

Properties and performance of Normal Pressed Rice Straw Thermal Insulation Boards

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Abstract— Rice straw is getting popular as an environmentally friendly renewable material. Among various applications, using rice straw to produce thermal insulation boards for building walls or ceilings are aliening with the globe goal to achieve zero energy buildings. This study investigated the performance of innovated thermal insulation boards. These boards were manufactured using locally available rice straw and cement mortar using a normal compaction procedure. Thermal insulation boards with different rice straw contents (0%, 10%, 20% and 30%) were produced. Mechanical and thermal properties for insulation boards were evaluated. Fire resistance test was also conducted on the proposed boards and other commercial boards to compare their degradation under harsh conditions. Results show that boards incorporating rice straw in the range from 20% to 30% exhibited the optimum mechanical and thermal performance. Rice straw boards exhibited higher fire resistance with respect to commercial thermal insulation boards. This highlights the high potential in having high performance eco-friendly insulation boards incorporating rice straw.

Index Terms— Rice straw, Thermal Insulation boards, Thermal conductivity, Fire resistance

1 INTRODUCTION

ENERGY is the driving force for most anthropogenic activities. In spite of all the efforts to find alternative sources, fossil fuels are still the primary source of energy. Many environmental problems are associated with human's fossil fuel dependence, including global warming and air quality deterioration. Recently, many countries have committed to the "2030 Challenge" targeting that all new buildings and major renovations shall be carbon neutral by 2030. This results in a growing interest in reducing the overall global energy consumption. Hence, the focus has been directed towards building as it accounts for a large share of energy consumption and carbon dioxide emission (NAIMA, 1996). Therefore, the concept of energy efficient building has been evolved targeting lower fossil fuel energy consumption and low-carbon buildings. Thermal insulation for buildings is one key to reduce their energy consumption (Lechtenböhmer and Schüring, 2009).

On the other hand, natural fiber materials had attracted many researchers. These materials have a cell microstructure leading to a lower density and high thermal insulation. It was proven that thermal insulation materials based on natural fibers have competitive thermal technical characteristics, such as heat capacity or thermal conductivity, in comparison with conventional thermal insulation materials (Asdrubali et al., 2015; Korjenic et al., 2011; Jelle, 2011; Shea et al., 2013; Panyakaew and Fotios, 2011; Zhou et al., 2010). Moreover, natural fibres are re-

newable materials with reduced environmental impact compared to synthetic fibres.

Cement bonded boards (CBB) or sometimes referred to as "cement based composites" are currently widely produced and applied in many developed countries. Generally, these boards are composited of natural fibrous material, such as wood or agriculture residues, and cement as a binding agent (Pererira et al., 2006). This CBB showed high dimensional stability along with high bio-deterioration and fire resistance (Frybort et al., 2008; Frybort et al., 2009; Morsy, 2011). One of the widely used natural fibre in construction sector is rice straw. It has been used as a building insulation material for a long time due to their hollow structure, low density and high heat insulation (Ashour et al., 2011; Goodhew et al., 2004). Rice straw is available in vast quantities in the rice paddy growing countries. In Egypt, nearly 8 million tons of rice are produced annually, generating a massive amount of rice by-products (including rice straw) (Nehdi et al., 2003). Uncontrolled burning of such agricultural wastes considered a serious environmental/health problem as the generated pollutants reduce air quality.

The reuse of rice straws in building can contribute in reducing its environmental impact without sacrificing occupant comforts (Ashour et al., 2011; Goodhew et al., 2004). Effects of incorporating rice straw on physical and mechanical properties of fly ash cementitious binder-rice straw composite were evaluated by (Morsy, 2011). It was proven that rice straw cementitious mixture can be used as carrying material for making bricks. As an insulation material, limited research in the literature had investigated the effectiveness of rice straw in improving thermal insulation properties (Ashour et al., 2011; Goodhew et al., 2004; Wei et al., 2015). In these previous studies, rice straw had been examined as an infill for walls or block produced with high frequency hot-pressing.

