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Enhancing the Thermal Insulation Behavior of Cement Mortar Using Waste Additives

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Abstract

Building materials having low thermal load and low thermal conductivity will provide thermal comforts to the occupants in building, also low thermal conductivity means energy saving. In an effort to enhance the insulation properties of the cement mortar and to reduce the environmental burdens of the industrial, agriculture and municipal solid wastes, these wastes can be recycled by adding them to mortar to produce light weight concrete. The aim of this study is to investigate the thermal insulation of mortar that has been mixed with several types of additives like saw dust and shredded automobile tires and its effectiveness as thermal insulation. The effect of changing the amount of waste added to the cement matrix was studied. Results showed that, at high amounts of waste addition, wood waste–cement composites showed lower density, higher porosity, higher water absorption and better thermal insulation performance than that observed with shredded tires-cement matrix.

Keywords: Energy savings; Thermal insulation; Thermal conductivity; Light weight concrete; Sawdust, Shredded automobile tires.

1. Introduction

High energy consumption is undesirable. Home energy efficiency involves more than just electricity savings; it is also considered as a hot environmental topic. Heating and cooling consume up the majority of the energy in our homes [1]. The unnecessary use of air conditioning is not only expensive but also not recommended because of its indirect effects on the environment and fossil fuel reserves. Approximately 1135 million metric tonnes of carbon dioxide are released every year during the production of electricity simply for air conditioners [2], harming the environment and accelerating climate change. That means decreasing the energy consumption at our homes requires a suitable way of thermal insulation.

The amount of energy consumed by air conditioning system does not only depend on the operational hours, but also on the energy efficiency of the system itself along with the power source. Conditioning systems with low energy efficiency use more electric power resulting in more CO_2 emissions. This large electrical energy consumption due to heating and cooling systems especially in commercial buildings necessitates improving the thermal insulation performance of these buildings for better energy conservation [3]. One solution to this problem is to try to decrease the dependence on such conditioning systems as possible [4]. This can be done by selecting building materials with lower thermal conductivity to be used in building construction in a way that seeks to achieve self-conditioning principle. Achieving the thermal insulation principle is an effective and important factor for energy savings in buildings [5].

Application of the waste recycling principle through incorporation of several types of solid wastes like agricultural and industrial wastes in order to produce green composite building materials has drawn the attention. The dependence on using environmentally friendly materials beside following the principle of wastes recycle has increased significantly due to increased level of awareness and

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attention of the society about the environmental pollution problems [6]. Production of building materials with high thermal insulation properties from recycled waste can be a good solution to this problem.

One strategy to enhance the thermal insulation properties of a cement matrix (mortar or concrete) is to decrease the thermal conductivity value of the final matrix. Regarding the cement matrix, the thermal conductivity value depends on several factors like the porosity of the matrix, density, age, proportions of its constituents, water-to-cement ratio, and the degree of humidity of the final cement composite [7]. After literature analysis it was found that, density is the most controlling factor, as decreasing the density of the matrix enhances greatly the final thermal insulation performance of the cement composite. Also, moisture content is considered as the second big factor that affects the thermal conductivity value. From the energy savings point of view, high moisture content means bad thermal insulation. Since the water thermal conductivity is nearly twenty times greater than that of air, water absorption is always associated with high increase in thermal conductivity of the building materials.

Several previous studies discussed the effect of decreasing the density of the cement matrix by incorporating waste materials (agriculture waste, industrial waste, etc.) that have lower thermal conductivity values than the original cement matrix constituents. Some works incorporated the waste by partial replacement for the fine aggregate and others incorporated the waste by partial replacement for cement binding material.

Other studies tried to through the light on how wood wastes addition to mortar affect its thermal properties [7-10]. Wood shavings can be incorporated into the cement mortar without preliminary treatment to enhance its thermal properties. Bederina et al. 2007 [7] studied the effect of addition of saw dust with different percentages to the cement mortar. Bederina et al study showed that, incorporation of wood waste into the cement matrix resulted in a decrease in its density and hence a decrease in the thermal properties with a considerable extent. It also found that, increasing the wood content has decreased the weight of the samples by decreasing their densities [8] and this resulted in a decrease in the thermal conductivity of the final composite and hence better heat insulation. In a trial to enhance the insulation properties of masonry building blocks, Madrid et al. 2018 [9] studied the effect of replacing the fine aggregate (sand) by saw dust waste on the thermal properties of the cement matrix.

