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Engineering Parameters for Gypsum Board Reinforced by Rice Straw Fibers

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Abstract

This paper focused on the viability of utilizing rice straw, a plentiful agricultural waste product, as reinforcement for gypsum-based composites to create environmentally friendly insulation boards. While, building industry has shown a great deal of interest in for using rice straw as a raw material for composite aggregates and increasing the utilization of agricultural waste for construction. The aim of the study was to find out how treating rice straw with gypsum changed the physical and mechanical characteristics of the finished boards. After being, the straw fibres cut into pieces ranging from 10 to 30 mm. Rice straw was treated with sodium hydroxide and combined in different amounts with gypsum. Boards containing 6% rice straw exhibited lower density (1.08 g/cm³ vs 1.18 g/cm³), higher water absorption (35.4% vs 28.6%), increased porosity (38.9% vs 33.7%), and decreased compressive strength (5.1MPa vs 12.6 MPa). While the addition of rice straw decreased mechanical properties. The obtained results revealed a positive correlation between the amount of rice straw and water absorption. In addition, the mixture of rice straw and gypsum leads to increase porosity. Finally, this mixture cause of decreasing compressive strength.

Keywords: composite materials, gypsum boards, rice straw, compressive strength, physical properties

Introduction

In recent years, the building industry has become more and more interested in using plant resources to create building materials. This can be ascribed to the necessity of finding alternatives to the synthetic materials now in use, which frequently have negative impacts on human health and the environment **(Anvar *et al.*, 2019, Adilkhodjaev *et al.*, 2020a and Adilkhodjaev *et al.*, 2020b).**

Worldwide, agricultural waste comprises wheat straw and flax fire, and it constitutes a significant source of raw materials. One way to make some sense out of such wastes is to use them as a reinforcing fiber when making building materials. One example of a material derived from natural plant raw materials is a gypsum fiber sheet, which has excellent thermal, physical, and mechanical qualities **(Adilhodzhaev *et al.*, 2019 and Shaumarov *et al.*, 2019).**

Gypsum composite boards, because of their outstanding characteristics as environmentally friendly building materials, such as energy saving, sound insulation, thermal insulation, low price, decoration capability, availability, constructability, and easy production, were among the most frequently used materials in civil engineering and have been widely employed in residential construction as roof or wall sheathing **(Guna *et al.*, 2021)**. Furthermore, plasterboards are commonly used in construction for thermal insulation and air purification, but high-purity natural gypsum products are essential in wallboard manufacturing due to the detrimental impact of impurities on gypsum properties **(Bouzit *et al.*, 2019)**. However, gypsum board composites have been used without any additional reinforcements or additives in the form of plasterboard regarding their inadequate impact resistance, brittleness, and heaviness for some building applications. The most frequent additives used in gypsum boards are natural fibers **(Tichi *et al.*, 2020, Singh *et al.*, 2022 and Tichi *et al.*, 2022)**, such as flax, sisal, rice, jute, wheat, hemp, maize, sunflower, cotton, barely, and wood fiber, mineral particles, synthetic fibers **(Martias *et al.*, 2014),** including polyamide, and glass fiber, and polymers **(El-Maghraby *et al.*, 2007).** Rice straw, a plentiful agro-based residue, presents a promising opportunity for integration into gypsum composite boards to address various challenges and enhance their performance as construction materials. The composition of rice fiber is notable, with cellulose, hemicelluloses, lignin, and wax comprising significant proportions of 41 to 57, 7 to 33, 8 to 19 and 8 to 38%, respectively **(Adilkhodjaev *et al.*, 2020)** This blend of components in rice straw, including cellulose, hemicellulose, lignin, ash, and other minor elements, offers a unique combination for composite board production. Specifically, rice straw contains cellulose (32 to 38.6%), hemicellulose (35.7 to 19.7%), lignin (22.3 to 19.5%), and ash (10 to 17%). Through leveraging these properties, the incorporation of rice straw into gypsum composite boards can lead to improve structural integrity and sustainability in construction applications **(Goodman, 2020).**

Composed of gypsum uniformly reinforced with cellulose fibers, gypsum fiber sheet is an environmentally acceptable building material. It is used in interior design, more especially in the process of installing wall cladding and constructing prefabricated floor bases. The combination of gypsum and fiber use yields all the technical properties of gypsum fiber sheets. Using fibers has a similar synergistic effect on a range of construction materials. For instance, the Egyptians recognized even in prehistoric times that strengthening a home's clay construction and decreasing its tendency to split could be achieved by adding straw, sheep wool, or reed cane **(Dabees *et al.*, 2022)**.