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Therefore, this study examines the potential of developing thermal insulation boards using only normal/simple compaction process. This will allow transformation of the Egyptian rice straw from an environmental concern to a valuable waste with both economic and environmental benefits.

In the current research, three main phases will be conducted. The first phase will be dedicated to identify the best treatment procedure for the rice straw to enhance its bond characteristics with cement matrix. This will be followed by the second phase aiming to the evaluation of different binding material compositions to identify the optimum. Afterwards, the effect of rice straw size on physical and mechanical properties of rice straw CBB will be investigated by using two different sizes of rice straw with the optimum binding material found out by the second phase. Finally, phase three will focus on the effect of rice straw content, with the selected suitable rice straw size based on the previous step results, on mechanical properties and thermal performance of rice straw CBB produced by the selected binder.

2 EXPERIMENTAL WORK

2.1 Materials

Ordinary Portland cement CEM I 42.5 was used as the main binder. Fly ash with a specific gravity of 2.4 and specific surface area of 308 m²/kg was used as a partial replacement of cement. Locally produced gypsum and hydrated lime with specific gravity of 2.21 were also used. Rice straw was harvested from an agricultural field in Egypt and it was added to the mix as a mass replacement of the cement. Natural siliceous sand with a fineness modulus equal to 2.75, a bulk density of 1630 kg/m³, and a specific gravity of 2.67 was used as fine aggregate. Normal tap water was used in all mixtures.

2.2 Rice Straw Preparation

One of the main challenges facing CBB is the incompatibility between cement (i.e. an inorganic material) and natural fibres (i.e. organic materials) (Sandermann et al., 1960; Moslemi et al., 1994). Some of the extracted organic materials from natural fibres (i.e. acid derivatives and the water-soluble materials) have been found to inhibit cement setting leading to a lower strength (Frybort et al., 2008; Milestone, 1979; Miller and Moslemi, 1991). Hence, natural fibres must be treated to get rid of these organic inhibitors before being used in cementitious materials.

In the literature, different treatment methods for natural fibres are available. One of the commonly used methods is treating rice straw with accelerators to advance the hydration process. Several accelerators, including sodium hydroxide (NaOH), calcium chloride (CaCl₂), sodium carbonate (Na₂CO₃), and Ammonium chloride (NH₄Cl), were tested concerning their potency to shorten setting and curing time while achieving adequate properties for CBBs (Moslemi et al., 1983; Hofstrand et al., 1984; Kavvouras, 1987). Moreover, it has been found that treating rice straw with NaOH solution will effectively remove the extractives and increase the surface roughness and crystallinity index of the rice straw. This in turns will enhance the chemical

bond and mechanical interlock between the straw and surrounding cementitious matrix leading to a high strength composite (Moslemi et al., 1983; Morsy, 2011).

On the other hand, effects of calcium chloride (CaCl₂) on the hydration process of cement composites incorporating rice straw particles had been well studied (Morsy, 2011). It had been concluded that the addition of CaCl₂ with a ratio equal to 6% by weight of cement to rice straw cement composites resulted in a remarkable increase in compressive strength and hydration degree. To investigate the effect of both NaOH and CaCl₂ treatment, two groups of mixtures were prepared, one with untreated rice straw while the other incorporated NaOH treated rice straw. For each group, half of the mixtures incorporated 6% CaCl₂, while the other half was mixed without CaCl₂, as summarized in Error! Reference source not found..

Rice straw was initially chipped into particles with a length of 30 mm, as shown in Fig 1. Rice straw was then treated with NaOH solution following the guidelines stated in ASTM-D1109 as follows: soaking in 1 % NaOH for 24 hours then filtered through 2 mm screen. The ratio between rice straw and soaking solution was 1:10 by weight. After filtration, rice straw was washed with tap water until washing water became clear. Treated rice straw was dried in an oven at 105 ± 2 Co and packed in polyethylene bags until usage.

