RESEARCH PAPER

Recycling Egyptian rice straw for the production of low-cost building materials for energy conservation

Nariman F. Ibrahim [a], Nada M. Aboeleneen [b], Nabil M. Abdelmonem [c],
Faisal H. Sorour [d,*]

[a] Department of Chemical Engineering, Higher Institute of Engineering and Technology, Tanta, Egypt
[b] Department of Chemical Engineering, Higher Institute of Engineering and Technology, New Damietta, Egypt
[c] Department of Chemical Engineering, Faculty of Engineering, Cairo University, Cairo, Egypt
[d] Department of Chemical Engineering, Canal High Institute for Engineering and Technology, Suez, Egypt

Abstract

One form of solid agricultural waste that is produced in significant quantities in Egypt is rice straw, which is burned by farmers causing harm to the environment and human health. The goal of the work is to create an effective sustainable insulation option to replace conventional materials using Egyptian rice straw (ERS) as a renewable, biodegradable material in buildings as a means of protecting the natural environment. Experimental results show that chemical composition of ERS includes high portions of silica, fiber, and ash which assessed ERS's thermal insulation capabilities and feasibility when added to mortar and concrete. The ERS was added to the concrete and studied the effect of compressive strength. The results show that adding only 1% ERS by weight decreased the concrete compressive strength by 30.76%, indicating poor binding. However, the investigation of adding ERS in mortar from 0 to 20% shows that the optimum conditions for using ERS are the percentage of 20% ERS. The mortar thermal conductivity decreased by 70% with 20% ERS addition compared with standard mortar without ERS. Smaller ERS particle sizes (5−10 mm) provided enhanced insulation properties versus larger sizes (10−15 mm). General empirical equations were developed to relate thermal conductivity to the ERS ratio and temperature.

Keywords: Agriculture waste, Building materials, Energy saving, Recycling, Rice straw, Thermal insulation

1. Introduction

Rice is considered a primary agricultural crop worldwide; it covers approximately 165 million hectares of the world's agricultural land. However, the agricultural land in Egypt constitutes only ~ 5% of its total area, with a total annual production of 6 million tons.[1] Rice serves as a vital staple food across numerous Asian countries, with extensive annual production in rice-growing nations; however, improper utilization of rice straw through open burning contributes to environmental hazards.[2]

Egyptian rice straw (ERS), an abundant agricultural residue, is often openly burned in fields, releasing pollutants that contribute to climate change, air pollution, and respiratory health issues. The chemical composition of ERS may be summarized as moisture (22%), lignin (14.5%), cellulose (34%), nitrogen-free extract (4.2%), ash (19.5%), silica (14%), calcium (0.17%), phosphorus (0.10%), potassium (0.20%), magnesium (0.11%), sulfur (0.08%), traces of cobalt (0.05 mg/kg), copper (0.50 mg/kg), and manganese (0.40 mg/kg).[3] Egypt amassed 1.4 million tons of ERS amid steady rice production and increased consumption.[4]

Among the major problems in the world, air pollution is the most dangerous problem. The main reason for air pollution in Egypt is the combustion of agricultural waste such as the ERS. Most of the ERS undergoes combustion and releases emissions;

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* Corresponding author.
E-mail address: sorourfh@outlook.com (F.H. Sorour).

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these emissions have environmental and health impacts.[5] Burning of ERS in an open atmosphere poses health risks as the pollutants produced from combustion raise concerns about potential negative impacts on public health. Agricultural burning generates fine particles that can lead to respiratory problems like bronchitis and pulmonary fibrosis.[6] Recently, the world has witnessed significant variations in the world's climate, particularly, the phenomenon of global warming, which led to elevated temperatures and humidity during summer and lower temperatures in winter. One of the factors contributing to unnatural changes in weather is the unregulated practice of open burning of ERS in agricultural fields after harvest. Intensified ERS burning emits greenhouse gases, including nitrous oxide and methane, contributing to air pollution, health problems, and environmental issues.[7,8]

As a result of high summer temperatures, the use of air-conditioning systems has increased further exacerbating air pollution. To create a thermally comfortable environment, an approach involves incorporating thermal insulation materials early in the building process, such as within the structural elements like wood framing, brickwork, mortar, floors, and walls. The idea behind thermal insulation revolves around using materials with small conduction heat transfer coefficients. This approach would effectively mitigate heat loss or gain, leading to decreased temperatures and reduced energy use and costs.[9] Several types of material are suitable for this reason. They could be classified into many categories; the first category is conventional thermal insulation materials which include mineral wool, fiberglass, polystyrene, cellulose, polyurethane foam, rock wool, and asbestos.[10] The second category is unconventional materials such as rice husk, sheep wool, expanded polystyrene, coconut fiber, sheep's wool, cotton wool, cotton fiber, corn cob, date palm fiber, bagasse, climb husk, wheat straw, pineapple leaves, and cellulose as rice straw[11] and composite materials such as silicon calcium, gypsum foam, and wood wool.[12] Emerging technology materials like transparent materials and active materials are considered.[13]

