf/cm^2) using Shirley thickness tester. Tensile test specimens were prepared in both warp and weft directions according to ASTM D5034 using Shirley Testing Machine. The specimens were tested at room temperature (approximately 23°C). The average values of the fabrics properties are given in Table II.

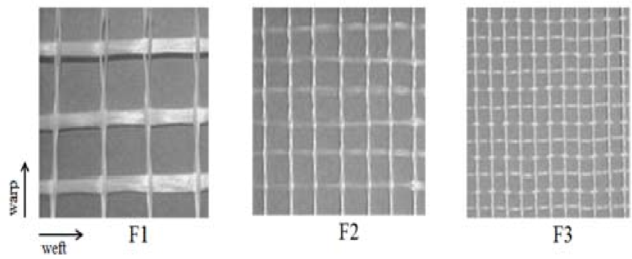


Fig 1. Structure example of fabrics.

TABLE II
THE AVERAGE VALUES OF THE FABRICS PROPERTIES

Sample code	Weight of fabric (gr/m^2)	Thickness of fabric (mm)	Number of yarns (cm^{-1})		Load at break of fabric (N)		Elongation at break of fabric (mm)	
			Warp	Weft	Warp	Weft	Warp	Weft
F1	135	0.6	1	1	353	413	3.6	8.3
F2	75	0.3	2	2	319	227	2.8	2.3
F3	50	0.17	3	3	325	186	4.7	4.6

The fabrics thickness was measured under a constant pressure (50gf/cm2) using a Shirly thickness tester

In fabrics, the cover factor is considered as the fraction of the total fabric area covered by the component yarns. Fig. 2 schematically shows the warp and weft yarns of a fabric. The cover factor of fabric is defined as the ratio of warp and weft yarns cover to the fabric surface. This value can be calculated by using the rectangular GFIH in Fig. 2. According to the selected rectangle, common areas must be removed from the warp and weft yarns (LFJK rectangular area in Fig. 2). The cover factor of warp, weft and fabric is calculated by using (1), (2) and (3).

$$C_1 = p_2 d_1 / p_1 p_2 \tag{1}$$

$$C_1 = p_1 d_2 / p_1 p_2 \tag{2}$$

$$C_f = (p_1 d_2 + p_2 d_1 - d_1 d_1) / p_1 p_2 \tag{3}$$

C : Cover factor
d: diameter of yarn
p: space between two yarns

The subscripts 1, 2 and f are used for the warp yarn, weft yarn and fabric, respectively.

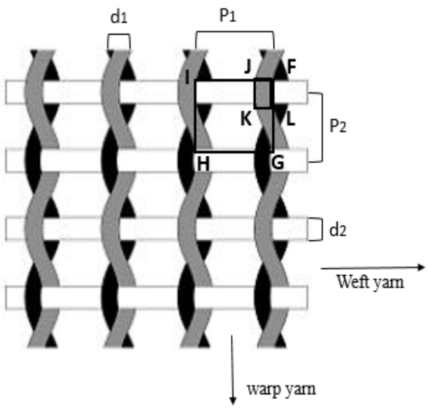


Fig 2. A schematic image of the fabric.

According to the above equations, three fabric cover factors per unit area (1 cm^2) were obtained as 0.3, 1.56 and 3.52 for F_1, F_2 and F_3 respectively. The larger the value of the fabric's fractional cover, the more compact is the fabric's structure.

B. Sample Preparation

Cubic rectangular molds with a size of 40×40×160 (mm) were used to prepare bending samples. Cubic molds with dimensions of 50× 50×50 (mm) were used for preparing compressive samples. Bone-shaped molds were used for preparing tensile samples [19]. All the fabrics were cut according to the dimensions of gypsum mold. The samples were prepared by the hydration of β-hemihydrate powder, $CaSO_4 \cdot 1/2H_2O$. The ratio of gypsum and water for preparing the paste was 50/50. The paste was mixed by hand for 1 min. Before preparing the mortar, gypsum powder was passed from a sieve with 0.36 mm diameter holes [20]. The procedure for preparing the two-layer composites is as follows:

• Lubrication of molds
• Pouring the prepared mortar into the mold to reach a height of 5 mm.
• Putting the layer of fabric on the mortar.
• Pouring the prepared mortar into the mold to reach a height of 30 mm.
• Putting the second layer of fabric on the mortar.
• Filling out the molds.
• Heaping up the empty spaces by using impact bar.
• Smoothing the surface of the samples and taking them out from their molds after the setting time of gypsum.