These preliminary mixes with the purpose of investigating the rice straw treatment efficiency have been prepared by mixing cement with rice straw, treated or untreated, equal to 20% by weight of cement and finally the water was added. The amount of water was calculated using Eq. 1 recommended by (Hachimi et al., 1990).

$$WC = 0.35 C + 1.7 (WS - M) \quad \text{Eq. 1}$$

Where **WC**: The amount of water (g), **C**: Weight of cement (g), **WS**: Weight of straw (g), **M**: Moisture content in the used rice straw (g).

For all mixes, only the compressive strength test was employed to judge the efficiency of the treatment method.

TABLE 1
PRELIMINARY MIXES PROPORTIONS (MASS/CEMENT MASS)

Mix ID	Cement	Rice straw (30 mm)	CaCl ₂
P1	1	0.20 (untreated with NaOH)	0
P2	1	0.20 (untreated with NaOH)	0.06
P3	1	0.20 (treated with NaOH)	0
P4	1	0.20 (treated with NaOH)	0.06



Fig. 1. Chipped rice straw fibre with 30 mm length

2.3 Binding Materials Selection

Binding materials play a significant role in the overall performance for the produced cement bonded boards. However, in the literature there is no clear, direct or well-established trend that can be followed to select a suitable binding material composition. Hence, in order to select the optimum composition, the second phase of this study was dedicated to test and evaluate the performance of different binding material compositions. According to the literature, fly ash is known to enhance the compatibility between cement and rice straw (Morsy, 2011).

Moreover, previous work by (Boltryk et al., 2018, Okino et al., 2005; Meneis et al., 2007) recommended the use of gypsum and hydrated lime as mineralizing agents in order to neutralize harmful organic compounds in rice straw fibres and to stabilize the physio-chemical properties of the cement composite. Hence, fly ash, gypsum and lime were selected in order to be used as partial replacement of cement individually and combined in this phase. Moreover, for all tested mixtures, rice straw content was kept constant as 20% by weight of cement.

For this second phase, several mixtures which are shown in **Table 2** were tested to identify the best mixture for producing thermal insulation boards which compromises between good mechanical properties, applicability and economy. For all these mixtures, rice straw content was maintained constant at 20% by weight of cement. The optimum binder was evaluated and selected based on some test results. These tests included density, compressive strength test and flexural strength test.

With the purpose of studying the effect of rice straw size on physical and mechanical properties of CBB, two sizes of rice straw were utilized; 10 mm and 30 mm. Two mixes have been prepared with these two different sizes with the most suitable binding material resulted from the second phase. Mixes were evaluated by density, compressive strength and modulus of rupture tests.

In the last phase, different mixes have been prepared with different rice straw contents; 10%, 20% and 30% by weight of cement. Rice straw was treated with best treatment method resulted from phase I and with the size of rice straw was selected based on the previous step. The binder composition used in

Phase III was selected based on the results of Phase II. All mixes were evaluated by determining its mechanical properties such as compressive strength and flexural strength as well as its thermal properties such as fire resistance and thermal conductivity.

TABLE 2
MIX PROPORTIONS AS PERCENTAGE WITH RESPECT TO CEMENT

Mix ID	Materials (mass/cement mass)						
	Cement	Sand	Lime	Gypsum	Fly Ash	Rice Straw	CaCl ₂
1	1	3	---	---	---	0.2	0.06
2	1	3	---	---	0.7	0.2	0.06
3	1	3	---	0.07	---	0.2	0.06
4	1	3	0.035	---	---	0.2	0.06
5	1	3	0.035	0.07	0.7	0.2	0.06