On the other hand, Rice production is associated with vast quantities of straw, which have historically been eliminated by burning fields in the open. However, the burning of agricultural leftovers, particularly rice straw in Egypt (about 4.4 million tons per year), results in what is called locally as Black Cloud, reverse process and utilization of rice straw is a major challenge due to technical, social, institutional, and socioeconomic constraints, what was once a valuable resource is now being burned as a waste **(Halvarsson *et al.*, 2010, Li *et al.*, 2010, Zhang *et al.*, 2015 and Marques *et al.*, 2020).**

Many studies have been conducted on the effects of adding rice straw to cementitious composites, emphasizing how these studies have affected the materials' mechanical characteristics, longevity, and overall performance. While, rice straw improves water absorption, drying shrinkage, compressive strength, flexural strength, and durability under wet/dry cycling **(Van Nguyen and Mangat, 2020).** The rice straw has a beneficial effect on the properties of alkali-activated cementitious composites, improving their water absorption, flexural and compressive strength, durability under wet/dry cycling, and drying shrinkage **(Mahdy *et al.*, 2023)**. Also, they found that treating rice straw with alkali strengthens the link between the straw and the matrix, which enhances the performance of the composites even more**.** The composition of rice fiber is notable, with cellulose, hemicelluloses, lignin, and wax comprising significant proportions of 41 to 57, 7 to 33, 8 to 19, and 8 to 38%, respectively **(Aladejana *et al.*, 2020)**.

Gypsum, an old material, is still frequently used in construction because of its availability, low price, lightweight, great thermal and acoustic isolating properties, fire resistance, and low energy consumption **(Martias *et al.*, 2014)**. Notwithstanding these benefits, its brittleness and poor mechanical strength may restrict its applications and pose certain issues when they are subject to particularly applied pressures, particularly impacting one **(Arikan and Sobolev, 2002). Kaya *et al.* (2021)** found that the modulus of rupture, modulus of elasticity, thickness swelling, water absorption, and internal bonding strength were all negatively impacted when pine particles were replaced in the gypsum matrix at levels ranging from 10% to 50%.

According to, adding hardwood fibers to gypsum composite boards at 1 to 8% can drastically lower their compressive strength and flexural characteristics **(Hošťálková *et al.*, 2019)**. **Vavřínová *et al.* (2022)** revealed the mechanical and thermal performance of the composite boards about the combined effect of three different types of gypsum (Class I, II, and III) with wheat straw at levels of 0, 2.5 and 5%.

Due to the lack of information in this field, this study aimed to investigate the effect of adding rice straw to gypsum on the mechanical and physical properties of the resulting composite.

2. Material and Methods

2.1. Materials

2.1.1. Raw Materials

Rice straw was sourced from the Faculty of Agriculture, Benha University, while other materials such as gypsum, cement, and Addibond were produced from local companies. The straw was cleaned and followed by treatment with sodium hydroxide. Subsequently, the straw was cut into short segments ranging from 1 to 3 centimeters in length and vacuum-packed for storage until use. Tap water was employed in the mixture, maintaining a water/gypsum ratio of 60%. In addition, the recipes were produced by mixing the straw fibers in the composite with different ratios are 2, 3, 4, and 6% **(Fig. 1)**.

(A) (B) (C) (D)

Fig.1. Materials used in sample preparation, a) gypsum and cement, b) water, c)rice straw, d)Addibond.