The produced samples were stored in the laboratory condition at 20±2°C and about 65% relative humidity for 7 days. At the end of this period, they were dried in an oven at 40°C to reach a constant weight [21]. A group of samples were also prepared from 100% gypsum without fabric (plain gypsum). After 28 days, all the samples were tested under bending, tensile and compressive loading. The number of samples for each test was six.

C. Testing Machines

For bending test, a measuring device capable of bearing the bending load rate of 30 $N.s^{-1}$ was applied in the absence of sudden impulses in a way that breakage occurred within 30 to 90 seconds. This testing machine performs the three-point bending test. It has two haven rollers which are spaced 100 mm and the third roller rests in the middle of the haven rollers. The details of the design of the three-point bending test method and its configuration are presented in Fig. 3.

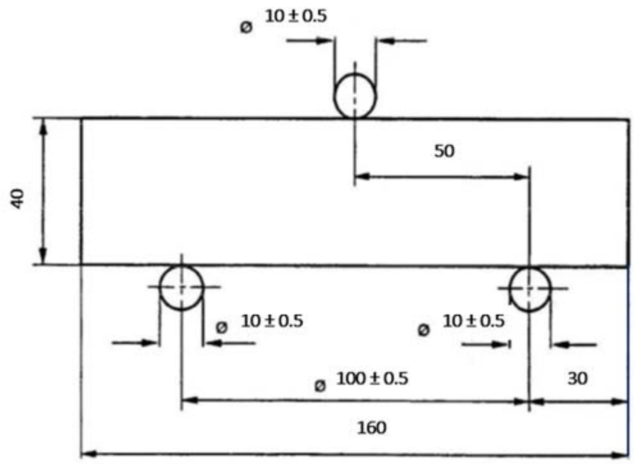


Fig 3. Design details of the 3-point bending test method and its configuration.

For the compression test, a measuring device with two parallel plate cons was used. The top plate could move freely and apply an axial compressive load on the samples. The value of the maximal force corresponded with the pressure load area was read on the device.

III. The Analysis of Results

One-way analysis of variance (ANOVA) was used to evaluate the effect of the fabrics on the improvement of various properties of the gypsum composites. We used the plain gypsum, two layer gypsum composite along with warp and weft directions of fabrics, and types of woven fabrics as independent variables levels (seven levels) of the variance analysis. Then bending, tensile and compressive tests were performed on them. The ANOVA results of each tested property are given in table III.

Table III shows there is a significant difference between the groups and the significance levels. The P Values lower than 0.05 demonstrate confidence intervals greater than 95% in all cases.

A. Results of Bending Tests

By examining the values obtained from the tests on the plain and reinforced samples with different fabrics, the following results were obtained. Table IV shows the average values of the bearable bending force for the seven groups.

TABLE III
A SUMMARY OF ANOVA DATA ANALYSIS

Mechanical Properties	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square (Variance)	F	Sig.
bending	Between Levels	17859.476	6	2976.579	8.576	.000
	Within Levels	12147.500	35	347.071		
	Total	30006.976	41			
Tensile	Between Levels	107.653	6	17.942	14.541	.000
	Within Levels	43.185	35	1.234		
	Total	150.838	41			
Compressive	Between Levels	3.246	6	.541	11.736	.000
	Within Levels	1.613	35	.046		
	Total	4.859	41			

TABLE IV
AVERAGE RESULTS OF FABRIC REINFORCED GYPSUM COMPOSITES IN BENDING, TENSILE AND COMPRESSION TESTS

sample	reinforcement direction	bending load (N)	Tensile load (N)	Compressive load (N)
plain	-	336.5	54.3	3600
F1	warp	987.8	78.25	3360
	weft	894.3	68	3320
F2	warp	730	77.75	3110
	weft	705.6	90.5	3010
F3	warp	869.7	93.3	3750
	weft	701	104	3650