3 EXPERIMENTAL TESTS AND SAMPLE PREPARATIONS

Each mixture was poured in different molds according to the test type and compacted with a tamping bar (**Fig. 2**). Unit weight and compressive strength were evaluated using cubic specimens 158mm × 158mm × 158mm according to the standards BS EN 12390-7 (2009) and BS EN 12390-4 (2000), respectively. Flexural strength test was conducted on prismatic specimens 150 mm × 150 mm × 750 mm conforming to the standards BS EN 12390-5 (2009) and modulus of rupture was calculated using the three points bending test. In order to evaluate the ability of fabricated CBBs to conduct heat, thermal conductivity test was conducted on specimens with dimension of 300 mm × 300 mm × 50 mm according ASTM C-518. Based on the measurements of the temperature and heat flux difference across the specimen thickness, the thermal conductivity was determined as shown in Eq. 2:

$$K = \frac{\Phi \Delta x}{\Delta T} \tag{Eq. 2}$$

Where Φ is heat flux (W/m²) flowing through the sample, K is its thermal conductivity (W m⁻¹ K⁻¹), Δx is the sample thickness (m), ΔT is the difference in temperature between the hot and cold surfaces of specimen (C°).

Moreover, the fire resistance for CBBs was evaluated according to the standard method ASTM E119 - 18ce1 for evaluating fire resistance for building construction and materials. A sample size of 300mm×300mm×50mm was subjected to the time-temperature curve of ASTM E119 - 18ce1 on one face, while the temperature of the other face of the sample was recorded every 1 minute during the testing period. The test was ended when the temperature of the unexposed face of the sample reached 140 °C above the ambient temperature. Specimens for different tests were cured with wet burlap until demolding. All tests were conducted at age 28 day.

3.2 Test Methods

Slump of the different concrete mixes were determined according to EN 12350-2 [11]. Compressive strength of concrete was determined according to EN 12390-3 [12] using cubic specimens with dimensions of 100 x 100 x 100 mm. In addition, density of hardened concrete was conducted according to EN 12390-7 [13]. Indirect tension test was conducted according to EN 12390-6 [14] using cylinders of 100 mm diameter and 200 mm height to determine the splitting tensile strength. Flexural strength was determined according to EN 12390-5 [15] using prisms with dimensions of 100 x 100 x 500 mm. The abrasion resistance test was performed according to DIN 52108-07 [16] using cubic specimens of 70x70x70 mm. Percentage of absorption was determined according to ASTM C 642 [17]. Finally, as an indication about durability and permeability, sorptivity test was accomplished according to ASTM C 1585-04 [18].

Three replicates were used for each test and the average value will be used throughout the study. The mechanical properties were determined at 28 days of age except the compressive strength which was determined at 7 days and 28 days.



Fig. 2. Preparation for different specimens for all tests

4 RESULTS AND DISCUSSION

4.1 Effect of Rice Straw Treatment on Properties of Rice Straw Mixtures

Table 3 summarizes results for compressive strength test for rice straw boards incorporating 20% rice straw. As expected, treating rice straw with NaOH had a significant effect on compressive strength developments. Mixtures incorporating treated straw showed a three times higher compressive strength than that of mixtures with untreated straw due to the removal of rice straw organic extractives that acts as inhibitors of cement setting leading in turn to a lower strength (Frybort et al., 2008). Moreover, results revealed that the addition of CaCl₂ is also essential to get a good strength. For instance, adding CaCl₂ to mixtures incorporating untreated straw had boosted the strength to about 2.65 times that of mixtures without CaCl₂. Similar trend was found for mixtures with treated rice straw. This can be ascribed to the stronger bond between straws and surrounding cementitious materials due to the enhancement in the cement hydration process induced by CaCl₂ addition (Morsy, 2011).

4.2 Properties of Treated Rice Straw Mixtures

TABLE 3
Effects of chemicals on properties of rice straw boards

Mixtures	Compressive strength (kg/cm ²)
Untreated + cement	2.27
Treated + cement	9.61
Untreated + Cement + CaCl ₂	6.01
Treated + cement + CaCl ₂	23.1

In this section, effects of different binding materials on the properties of rice straw board mixtures were evaluated. Densities, compressive and modulus of rupture results for tested rice straw boards mixtures are summarized in Table 4.