This research aims to highlight ERS's potential as a low-cost material for thermal insulation, minimizing both waste and cooling energy consumption. It also aims to study the impact of the addition of ERS in concrete and mortar in thermal insulation and assesses the impact of varying levels of ERS in mortar as an insulating material. The study also investigates the impact of ERS particle size on the effectiveness of thermal insulation and its feasibility for application. Finally, the general equation relating the modified mortar thermal conductivity with the ERS ratio was predicted and the cost of using ERS in insulation building materials was calculated.

2. Materials and methods

2.1. Materials

In this study, ERS, Portland cement, grave, and sand were the main components for manufacturing low-thermal conductivity materials. After harvesting a rice crop from Damietta, Egypt, the ERS was collected. The Portland cement, grave, and sand were purchased from a local supplier. In this investigation, tap water was also used, which represents 50% of the total weight of the solid material.

2.2. Methodology

The molecular composition analysis of RS was tested in the biochemical laboratory of the Faculty of Agriculture at Al-Azhar University. The first section of this work is to use ERS in cement concrete by washing the straw with tap water and then using distilled water. This was followed by drying for 2 days at room temperature, and grinding it to a length of 2.65 μm. Making concrete cubes of 15 cm × 15 cm × 15 cm after adding the ERS, with various proportions (0, 1, 5, 10%) calculated based on the total weight of cement. After 14 days, the compression test was done to measure the compressive strength of it.[14] The second section of the work is to use ERS in the mortar of the constructions for the objective of thermal and acoustic insulation. The operating variables of thermal insulation of the ERS were studied to determine the optimum conditions for this process such as the impact of particle size and the percentage of ERS. Also, the general equation for the relationship between ERS ratio and thermal conductivity is predicted using the average temperatures calculated from the lower plate temperature, which is changed by changing the current and voltage of the measuring apparatus used for calculating thermal conductivity.[15]

2.3. Experimental work

2.3.1. Preparation of test specimen

For the samples used in the thermal conductivity device, mortar was added to the washed, dried, and grounded ERS of 2.63 μm in proportions of 0, 5, 10, 15, and 20%. The specimens were compressed in a cylindrical shape with a radius of 1.5 cm and length of 1.8 cm with a manual hand compression device

(Model: pm, Press, max: 20 Mg, Serial No. year: 1996, Gauge: 0–60 Mpa, Resolution: 2 Mpa) with an applied load of 10.23 KN to be tested in the thermal conductivity device to know the degree of isolation of samples.[16]

For the samples used in the thermal conductivity test, which was carried out at the National Center for Housing and Building Research according to the standard specification, ASTM C-518, the ERS was washed with distilled water to clean it from dust and then dried in the dryer for 10 h at 50 °C and then cut into pieces ranging from 10 to 15 mm and from 5 to 10 mm. Prepare sample 0 in a plate shape measuring in size 30 × 30 × 5 cm (normal mortar) by mixing sand (6 kg), cement (1.132 kg) and water as usual. Prepare Sample 1 in plate shape (ERS 10–15 mm) by mixing 5.200 kg of sand, 950 g of cement, and 197 g of ERS (20%) and water and Sample 2 in plate shape (ERS 5–10 mm) by mixing 5.200 kg of sand, 950 g of cement, and 198 g of ERS (20%) and water. After 4 days, the samples were immersed in water for 28 days to allow cement reactions and then dried in a dryer for 24 h at 24.5 °C.[17]

2.2.2. Thermal conductivity calculation

A sample B of thickness x and radius r was put between the two metal circles A and C. The steam is produced by the power supply and transported through a hose to the vacuum chamber. There is a time of holding on until the readings T_H and T_L of thermometers are steady. Thus, the temperature slope in the consistent state is $(T_H - T_L)/X$. The pace of intensity moves through the still up in the air by estimating the voltage distinction and current. To calculate the conduction heat transfer coefficient the accompanying hypothetical methodology is used:

$$Q = k\,\pi\,r^2 \frac{T_H - T_L}{X}$$

where the specimen radius is r (m), surface temperatures were T_H and T_L (°C), the specimen thickness is X (m), and the conduction heat transfer coefficient of the specimen material is k (W/m°K).[18,19]