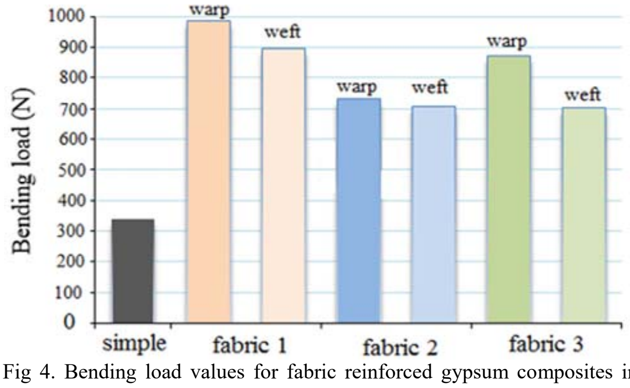
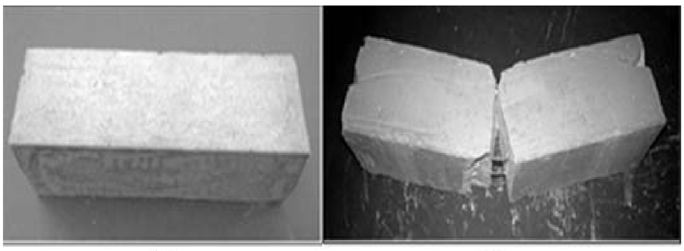


Fig 4. Bending load values for fabric reinforced gypsum composites in warp and weft directions.

There is a significant difference in the bending strength values of different fabrics. According to Table IV, it is observed that in all tested composites, reinforcement in the warp direction led to higher bearable bending force in comparison with the weft direction. Fig. 4 shows the amount of the fabric reinforcement in gypsum composites. A comparison of Tables II and IV indicates that the more the strength of the fabric to tear was, the more the amount of their reinforcing effect on the bending properties of gypsum composites was observed. There is only an exception for fabric 1. Although the durability of fabric 1 to tear in weft direction is more than that in warp direction, the reinforcing effect in warp direction of the fabric is more than that in weft direction. The adhesion between fabric and mortar is one of the most important factors in the reinforcement effect of fabrics in mortar. The thickness of yarns in fabric 1 is more than the other two fabrics.

Considering that the surface of the fabric was coated with polymeric materials, mortar penetration in the fabric decreases. Warp yarns of the fabrics are two-plied and have twists. As a result they create more and better space for mortar penetration. Fig. 5 shows the images of a reinforced gypsum mortar sample before and after the test. As shown in Fig. 5, the layers of fabric keep the broken pieces of gypsum together and prevent the load divergence. This is very effective in reducing the damage caused by earthquakes, because pieces are not separated even after the plaster failure.



(a) (b)

Fig 5. The reinforced samples (a) before, (b) after the bending test.

B. Results of Tensile Tests

By examining the values obtained from the tests performed on the plain and reinforced gypsum samples with different fabrics, the following results were obtained. Table IV shows the average values obtained from tensile strength force.

The process of specimen's destruction in the tensile test is as follows: when the tensile force reaches the amount that creates horizontal cracks in the gypsum composites, the layers of fabrics keep the pieces of samples together. By increasing the load, due to the high strength of the fabric component, the adhesion factor between fabric and gypsum determines the reinforcement effect. According to Fig. 6, fabric 3 had the best performance in the composite reinforcement. This reinforcement effect in weft direction of fabric is more than that in warp direction. The diameter of weft yarns of fabric 3 is lower than that of warp yarns and this factor creates better adhesion between the mortar and weft yarns. In addition, the maximum force and elongation at break in weft yarns are higher than those in warp yarns. Fabric 3 has higher density and finer yarns. This fabric has a lower yarn freedom than the other two fabrics. Therefore, the visual examination of the samples after the test revealed that by applying tensile loads to the samples, the yarns of the fabrics were not pulled out of the mortar and no individual behavior of any yarn in fabric 3 were observed. As shown in Fig 7(a), when the tensile force reached its maximum value all the surface of fabric 3 lost its adhesion to the mortar, causing the pieces of the sample to collapse. This behavior was respectively observed less in fabrics 1 and 2.

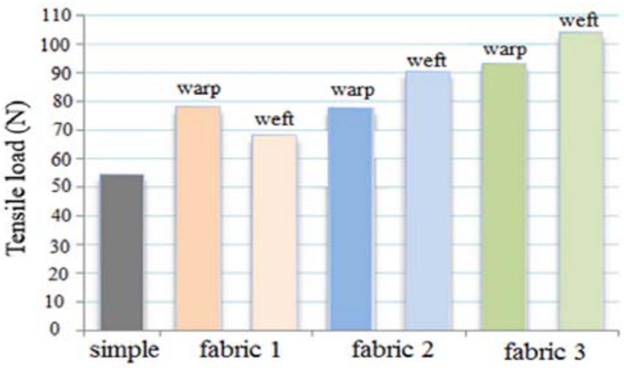


Fig 6. Tensile load values for fabric reinforced gypsum composites in warp and weft directions.