2.1.2. Devices

The experiment was started by cutting the straw into pieces using scissors. The resulting pieces were then transferred to metal trays. Subsequently, the trays were placed in an electric oven for drying. After drying process, the samples were placed in bags and subjected to a vacuum. The dried samples were then weighed precisely using a sensitive scale with a capacity of 30 kg. Finally, the samples were subjected to a compression test for evaluating their mechanical properties **Fig.2.**

(A) (B) (C)

(D) (e) (F)

Fig.2. The apparatus employed to experiment, a) scissors, b) metal trays, c) electric oven, d) vacuum tube, e) Electronic digital balance, f) compressive strength testing machine

2.2. Methods

2.2.1. Recipes preparation

Sample preparation was conducted within the technical laboratory of the National Housing and Building Center in Dokki. The following methodology was adopted for mixture preparation. Three replicates for different recipes were prepared with different mixing ratios as illustrated in Table 1.

Table 1: Mixing ratio for different recipes.

Recipes No.	Gypsum (%)	Cement Ratio (C/G)	Rice Straw Ratio (R/G)	Water Ratio (%) (W/G)	Fiber Length (cm)	Alkali Solution	Additive Adibond65 (G) (A/W)
1	92	8	0	60	-	1%	1-60
2	90	8	2	60	1-3	1%	1-60
3	98	8	3	60	1-3	1%	1-60
4	88	8	4	60	1-3	1%	1-60
5	86	8	6	60	1-3	1%	1-60

The components were estimated by dry weight and dry mixing till homogeneous distribution of ingredients. Then water and addibond were incorporated into the dry mixture. The specific admixture and its quantity were adjusted based on the desired properties of the final material. The mixture was vigorously blended using a suitable mixer for three minutes to achieve a uniform and workable dough. The prepared dough was carefully poured into steel molds, To eliminate air voids and ensure adequate compaction, the molds were subjected to vibration for one minute on a vibration table **Fig. 3.** Then the samples were meticulously removed from the molds **Fig. 4.**

Fig.3. Molds used for casting samples

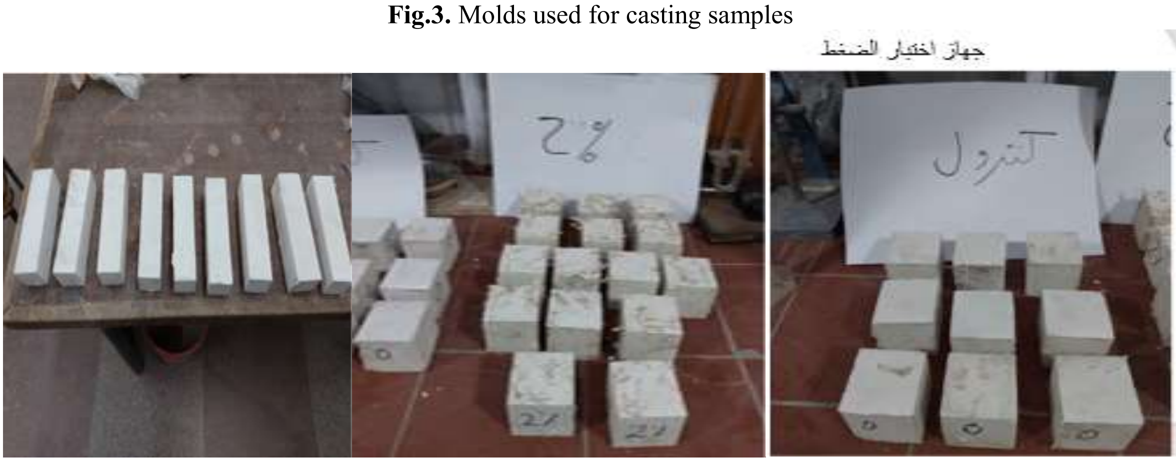


Fig.4 Produced samples for the laboratory's investigations.

2.2.2. Measurement

All samples were manufactured according to ASTM standards, the following tests were done.

- **Bulk density**

The bulk density of gypsum board was determined by placing the gypsum board in a known volume scaled flask and the weight of gypsum board in the scaled flask was measured. The sample weight was recorded and the bulk volume was measured according to **ASTM C 642-97 (1997)**. The bulk density was calculated using Equation (1):

$$P_s = \frac{W_d}{v} \quad (1)$$

Where: P_s: is the bulk density of specimen's g cm^{-3}, W_d is the Weight of the specimens g and v is the Volume of the sample cm^3.