TABLE 4
PROPERTIES OF RICE STRAW BOARDS

Mix ID	Density (g/cm ³)	Compressive strength (kg/cm ²)	Modulus of rupture (kg/cm ²)
1	1.58	23.1	4.23
2	1.85	20.70	3.55
3	1.68	30.31	13.68
4	1.48	58.73	16.21
5	1.08	13.9	2.53

It was found that a partial replacement of cement with FA (mix 1) resulted in a slight reduction in the strength which was with about 11%. This can be ascribed to the low rate of hydration for fly ash. The addition of gypsum in mix (3) has slightly increased mechanical properties which can be ascribed to the fact that gypsum accelerates cement hydration through continuous reaction with aluminum oxide ((Bao-min and Li-jiu, 2004). This will compensate any retardation/inhabitation for cement hydration induced by rice straw addition. The noticed remarkable increase in the mechanical properties of mixture (4) could be ascribed to the increase in workability due to lime addition and consequently reducing voids which in turns enhanced the compressive strength. Mixture (5), which was suggested by (Morsy, 2011) to produce a green cementitious binder through incorporation of pozzolanic material content, did not yield a promising mechanical properties compared to the mixtures investigated in the current research. Fly ash can be activated by gypsum and lime. However, this activation process must be combined by heat curing to achieve adequate strength. It is very interesting that this mixture possessed the least density which probably will enhance its thermal insulating ability as will be discussed later. It should be mentioned that modulus of rupture had no clear trend and could not be correlated to the compressive strength. This can be ascribed to the fact that flexural strength is very sensitivity to the orientation of rice straw fibers.

In order to achieve optimum thermal insulation boards, cementitious composite with the lowest density would be the best. However, in this study, mixture 4 was selected as it has the best compromise between density and appropriate mechanical properties. Hence, it will be capable to sustain the expected working stresses. Therefore, mixture 4 had been selected for investigation conducted in next phases.

4.3 Effect of Rice Straw Size on Properties of the Rice Straw Boards

As mentioned before, the last section of phase II focused on determination of rice straw size effect of properties of rice straw boards. Two size were utilized; 10 and 30 mm. Two mixes with the two rice straw sizes and with a straw content equal to 20 % by weight of cement have been prepared with the optimum mixture resulted from phase I. both mixes were evaluated based on density, compression, and flexural tests. Results of all these tests are graphically represented in Fig. 3.

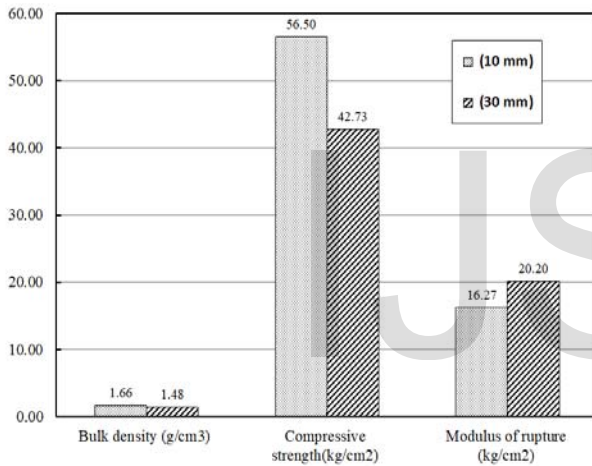


Fig. 3. Effects of straw size on rice straw boards properties

For bulk density, test results showed that changing the rice straw size from 30 to 10 mm was associated with an approximate increase of 12 % in bulk density. Cutting rice straw in smaller length has resulted in enhancing the mix workability and in turn reducing voids in mix and increasing finally the bulk density. The increase in compressive strength noticed when the straw size was decreased from 30 to 10 mm it to be attributed to the same factors which increased the bulk density; better workability and less voids. Meanwhile, reducing the straw size from 30 mm to 10 mm has led to decreasing the modulus of rupture, as can be seen in Fig. 3, as the larger size of rice straw acts as fiber reinforcing for the cement mix more efficiently. As modulus of rupture and bulk density, or in other words thermal conductivity, is of more importance for thermal insulation boards, rice straw size of 30 mm has been further used in the next stages of the current research.