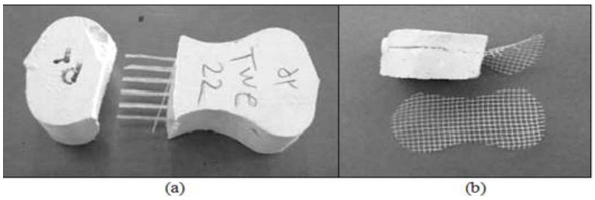


Fig 7. The samples reinforced by (a) fabric 2, (b) fabric 3 after tensile tests.

The yarns of fabrics 1 and 2 are thicker leading to little resin infiltration of fabric yarns, and the freedom of yarns in fabric 3 is much more than in fabrics 1 and 2. This causes the yarns in fabrics 1 and 2 to move individually in the structure of the fabric.

In fabric 2, the reinforcement effect in the warp direction of the fabric is more than in the weft direction. The diameter of the weft yarns of fabric 2 is lower than the diameter of warp yarns and this creates better adhesion between the mortar and weft yarns and the maximum breakage force of the weft yarns is more than that of the warp yarn. By visual examination of the samples after the test, it was observed that when the applied tensile force was in the warp direction, the yarns of fabric 2 were not pulled out of the mortar completely, whereas when the applied tensile force was in the weft direction, as shown in Fig. 7(b), the yarns of fabric 2 were pulled out of the mortar for half of the samples. The leno weave of the fabric gave the weft yarns more freedom to pull themselves out of the sprocket-shaped warp yarns. But the better adhesion of the weft yarns to mortar caused these yarns to reach this degree of freedom after applying more force and to be pulled out of warp yarns gradually.

According to Fig. 6, in fabric 1 the warp direction has shown better reinforcement effect unlike the other two fabrics. Although the thickness of warp yarns of fabric 1 was more than that of weft yarns, the remarkable thickness of weft yarns and their complete coverage with resin decreased the amount of mortar penetration in weft yarns. Therefore, the amount of warp yarn crimps and twists played an important role in the adhesion between the mortar and the yarns. The warp yarns of fabric 1 were double and also twisted unlike the weft yarns that were completely flat and smooth. This factor led to more adhesion between mortar and the warp yarns. The remarkable thickness of the weft and warp yarns of fabric 1 and the lack of mortar penetration in the structure of yarns caused the yarns to be pulled out of the mortar during the tensile loading. In all the samples on which the force was applied in the weft direction of the fabric, and in half of the samples on which the force was applied in the warp direction of the fabric, the yarns were pulled out of the mortar. Fabric 1 had less geometric stability than fabrics 2 and 3 due to its low density and the low penetration of the resin (high thickness of yarns at the contact points of warp and weft yarns in fabric), and a bunch-yarn movement in one direction was obvious. The complete coverage of yarns with resin and the high thickness and smoothness of the weft yarns were the most important factors that caused the yarns to be quickly pulled out of the mortar.

C. Results of Compression Tests

By examining the values obtained from the plain and reinforced gypsum samples with different fabrics, the following results were obtained. Table IV shows the average values obtained for compressive strength force.

Fabric buckling due to axial compressive force is one of the important factors in composite failure. The more the flexibility of the fabric, the more is the fabric buckling due to the axial compressive force.

As can be seen in Fig. 8, the compressive strength of the gypsum composites compared to the plain sample was reduced when fabrics 1 and 2 were used. The compressive strength of the gypsum composite in which fabric 3 was used increased compared to the plain sample.