- **Water absorption**

The water absorption test was performed to investigate the weight increase of the material after water immersion according to **ASTM C 642-97 (1997)**. The weight of the specimen was measured before and after immersion in distilled water. Composite samples 1 x 1 x 0.5 cm in size were immersed in distilled water for 24 h at room temperature. Equation (2) was used to calculate water absorption

$$W_A = \frac{M_2 - M_1}{M_1} \times 100$$

Where: W_A is the water absorption, %, M1 is the average mass of dry specimen's, g and M_2 is the average mass of wet specimen's, g

- **Porosity**

Porosity was determined using the following equation **from ASTM C 642-97 (1997).**

$$P = \frac{W_a - W_d}{W_a - W_w} \times 100 \quad (3)$$

Where: P is the saturated porosity, %, W_a is the specimen weight in air of saturated sample, g, W_d is the specimen dry weight after 24 h in oven at 105 ± 5ºC, g and Ww: Specimen weight in water. g.

- **Compressive strength**

The compressive strength of the gypsum board was tested according to **ASTM C 109/C109M**. A servo hydraulic material testing system with a maximum capacity of 100kN was used to apply a constant loading rate test of 13.72 MPa per min until failure. The testing machine was located in the lab of testing materials (Fig 2F). A cubic specimen of 40 mm dimension was used for each test. The compressive strength (CS) was calculated as follows:

$$C_s = \frac{p}{B \times L} \tag{4}$$

Where: C_s is the compressive strength, N mm^{-2}, P is the maximum load, N, L is the length of sample, mm and B is the width of sample, mm

3. Results and Discussion

3.1. Bulk density

Fig. 5 shows the effect of different mixing ratios between rice straw and gypsum (0, 2, 3, 4 and 6%) on the bulk density of gypsum board composites. The results indicate that the bulk density of gypsum board composites decreases with increasing the mixing ratios. It could be seen that, the bulk density of gypsum board composites was decreased from 1.19 to 1.09 g cm^{-3} when the rice straw percentage increased from 0 to 6%, respectively. The results revealed that the height value of density of the composite (1.19 g cm^{-3}) was found with 0% of rice straw, while, the lowest value of the bulk density of the composite (1.09 g cm^{-3}) was found with 6% of rice straw increased in mixture. The bulk density of the gypsum board composites was decreased when rice straw increased in mixture percentage due to the bulk density of rice straw is less than that those of gypsum. This trend is consistent with the findings of other researchers, who have also observed that adding rice straw generally reduces the density of gypsum composites **(Carmen and María, 2017)** whose found that the glass fibres and straw could reduce the density of gypsum-wood composites. Also, **Babu and Ratnam (2021)** found the density of gypsum-fiber composites is decreased when hemp fibers are used, the density of the composite was decreased from 1.195 to 1.148 g cm^{-3}, when, the fiber percentage increased from 3 to 6%, respectively**. Tichi and Khatiri (2024)** found that the lowest density of 0.80 g cm^{-3} was recorded at a 30% rice straw mixture without the addition of bacterial cellulose, while, the highest density of 1.20 g cm^{-3} was recorded at a 10% rice straw mixture with a 3% bacterial cellulose addition.