Madrid et al. 2018 [9] and Baltazar 2021[8] tried to produce light concrete building block through the incorporation of sawdust as a fine aggregate replacement. They also tried to show how the thermal conductivity of the final block will be affected because of changing the replacement percent. Their results showed that, incorporation of wood waste results in a decrease in the final mechanical strength and this may be due to the increased porosity. Also, the thermal insulation performance of the final composite showed an improvement due to the resulted decrease in the thermal conductivity. In general, replacement of the light aggregate by wood wastes in the cement matrix is revealed to be advantageous by obtaining lightweight product with better thermal insulation performance.

Some researchers proved through their studies that, cement as a binding material can be replaced by other binder when recycling the waste materials [10]. Hafidh et al. 2021 [11] studied the effect of incorporating sawdust into the cement matrix by partial replacement of cement component. This was done in a trial to develop sustainable green concrete with low thermal conductivity, high thermal resistance, and low weight. The study showed that, increasing the amount of sawdust decreased the density of the lightweight concrete and also decreased its hardness. Previous studies also showed that, the particle size of the additive is also very important factor. Since it affects both thermal and mechanical properties of the final specimen. For example, decreasing the particle size of the additive used will has a positive effect on the thermal properties while a negative effect on the mechanical properties of the final mortar specimen.

The disposal process of the scrap automobile tires represent a potential health and environmental problems [12]. Automobile tires are bulky, so the accumulation of the scrap tires represent an environmental problem. Their disposal includes dumping in landfills or combustion in this way of disposal large amounts of toxic gases are emitted to the atmosphere resulting in big pollution problems. Literature analysis showed that, the scraped tires can be recycled in different ways. They can be used as fuel in the rotary kiln of the cement industry due to their high calorific value [13]. Other studies suggested that grinding these tires into powder with larger specific surface area can enhance their adhesion and interaction with different matrices like cementous and rubber regeneration industry [14]. Recent studies showed the possibility of compositing the waste tires powder into the cement matrices in order to enhance the sound properties of the concrete bricks [15].

This work aims to study the effect of adding waste sawdust and shredded automobile tires to the cement mortar on the thermal and physical properties. The effect of changing the amount of waste added to the cement matrix was studied. The tested properties are the density, the porosity, the water absorption and the thermal insulation.

2. Experimental

2.1. Raw Materials

The raw materials used are:

- **Portland Cement:** The cement used in this study was Portland cement type satisfying the requirements of the standard ASTM C 150-07 [16]
- **Fine Aggregate:** Natural silica sand conforming to ASTM 331-05 [17] was used throughout this study. It was confirmed to possess an especially high level of cleanliness, which is applicable for concrete mix.
- **Water:** tap water was used as mixing water.
- **Additives:** The additives which are used in this study are saw dust, and shredded automobile tires.

2.2. Assessment of Raw Materials

2.2.1. XRF Analysis of additives used

The additive waste materials, sawdust and shredded automobile tire powder were analyzed for their chemical composition using XRF technique. XRF spectroscopy is an excellent technology for qualitative and quantitative analysis of material composition. Through this technique the solid sample was excited with energetic X-ray beam emitted from a primary X-ray source [18].

2.2.2. Particle density Determination

Besides cement and fine sand density, the density of each additive is determined using the standard pycnometer technique. Following this technique, the density of solid powders can be determined with a high level of precision. A pycnometer is a round glass flask with a close-fitting ground glass stopper with a capillary hole. This capillary hole releases the excess liquid after closing a top-filled pycnometer with high accuracy level. According to this technique, the solid powder is dispersed in a liquid of known density usually distilled water is used as working fluid [19].

2.3. Samples preparation

The samples are prepared as follow:

- The cement, and fine aggregate were mixed according to ASTM C140 [20] with a proportion of 1:3 and water/cement of 0.7.
- Five samples with different wt% (2%, 4%, 6%, 8%, 10%) from cement were prepared for each additive type to study the effect of the additive amount on the thermal properties of the sample.
- Cement, sand, and the additive are mixed for 5 minutes on dry basis to form homogenous mixture.
- Water is added gradually to the solid mixture with continuous manual mixing for about 10 minutes using a trowel according to ASTM C172 [21].
- The final homogenous paste is poured into a clean wood mold with dimensions of (20*20*2) cm^3. Before adding the cement paste, the inside walls of the molds were coated with oil to prevent the concrete from sticking to the surfaces. In addition, rods which have a smooth hemispherical tip were used for compacting as specified in ASTM C143 [22].
- Samples are left to dry at room temperature for 24 hours required for setting process then the specimens are demolded after that.
- Samples were immersed in a water bath at room temperature in a water curing process to provide the time and conditions necessary for hardening process then after water curing for 7 days, the samples are removed from water and dried in an oven at 110 °C for 24 hours.
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2.4. Samples Testing