4.4 Effect of Rice Straw Content on Properties of the Rice Straw Boards

4.4.1 Dry density

Fig. 4 illustrates the effect of rice straw content on the dry density of the fabricated boards. Rice straw dry density was about 0.159 g /cm³. As expected, boards' densities decreased as the rice straw content increased. Generally, the higher the straw content, the lower the composite density. For instance, the density for boards with 0% rice straw was around 2.04 g/cm³ while adding 30% rice straws reduces density around 1.39 g/cm³. This can be ascribed to the lower bulk density of rice straw compared to that of the cement. Another possible reason is the higher amount of voids entrapped higher straw content, while at lower content there is better bond with the cementitious matrix.

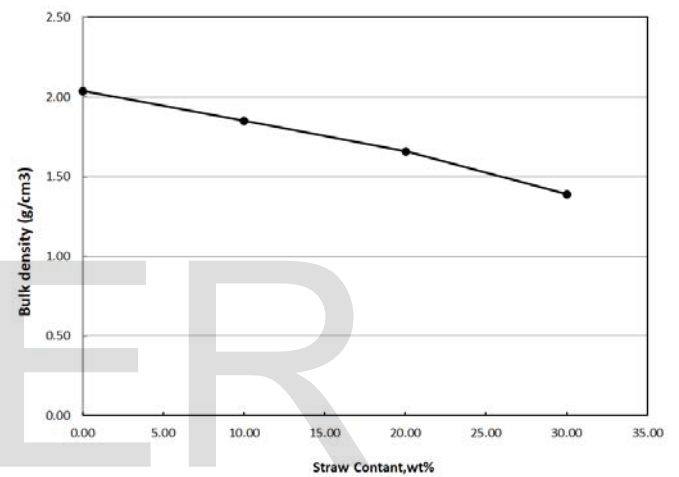


Fig. 4. Effects of straw content on composites density

4.4.2 Compressive strength

The compressive strength of the rice straw boards with respect to the straw particle content at 28 days is presented in Fig. 5. Results showed that increasing of the straw content reduced the achieved compressive strength of the composites. Compressive strength of the composites ranged from 34.5 to 119.3 kg/cm². Compressive strength value decreased from 119.3 kg/cm² for net cementitious paste (mixture 1), to 73.2, 56.5 and 34.5 kg/cm² for 10, 20 and 30 % straw content. Higher fiber content increases porosity of the composite material and results in a loss of compressive strength. Also, the decrease in the compressive strength is attributed to the physical properties of the straw particles, since they are less stiff than the cement paste.