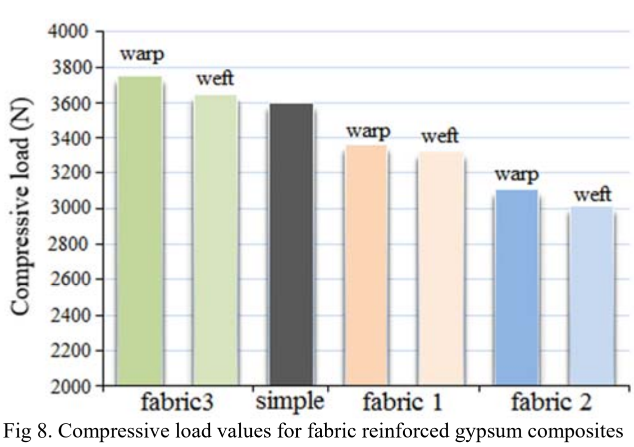


Fig 8. Compressive load values for fabric reinforced gypsum composites in warp and weft directions.

Among the three fabrics used in this study, the diameter of yarns in fabric 3 was smaller than in other two fabrics. As a result, the flexibility of fabric 3 was more and its flexural strength was less than the other two fabrics. Moreover, the adhesion between the mortar and fabric 3 was very good. Due to the greater bending resistance of the fabric in the warp direction, the amount of fabric buckling would be lower and this exerts a lower force on the plaster wall. Therefore, compressive resistance of the reinforced gypsum composite in the warp direction of fabric 3 was more than the weft direction. Due to the thickness of fabrics 1 and 2 and the separating surface that they created in the samples, a reduction in the compressive resistance of these fabrics was expected. The adhesion between fabric and gypsum is very important. Therefore, by calculating the cover factor of fabric, the surface of adhesion between the fabric and mortar can be obtained.

According to the calculations, the cover factor of fabric 1 was lower than that of fabric 2. Therefore, the surface of adhesion of gypsum in the composites made with fabric 1 was more than that of the composites made with fabric 2; thus the compressive resistance of samples when fabric 1 was applied was lower than when fabric 2 was applied. In the final step, the percentage of increase in bending, tensile and compressive strength of plain gypsum compared with glass fabric / gypsum composites was analyzed and shown in Table V.

TABLE V
THE PERCENTAGE OF INCREASE IN THE STRENGTH OF GYPSUM COMPOSITE

	Reinforcement gypsum composite direction (%)					
	fabric 1		fabric 2		fabric 3	
Mechanical properties	warp	weft	warp	weft	warp	weft
Bending	193.5	165.7	116.9	109.7	158.4	108.3
Tensile	44.1	25.2	43.2	66.6	71.8	91.5
Compressive	-	-	-	-	4.16	1.38

In general it can be expressd that by using fabric 3 which has higher density, lower weight and finer yarns in comparison with other fabrics, the amount of composite compressive strength force decreased, the bending strength force increased three times and the tensile strength force nearly doubled. Therefore, to reinforce all three flexural, tensile and compressive properties, fabric 3 is the most appropriate fabric.

IV. CONCLUSIONS

Glass fibers are the most important materials used in composites. In this study, three types of fabrics made from glass yarns were used in gypsum mortar and the mechanical properties of the plain gypsum were compared with the gypsum-fabric composites. The results are as follows:

All the samples in which fabrics were applied showed an increased resistance to bending and tensile forces compared with the plain samples.

The durability of fabrics is an important factor in reinforcing the bending strength of gypsum composites. The more the durability of fabric, the more is its strengthening effect in the mortar.

The frustration of yarns from the inside of the mortar is just shown in very thick and impervious yarns.

The sturdy connection of fabric to mortar is the most important factor in the reinforcement of the tensile properties of gypsum composites. The stronger is the connection between the fabric and the mortar, the more is the productivity of fabric properties and as a result the more is the reinforcing effect of fabrics. If there is an appropriate connection between the fabric and the mortar, the strength of the yarns will play an important role in reinforcing the tensile strength.

Thick fabrics create a separator surface in the samples and reduce their compressive resistance. In thick fabrics with a less cover factor the connection between gypsum and gypsum increase and the compressive resistance decrease with a lower rate in comparison with other fabrics. In fabrics with a low thickness, the buckling of fabric decreases with an increase in the stiffness of fabrics, and as a result the fabric has a greater influence on the compressive resistance of the composites.

In terms of the fabrics used in this paper, Fabric 3 (with higher density, lower weight, and finer yarns) has the best performance in tensile and compression tests and fabric 1 (with lower density, higher weight, and thicker yarns) has the best performance in bending tests.

The warp direction of the fabric has a more reinforcing effect than the weft direction in bending and compression tests.

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