2.4.1. Bulk Density Determination

After drying for 24 hours in an oven as mentioned above, the bulk density of the prepared samples was determined according to ASTM C 373/1988 [23]. Samples are left to cool inside the oven and then weighted; finally the density was calculated using the following relation:

$$\rho = \frac{m}{v} \text{ , kg/m}^3 \quad (1)$$

Where:

- M: is the mass of the dry sample, g and
- V: the sample volume, cm^3

2.4.2. Apparent Porosity

According to ASTM C 373/1988[23], determination of the sample porosity requires subjecting the sample under test to continuous boiling for 5 hours. After boiling, the sample is hung with light copper wire and completely immersed in water tank in such a way that its surface lies under a constant water height and then the weight of the hung samples is determined. After subtracting the weight of both hook and wire, get the weight of the sample (D). The apparent porosity of sample can be calculated using the following relation:

$$\%P = [(W_d - D)/V*100] \quad (2)$$

Where:

- W_d: the weight of the dry sample, g
- W_b: the weight of the sample after boiling, g
- V: sample volume, cm^3

2.4.3. Water absorption

The water required to partially saturate the sample, the water required to completely saturate the sample, and saturation coefficient were determined according to ASTM C 67 [24].

2.4.3.1. Cold water absorption:

Here samples under test are partially saturated with water for a day. Samples were completely immersed in water tank at room temperature for 24 hours. After that, samples were removed, and their surfaces were wiped off with a damp cloth before weighing to measure its final weight (W_s). Finally, the percentage water absorption of a specimen can be calculated using the following equation:

$$\%\ \text{Absorption} = \left[\frac{W_s - W_d}{W_d}\right] \times 100 \quad (3)$$

2.4.3.2. Boiling Water Absorption

To completely saturate samples with water, samples that have been partially saturated with water were returned to the water bath. The water bath was subjected to heating till boiling was reached. Once the boiling process begins, samples are left under continuous boiling for 5 hours. Then samples were left to cool down inside the water bath to the room temperature by natural heat loss. After that, specimens were removed, and wiped off the surface water with a damp cloth and weighed to get (W_b). Finally, the percentage water absorption of a specimen can be calculated using the following equation:

$$\%\text{Absorption} = \left[\frac{W_b - W_d}{W_d}\right] \times 100 \quad (4)$$

2.4.3.3. Saturation Coefficient

Coefficient of water absorption due to capillary action of composite can be determined as follow:

$$\text{Sat. Coefficient} = \left[\frac{W_s - W_d}{W_b - W_d}\right] \times 100 \quad (5)$$

2.4.4. Thermal conductivity measurement

The thermal conductivity of the prepared sample was determined using the hot plate thermal conductivity method. For each additive type, five samples with prepared with different additive composition. For this test, samples are prepared with dimensions of (200*200*20) mm^3. Two temperature sensors were used to measure the specimen surface temperature (bottom and top temperatures, T_1 and T_2, respectively Then, the thermal conductivity (K) was determined according to Fourier's first law of steady state conduction, as follows:

$$K = \left[\frac{Q}{A} \times \frac{L}{T_1 - T_2}\right] \text{, W/m·K} \quad (6)$$

Where:
Q: the rate of heat transfer
L: the thickness of the specimen
A: the cross-sectional area of the specimen

3. Results and Discussion

3.1. Chemical Analysis Results (XRF) of Raw Materials

XRF analysis showed that, the wood wastes which are cellulosic materials composed mainly of silica and calcium oxide, while shredded tires powder composed mainly of calcium oxide, zinc oxide and silica. The compositions of the main oxides in these two types of wastes are illustrated in the table (1).

Table (1)
XRF analysis of both sawdust and shredded tires

Oxide	wt%	
	Sawdust	Shredded Tires
SiO_2	64.52	14.1
Al_2O_3	5.21	2.7
Fe_2O_3	2.05	1.1
MgO	4.82	0.7
CaO	9.68	47.0
ZnO	-	33.1
Na_2O	0.065	< 0.01
K_2O	0.09	< 0.01
P_2O_5	0.39	< 0.01
SO_3	0.76	1.2
MnO	0.012	< 0.01
L.O.I	12.4	-

3.2. Particle density of raw materials

The density values of the powder raw materials cement, sand, sawdust, and shredded tires powder are illustrated in the table (2).