3. Results and discussion

3.1. Characterization of ERS

As shown in Table 1, ERS has the same fundamental molecular composition as wood and is therefore botanically classified as a woody cell. However, hemicellulose contributes little to stiffness and strength mechanically. Lignin provides plant tissue with compressive strength. Without lignin, most fibers in plant tissue would buckle like wet noodles. The main variation between wood and straw is that wood contains a lesser percentage of lignin and cellulose, while straw contains a greater fraction of hemicellulose.[20] The elemental composition of rice straw is 37%C, 5.7%H, 0.815%N, and 1.165%S by weight.[21,22] The proximate analysis of rice straw is 71.5% volatiles, 10.385% fixed carbon, 10% ash, 8.115% moisture, and a higher heating value of 12.3 MJ/kg.[22,23]

Table 1. Chemical composition of Egyptian rice straw.

Component	Percentage
Cellulose	40%
Hemicellulose	35%
Lignin	15%
Extractives	10%

3.2. The effect of using ERS in concert with 5 and 10% in compressive strength

When ERS with a particle size of 2.63 μm is added at 5% and 10% as a percentage of solid materials, and after compressing the samples into cubes for 3 days and immersing them in water to prepare them for compression tests, they did not stick well because of the big amount of ERS in the sample which increases the fiber content; so, the percentage of ERS was decreased to a low percentage of 1% to study the difference between percentages and how it affects the mobility of work.

3.3. The effect of using ERS in concrete with 1% in compressive strength

When ERS is added with 2.63 μm particle size and 1% as a percentage of solid materials, after 14 days the compressive strength test was done and the results show that ERS made a decrease in the compressive strength of the sample. The compressive strength of the ERS-concrete cube is 36.73 kN/mm^2, while the standard cube is 53.061 kN/mm^2 with acompressive strength reduction equal to 30.76%. The test for compressive strength gives insight into all the properties of concrete; it measures the material's capacity to carry stresses on its surface without cracking or deflecting.[24] From this result, the ERS will affect negatively on concrete properties.

3.4. Effect of ERS on the thermal conductivity of mortar

The relationship between temperature and conduction heat transfer coefficient of the sample with 0, 5, 10, 15, and 20% ERS, respectively, was studied. Fig. 1

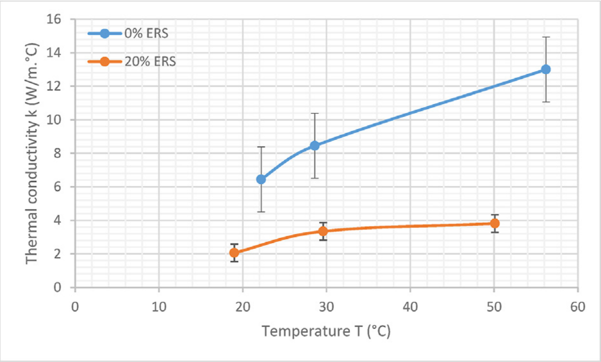

Fig. 1. Comparison between the effect of temperature on thermal conductivity at two values of 0 and 20 % Egyptian rice straw.

demonstrates a comparison between the effect of temperature on thermal conductivity between the standard sample and the sample with 20% ERS. Fig. 2 shows a comparison between the standard sample and other samples with 0, 5, 10, 15, and 20% ERS.

Figs. 1 and 2 show that an increase in temperature results in increases in thermal conductivity. For 5, 10, 15, and 20% ERS at a temperature of 22.5 °C, the thermal conductivity of the sample decreased from the standard sample by 5.279, 51.7, 59.9, and 68%, respectively. At 52.2 °C, the thermal conductivity for 5, 10, 15, and 20% ERS decreased from the standard sample by 15, 57.153, 67.593, and 70%, respectively. From the comparison of different treated mortar samples, the sample with 20% ERS based on the weight of cement is the optimum sample with a reduction of about 70% of thermal conductivity which means good insulation in buildings using this mortar.[25] From other studies increasing the straw content reduces density, compressive strength, and thermal conductivity but increases the flexural strength by up to 250% at 10% ERS content. The thermal conductivity of 30% ERS content was slightly lower than that of 20% ERS content. However, the compressive strength of 20% ERS content was much better compared with the case of 30% ERS content. Therefore, it is recommended to use 20% ERS content.[26,27]