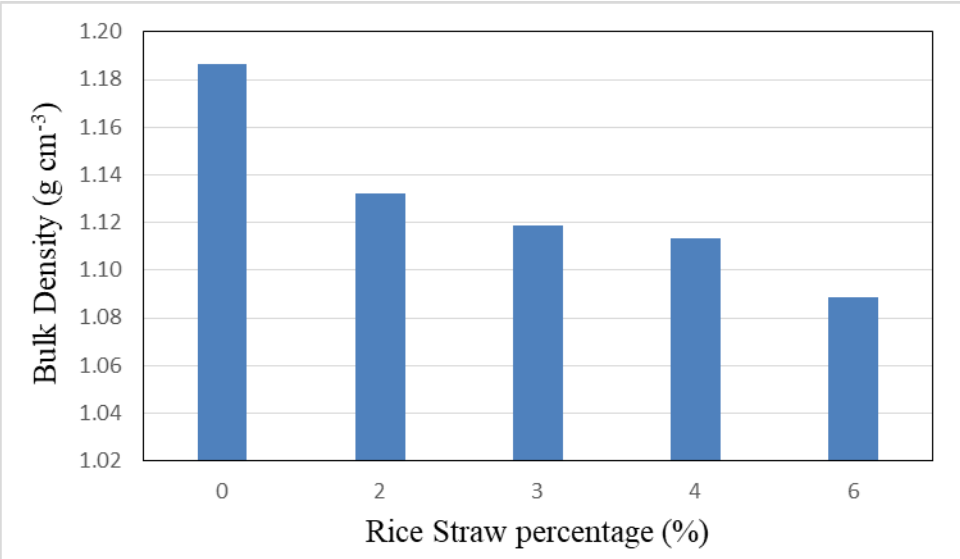


Fig. 5. Bulk density for different recipes.

3.2. Water absorption

Fig. 6 shows the effect of different mixing ratios between rice straw and gypsum (0, 2, 3, 4 and 6%) on the water absorption of gypsum board composites. The results indicate that the water absorption of gypsum board composites increases with increasing the mixing ratios. It could be seen that, the water absorption of gypsum board composites was increased from 28.69 to 35.47 %, when the rice straw percentage increased from 0 to 6%, respectively. The obtained results showed that, the greatest value of water absorption was 35.4% for 6% rice straw fibers content. On the other hand, the minimum value of water absorption (28.6%) at 0%. Previous studies have also shown reduction in sorption of water by gypsum after addition of natural fibers. **Carmen and María (2017)** mentioned that pure gypsum boards exhibited the maximum water absorption (27%), but sorption was greatly reduced upon the inclusion of wool and coir fibres. **Evans *et al.*, 1981)** stated that the water sorption results of gypsum boards including natural fibre additions are interesting.

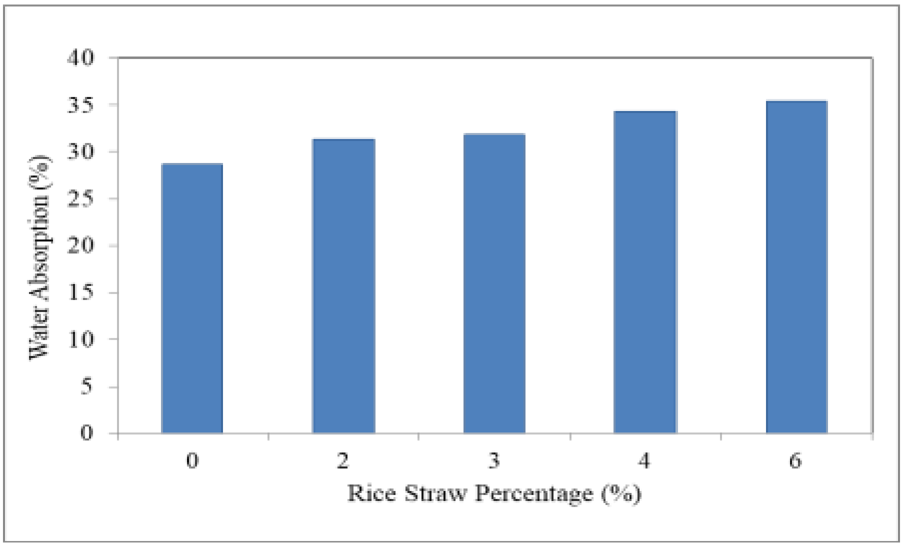
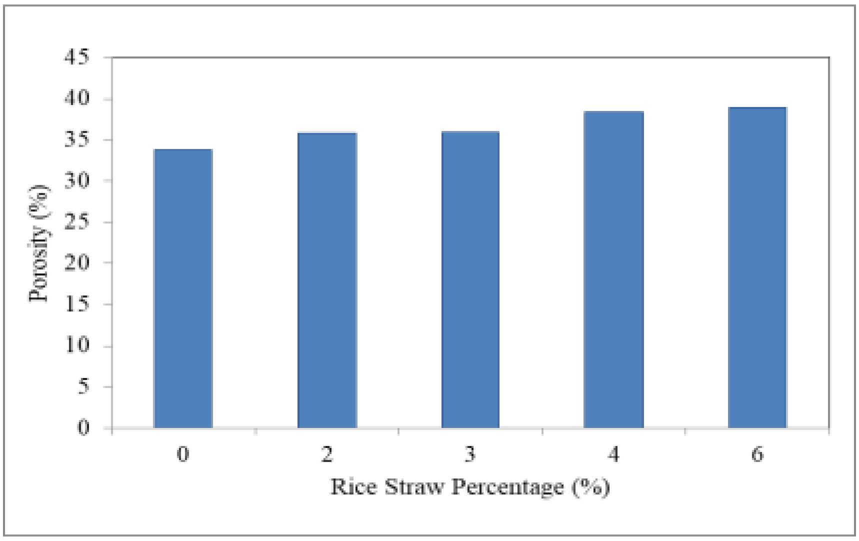