Table (2)

The particle density of the raw materials

Component	Cement	Sand	Sawdust	Shredded Tires
Density(g/l)	3150.0	2583.5	1242.5	439.6

3.3. The Effect of Additives on the Physical Properties of the Cementation Specimens

3.3.1. Effect on Bulk Density

Results showed that, the density of the final specimen decreases with increasing the percentage waste added as shown in Figure (3), where the density is a strong linear function in the amount of waste added since R^2 exceeds 0.95. The density of the specimens mixed with sawdust decreased smoothly as the saw dust is added until 10% addition. However, when mixed with shredded tires, the density of the cement specimen made a sharp decrease at 2% then decreased linearly with a smaller slope until 10%. At 10% sawdust addition, the density decreased significantly from 2251.6 g/l to 1632.0 g/l which is equivalent to 27.5% reduction. On the other hand, incorporating 10% shredded tires powder into the same cement matrix resulted in only 15.3% reduction in the final density.

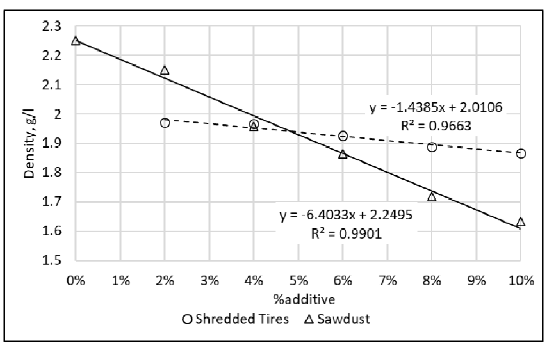

Fig. (3): The effect of addition of shredded powder and sawdust on the bulk density

3.3.2. Effect on Apparent Porosity

The experimental results showed that, incorporation of wood and tires powder increased the porosity of the final sample, which is expected to the thermal insulation performance of the cement matrix. The porosity of the cement matrix increased linearly with the addition of sawdust until reaching 42.8% at 10%. However, increasing the amount of shredded tires had a lower effect on the porosity change of the cement matrix, where the porosity increased slightly from 25.2 to 28.7% when increasing the addition of shredded tires powder from 2 to 10% as shown in Figure (4).

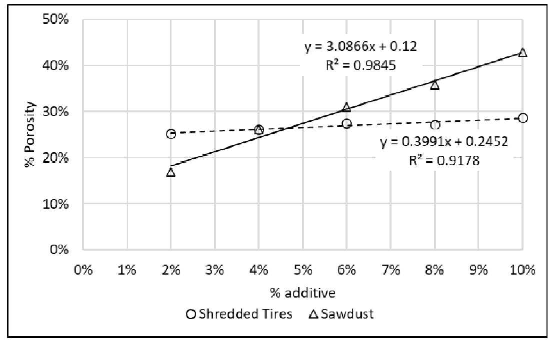

Fig. (4): Effect of percentage additives on the porosity

3.3.3. *Effect on Water Absorption*

3.3.3.1. Partial Saturation

The results of partial water saturation at 7 days of water curing showed that irrespective to the percentage of shredded tires addition, the amount of water absorbed by the specimen is nearly constant between 10 to 11%. On the other hand, the amount of water absorbed by specimen to reach the partial saturation condition increases from 16.8% to 42.9% with increasing the amount of sawdust added from 2 to 10% as described in Figure (5). The relation of the partial saturation as a function of the amount of waste added is irregular.

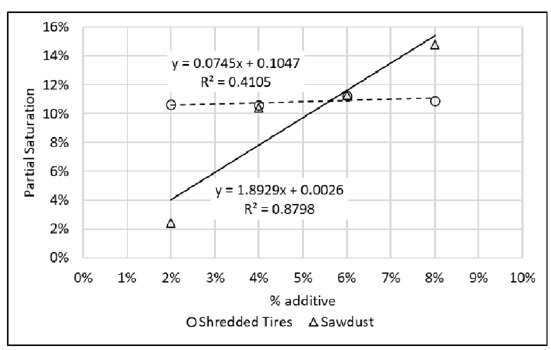

Fig. (5): Effect of percentage additives on the % cold water absorption (partial saturation)

3.3.3.2. Complete Water Saturation

Figure (6) illustrates that the amount of boiling water absorbed by specimen with wood waste additive increases in a significant way with increasing the amount of wood incorporation into the sample. On other hand, increasing the tires powder content in the sample had a lower effect on the amount of boiling water absorbed. However, the relation of the boiling water absorbed is a linear function in the percentage addition of both additives. Results revealed that, at 10% waste addition, water absorbed by sawdust is about 25% and 15% in case of adding shredded tires with same amount. This result was expected due to the high water absorption ability of sawdust and was also consistent with the literature.