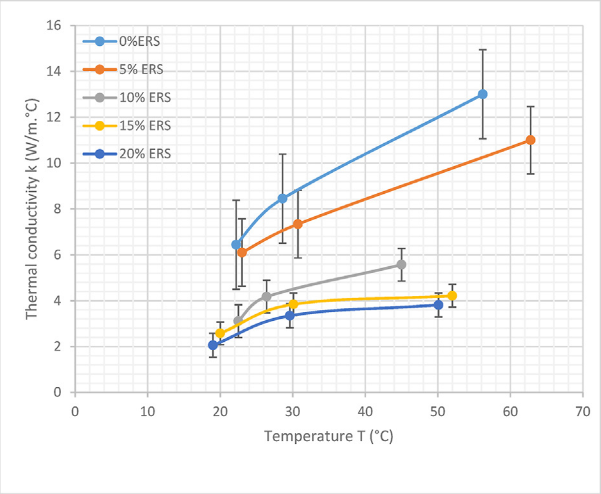

Fig. 2. Comparison between standard sample and samples with 0, 5, 10, 15, and 20% Egyptian rice straw used in this part of the work.

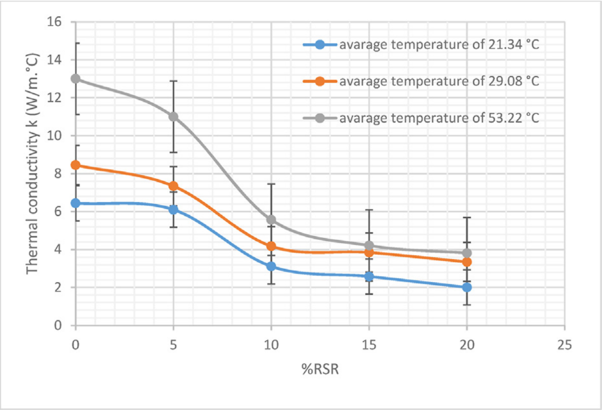

Fig. 3. Relationship between RSR (%) and thermal conductivity K (W/m.°C) of the sample at average low temperatures of 21.34, 29.08, and 53.22 °C.

3.5. Effect of ERS particle size on thermal conductivity of mortar

In this part, different samples of mortar with ERS of different sizes range from 5 to 10 and 10–15 mm, which were prepared and tested in a thermal conductivity measurement device. The impact of change in the particle size of ERS is indicated using

Table 3. Relationship between average low temperature and thermal conductivity as a logarithmic equation.

Average temperatures	K equation	R^2
21.34 °C	$k = 6.8839e^{-0.064\ RSR}$	0.90
29.08 °C	$k = 8.3501e^{-0.05\ RSR}$	0.92
53.22 °C	$k = 13.117e^{-0.068\ RSR}$	0.94

Table 2. Effect of the particle size of Egyptian rice straw on thermal conductivity.

Sample no.	Sample content	Thermal conductivity
0	Standard cement mortar	1.2 w/m°C
1	Treated cement mortar (ERS 20%, 10–15 mm length)	0.56 w/m°C
2	Treated cement mortar (ERS 20%, 5–10 mm length)	0.687 w/m°C

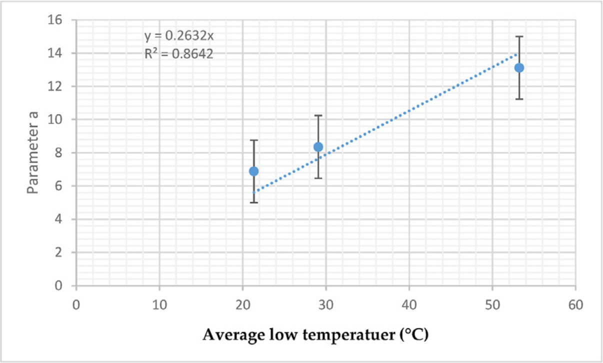

Fig. 4. Relationship between the parameter (a) and average low temperature.

the thermal conductivity device; three samples were formed to meet the thermal conductivity device requirements as shown in Table 2.

From Table 2, it is clear that increasing the particle size of ERS decreases the thermal conductivity so that the optimum size is in the range of 10–15 mm. The thermal conductivity of sample 2 with a range of particle size 5–10 mm shows a reduction in thermal conductivity of ~ 43.33% than the standard sample. Sample 1 with a range of particle size 10–15 mm shows a thermal conductivity reduction of 53.5% from the standard sample. This might be as a result of when the volume of ERS particles is small, the density is high and an increase in density

Table 4. Fixed cost calculation for using Egyptian rice straw in mortar.

Parameter	Calculations	Value
The flat area	The area of the building × 3	300 m^2
The sand amount	The flat area/40	7.5 m of sand
The cement amount	Amount of sand × 300	2250 kg of cement
The ERS amount	The percentage of ERS × The amount of cement	450 kg of ERS
ERS cost for 100 m^2 building	The amount of ERS for the building × the price of ERS	783

Table 5. Properties of different building insulation materials.