Fig.6. Water absorption for different recipes.

3.3. Porosity

Fig. 7 shows the effect of different mixing ratios between rice straw and gypsum (0, 2, 3, 4 and 6%) on the porosity of gypsum board composites. The results indicate that the porosity of gypsum board composites increases with increasing the mixing ratios. It could be seen that, the water absorption of gypsum board composites was increased from 33.78 to 38.94 %, when the rice straw percentage increased from 0 to 6%, respectively. The results revealed that the height value of porosity of the composite (38.94 %) was found with 6% of rice straw, while, the lowest value of the porosity of the composite (33.78 %) was found with 0% of rice straw. These results were in agreement with those obtained by (Gencel et al., 2022)whose found the average values of porosity were ranged from 28.5% to 30.1%. This shows that, the porosity raised with increment in microencapsulated phase change material (mPCM) quantity addition into gypsum composite. In assessment of control sample, increment in porosity was found to be 1.4, 3.5 and 5.6% with the addition of 1.5, 3 and 4.5% mPCM in gypsum composite, respectively.



.**Fig. 7.** Porosity for different recipes

3.4. Compression strength

Fig. 8 shows the effect of different mixing ratios between rice straw and gypsum (0, 2, 3, 4 and 6%) on the compression strength of gypsum board composites. The results indicate that the compression strength of gypsum board composites decreases with increasing the mixing ratios. It could be seen that, the compression strength of gypsum board composites was decreased from 12.65 to 5.15 MPa, when the rice straw percentage increased from

0 to 6%, respectively. The results revealed that the height value of compression strength of the composite (12.65 MPa) was found with 0% of rice straw, while, the lowest value of the compression strength of the composite (5.15 MPa) was found with 0% of rice straw. It's worth noting that other researchers have also observed similar trends, suggesting that adding rice straw generally weakens the compressive strength of gypsum composite. These phenomena may be due to the compressive strength is assumed at the end of the linear regime. The addition of flax fibers would reduce the compressive strength of the composite, regardless of the mixing method. The increased porosity of the composite material as a result of fiber addition is the major factor responsible the reduction in compressive strength **(Zak *et al.*, 2016)**. However, fibres by themselves are unable to withstand an axial compressive stress and as a result do not increase the composite's compressive strength. Instead, the fibres may be thought of as filler in the mortar matrix when subjected to compressive loading, creating voids and discontinuities in the matrix and lowering its strength as a result. **Singh *et al.* (2023)** presented that using rice straw fibers in gypsum composites reduces the compressive strength. The reference strength (without fibers) was recorded as 4.6 MPa, and when 5% fibers were added, the compressive strength was recorded as 2.8 MPa. **Adilkhodjaev *et al.*, 2020)** defined that using rice straw fibers in gypsum composites reduces the compressive strength. They found the compressive strength was decreased from 8.2 to 5.6 MPa, when the fibers ratio increased from 1 to 3 %, respectively.