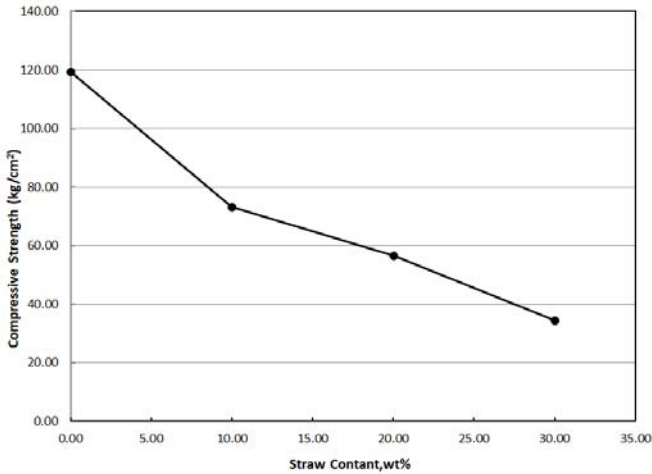


Fig. 5. Effects of straw content on compressive strength

4.4.3 Flexural strength

Effect of rice straw content on flexural strength of boards is shown in Fig. 6. Flexural strength of the composites increased as straw content increased up to 10 % and achieves a value of 21.73 kg/cm² which is around 2.50 times the flexure strength where there is no rice straw. This increase in flexure strength is attributed to the role of rice straw as a crack bridging element or as reinforcement for cement matrix. Conversely, flexural strength for higher straw contents had decreased (i.e. 16.27 and 10.4 kg/cm² for 20% and 30 % straw content, respectively). However, these values were still higher than the net cementitious mixture without rice straw (i.e. 8.67 kg/cm²). The reduction took place in flexure strength in case of straw content more than 10% could be clarified that the mix workability becomes worse with increasing the straw content leading to increasing the porosity which finally outweighs the positive effect the rice straw has on the flexure strength.

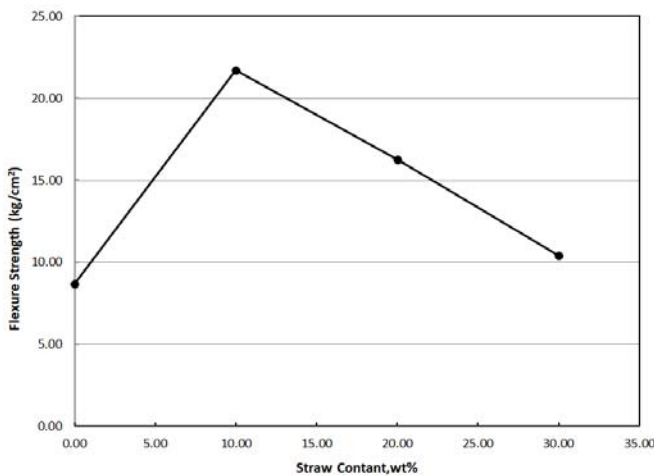


Fig. 6. Effect of straw content on flexural strength

4.4.4 Thermal conductivity

As a thermal-insulating material, the thermal conductivity is one of the most important properties that should be investigated. The thermal conductivity of fibrous insulation materials is affected by a number of basic factors such as straw content and temperature. In general, thermal conductivity increases with rising exposure temperature. The thermal conductivity of composites with respect to straw particle content is presented in Fig. 7. Generally, the results show that an increase of the straw content decreases the thermal conductivity of the composites. For example, increasing the straw content from 0 % to 30 % straw content results in a reduction in thermal conductivity from 1 w/mk to 0.21 w/mk. This is can be attributed to the reduction in mortar content and increase in voids as a result of increase the rice straw content. Therefore, a lower thermal conductivity coefficient is given. Moreover, increasing the rise straw content decrease the thermal conductivity due to the thermal insulation capability the rise straw possesses. In addition, the increase in rice straw content decrease the amount of the mortar content which could be thermally conductive compared with rice straw (Wei et al., 2015).

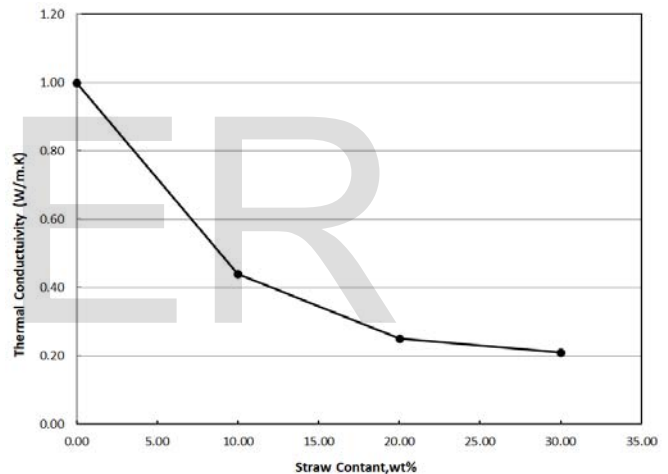


Fig. 7. Effect of straw content on composite thermal conductivity

Taking into consideration the mechanical properties and the thermal conductivity of the cement based boards with different rice straw contents it could be concluded that the optimum rice straw content is supposed to be 20% as this content represents a compromise between the acceptable mechanical properties and the relatively good thermal insulation. If the rice straw content increases from 20% to 30% a marginal decrease in thermal conductivity was detected, as can be seen in Fig. 6, and at the same time was accompanied by a remarkable decrease in mechanical properties as shown in Figs. 4 and 5.