Additive type	Thermal conductivity k (mW/m K)	Cost *(US $/m²)*	References
Glass wool	30–50	9.3–14.7	32
Rock wool	33–40	12–20	33
Expanded polystyrene	29–41	8.6–17	34
Extruded polystyrene	32–37	18–23	35
Polyurethane	22–35	24.91	36
Polyisocyanurate	18–28	20–24	37
Foamed glass	38–55	46–62	38
Perlite	40–60	38–42	39
Phenolic foam	18–24	23	40,41
Cork	37–43	25.6–44.7	42
Cellulose	37–42	24.6	43
Aerogel	13–21	61–214	44
Vacuum insulation panel	3.5–8	90–172	45
Nanomaterials	4–15	3000	46
Gas-filled panels	11–20	214	46
Coconut pith	42–86	84.35	47
Flax	33–90	15.18	48
Hemp	39–123	15–19.4	49
Rice husk	48–80	5	50
Wood fiber	38–50	26.6–37.8	51
Sheep wool	38–54	24	52
Cotton waste	38–44	19.32	53
Basalt fiber	31–32	27–30	54
Concrete	146	124.227	55
Fiberglass -Urethane	21	179	56
Fire brick	470	26.67	57
Cement plaster	720	8	57
Rice straw		0.253	This study

leads to faster heat transfer and higher thermal conductivity. In Samples 1 and 2, the density is lower due to a higher percentage of voids with air trapped in samples; the air also decreases thermal conductivity.[28,29]

3.6. The general equation relates the thermal conductivity with RSR

The relationship that exists between thermal conductivity and RSR to take the average low temperature of all samples is 21.34 °C, the average medium temperature is 29.08 °C, and the maximum average temperature that may occur is 53.22 °C. The average temperatures were obtained from the lower plate temperature, which is changed by changing the current and voltage of the measuring apparatus.[30]

Fig. 3 shows the relationship between the average temperature and thermal conductivity, illustrating the predicted equation that relates the thermal conductivity with RSR used to calculate the thermal conductivity for any sample with constant RSR at a specific temperature. From Table 3 the relationship between thermal conductivity (k) and RSR is expressed by the logarithmic equation $k = a\ e^{-bx}$. The mean value of $(-b)$ was equal to -0.06, and the relationship between parameter (a) and temperature is $a = 0.263\ T_{low}$ from Fig. 4. By substituting for (a) from the previous equation and the mean for (b) in the previous logarithmic equations, the general equation that relates the thermal conductivity to the RSR and lower plate temperature becomes as follows:

$$k = 0.263T_{low}\ e^{-0.06\ RSR}$$

3.7. Economic study

Assuming that the building area is 100 m^2, and the price of one tone of ERS is 1740 LE from Table 4 we found that the cost of using ERS in mortar for heat insulation by 20% of cement weight is 7.83 LE/m^2 area.[31]

3.8. Comparison between the properties of different insulation materials

This section compares the thermal and economical properties of different insulation materials used in building materials. Thermal properties are necessary for cost savings and operational energy savings. Table 5 presents the above-mentioned properties of different insulation materials.

3.9. Conclusions

In this study, thermal insulation calculations are used, and parameters like the particle size and the percentage of ERS were studied to optimize the optimum conditions to be used on a commercial scale for thermal insulation. The first part uses ERS with a particle size of 2.63 μm in concert cubes with various proportions that were calculated from the total weight of cement (0, 1, 5, and 10%). When the percentage was 1% ERS, the reduction in compressive strength was 30.76%. The second part is using ERS in a mortar with different percentages and the test shows that the thermal conductivity at a constant particle size of 2.63 μm of the ERS with 20% decreased by 70% from the standard mortar. The effect of the particle size on the thermal conductivity shows that the sample with 10–15 mm ERS is lower by 53.5% than standard cement mortar. The optimum conditions are to use ERS with a percentage of 20% based on the weight of cement and particle size of 10–15 mm to reduce the thermal conductivity of normal cement mortar. The cost of using ERS in the internal layer of mortar for a building with a 100 m^2 area is 783LE. ERS demonstrates significant potential as an abundant, renewable insulation material option. Therefore, the use of ERS is low in cost compared with the usual isolation methods, and it is also better as Egypt is one of the largest countries in the world in the production of ERS.

Ethics information

Our research upholds the highest standards of integrity and honesty, ensuring accurate data representation and appropriate source citation, while maintaining objectivity to enhance the credibility of our findings. All authors contributed equally to this work.

Conflicts of interest

There are no conflicts of interest.

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