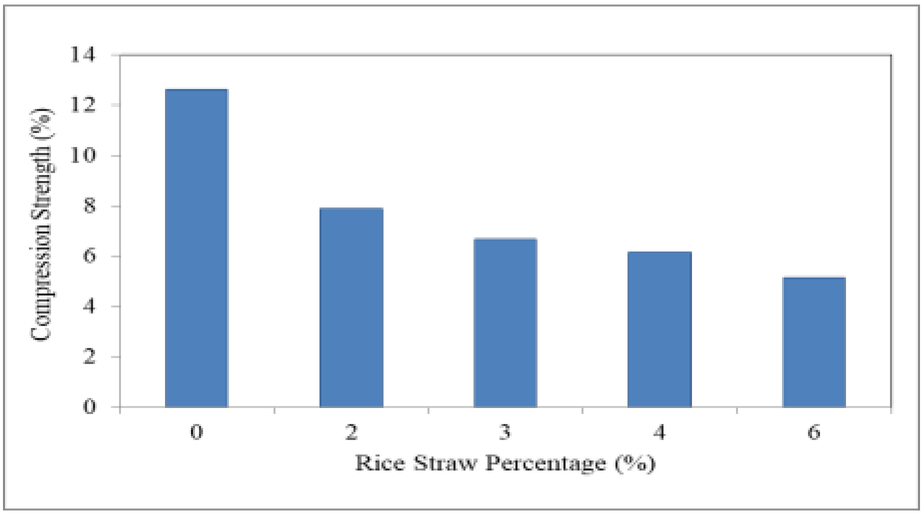


Fig. 8. Compressive strength for different recipes.

Conclusion

The addition of rice straw (2 to 6%) to gypsum composites shows promise in the development of lightweight, sustainable building materials. The obtained results revealed that fibers content led to decrease the density. The research shows that, the amount of rice straw and the ability of gypsum composites to absorb water are positively correlated. Water absorption continuously rises with the proportion of rice straw; it increased by a significant from 28.7%, to 35.5% in the 6% rice straw sample. This notable change in hygroscopic characteristics suggests that adding rice straw improves the composite's ability to absorb and hold onto water. The addition of rice straw to gypsum composites shows a typically favourable relationship with porosity, indicating interesting changes in material properties. Porosity ranged from 33.8% to 38.9% as rice straw content grows from 0 to 6%, with a remarkable 15.3% increase at 6% rice straw content. Finally, compressive strength decreases steadily and progressively as rice straw content increased from 7.8 MPa at 2% rice straw to 5.1 MPa at 6% for 0% to 6% respectively. Finally, fibers lead to slightly reduced compressive strength compared with the pure gypsum. This is mainly due to the strength loss of the fibers and the reduced density.

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العوامل الهندسية لألواح الجبس المقواة بألياف قش الأرز

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إن الهدف من هذه الدراسة هو إمكانية استخدام قش الأرز كمواد تقوية في المركبات الجبسية لإنتاج ألواح عازلة صديقة للبيئة. في حين أن صناعة البناء أبدت اهتمامًا كبيرًا باستخدام قش الأرز كمادة خام للمركبات العازلة وزيادة استخدام النفايات الزراعية في البناء. ويتم ذلك من خلال كيفية تأثير معالجة قش الأرز بالجبس على الخصائص الفيزيائية والميكانيكية للألواح النهائية. حيث تم بعد المعالجة تقطيع الألياف القش إلى قطع تتراوح بين 10 – 30 مم وتم معالجة قش الأرز بهيدروكسيد الصوديوم ثم تم خلطه بنسب مختلفة مع الجبس (0، 2, 3, 4، 6%). أظهرت الألواح المحتوية على 6% من قش الأرز كثافة أقل 1.08جم/سم^3 مقابل 1.18جم/سم^3 لنسبة خلط 0%، وكانت اعلى قيمة لامتصاص مياه 35.4% فى حين كانت اقل قيمة مقابل 28.6%. وتراوحت المسامية بين 33.7 – 38.9 %. وتراوحت قوة الضغط ما بين 5.1 – 12.6 ميجاباسكال. في حين أن إضافة قش الأرز أدت إلى انخفاض الخصائص الميكانيكية .واظهرت النتائج التي تم الحصول عليها عن وجود علاقة ارتباط إيجابية بين كمية قش الأرز وامتصاص المياه. بينما يؤدي إضافة قش الأرز إلى المركبات الجبسية إلى زيادة المسامية . وأخيرًا، يؤدي إضافة قش الأرز إلى المركبات الجبسية إلى انخفاض قوة الضغط.