4.4.5 Fire resistance

Table 5 shows a comparison between rice straw cementitious board and extruded polystyrene (XPS) according to fire resistance. The fire resistance of the rice straw cementitious board and extruded polystyrene (XPS) is presented in Fig 8.

Generally, the results show that an increase of the straw content decreases the time of the composites fire resistance. For instance, increasing the rice straw content from 20 % to 30 %, shortened the time the specimen can withstand from 70 minutes to 42 minutes. Increasing the amount of rice straw reduces the amount of mortar and thus reduces the time of fire resistance as the rice straw itself is a flammable material (Asdrubali et al, 2015; Jelle, 2011). However, the time for fire resistance of rice straw boards was extremely longer than that of the extruded polystyrene (i.e. 3 minutes only). Hence, fire resistance of rice straw boards is much better than the conventional industrial thermal insulation boards such as extruded polystyrene. The significant decrease in fire resistance of rice straw boards when the rice straw content increased from 20 to 30% emphasizes the conclusion stated previously; that 20% rice straw content could be considered the optimum content leading to the best trade-off between mechanical and thermal properties.

TABLE 5
FIRE RESISTANCE RESULTS

Sample	Result
20 % rice straw Cementitious Board	70 minutes
30 % rice straw Cementitious Board	42 minutes
Extruded Polystyrene (XPS)	3 minutes

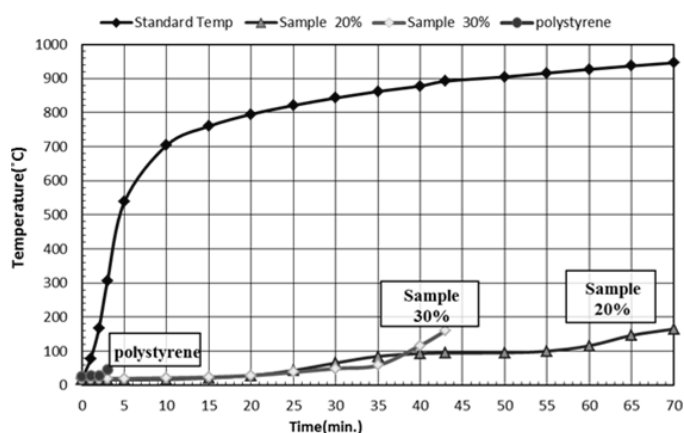


Fig. 8. Fire resistance comparison between CBB with different rice straw content and (XPS)

5 CONCLUSION

The current research focused on developing cement based rice straw boards and investigating its mechanical and physical properties. Based on the experimental program carried out in the current study, the following conclusions could be drawn:

- NaOH treatment of rice straw is very effective due to its role in removing viscous surface where the compressive strength has improved by approximately 90.2%.
- Small straw particles (10mm) better than large straw particles (30mm) where the compressive strength has improved by approximately 24.4%
- If there is no necessary to use high compressive strength, we can use large particles 30mm (ceiling thermal insulation).
- Increasing the straw content reduces the density, compressive strength, and thermal conductivity but increases the flexural strength up to 250% at 10% rice straw content.
- The thermal conductivity of 30% rice straw content was slightly lower than that of 20% rice straw content. On the other side, the mechanical properties of 20% rice straw content was much better compared with the case of 30% rice straw content. Therefore, it is recommended to use 20 % rice straw content.
- The fire resistance of rice straw boards was found to be much better than the conventional industrial thermal insulation material (XPS).
- The rice straw boards as a building material possess many advantages such as good thermal insulation and sustainability. Therefore, it can be successfully utilized in the construction of low cost and sustainable housing projects in Egypt.

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