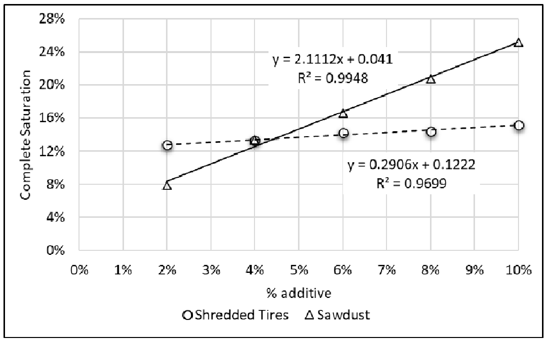

Fig. (6): Effect of percentage additives on the % boiling water absorption (complete saturation)

3.3.3.3. Saturation Coefficient

When liquid water comes into contact with the block surface, water is transported and redistributed through the pores by the capillary action. So, this coefficient depends mainly on the porosity and the degree of connection between the internal pores of the concrete specimen[9]. Figure (7) shows the effect of the amount of additive on the saturation coefficient of the final cement matrix.

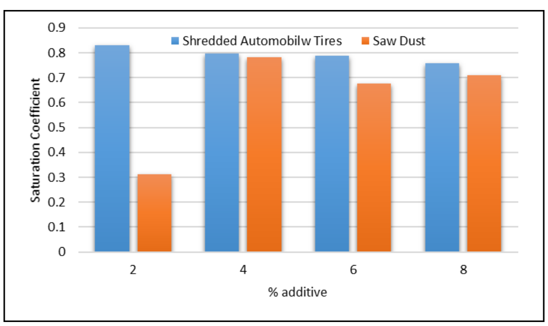

Fig. (7): Effect of percentage addition of both tires powder and sawdust on saturation coefficient

3.3.4. Effect on Thermal Conductivity

The thermal conductivity measurement results showed that it is a strong linear function in the amount of waste added since R^2 exceeds 0.9 as shown in Figure (8). Results showed that, at 10% addition of sawdust and shredded tires powder, the thermal conductivity values were reduced to 0.34 W/m·K and 0.69 W/m·K, respectively. This is equivalent to 72% and 43% reduction in thermal conductivity relative to the control sample[11].

The same phenomenon that took place with the density was noticed with the thermal conductivity, where the thermal conductivity of the specimens mixed with sawdust decreased smoothly as the saw dust is added until 10% addition. However, when mixed with shredded tires, the thermal conductivity made a sharp decrease at 2% then decreased linearly with a smaller slope until 10%.

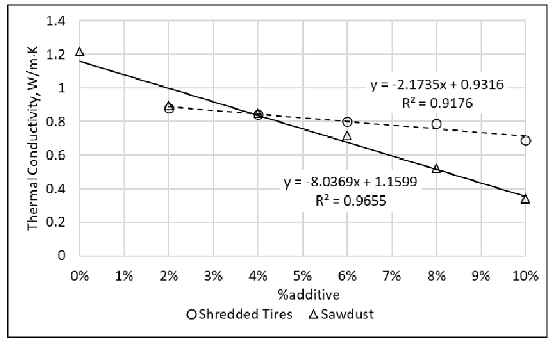

Fig. (8): Effect of percentage addition of both tires powder and sawdust on thermal conductivity

4. Conclusion

Each waste type used, sawdust and shredded tires powder, was added to the mortar with different amounts 2, 4, 6, 8, and 10 wt%. The effect of amount and type of additive on different physical properties like, bulk density, water absorption, %porosity, and thermal conductivity was studied. Results showed that, density, porosity, boiling water absorption, and thermal conductivity are strong linear functions in the amount of waste added with $R^2 > 0.9$.

The effect of both additives on all the studied properties was comparable until 6%. However, starting from 8%, the sawdust always showed a better performance on the desired properties than the shredded tires powder.

At 10% waste addition, sawdust showed 27.5% reduction in density of the specimen in comparison with a reduction of 15.3% only in case of shredded tires. Regarding the specimen porosity, sawdust-samples showed a significant increase in the final porosity of the specimen.

Regarding the effect of additives on the thermal properties of the specimen, at 10% waste addition, the thermal conductivity value was decreased to 0.34 and 0.69 W/m·K in case of sawdust and shredded tires, respectively.

As a conclusion, it is recommended to add sawdust to the cement mortar by 10%. This will produce cement matrix lighter by about 27.5% with a higher porosity and a thermal conductivity lower by 72% if compared to traditional cement mix without any additives.

5. Conflicts of interest

"There are no conflicts to declare".

6. References

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