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Experimental investigation of insulated mortar for building envelope systems

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A B S T R A C T

This paper presents an experimental study to investigate some of the thermal and strength behaviors of a new mortar material which was prepared by adding some of the residues of agricultural Iraqi biomass materials such as wood sawdust, reed, corn cobs, and their blending. These biomass materials are available in plenty of amounts in Iraq / Karbala City. These materials are blended with sand and cement, which are raw materials for mortar preparation, in different percentages to produce new types of mortar. The major focal area of interest is to identify the likelihood of applying these products as external wall insulating material to minimize heat transfer from outside to a building. Thermal conductivity, water absorption and skeletal density, and compressive strength at 7 and 28 days of the new mortars was also determined in the work. Comparing the performances obtained it was found that the new mortar containing wood sawdust had the highest compressive strength values While the best improvement in heat insulation was recorded in the mortar containing corn cobs compared to the other types. The results presented here prove that this mortar can be recommended for building purposes, specifically for exterior wall cladding. It provides good thermal resistance and improves the fortification of building walls; it also affords an added benefit of being cheaper and therefore fashionable for construction related uses.

1. Introduction

The global power demand has been rising due to factors such as the growing population, better standards of living, important uses of electrical equipment that greatly improve people's quality of life (Mishra et al., 2012). This rising demand has led to an increase in environmental emission since fossil fuel forces such as; oil, natural gas, and coal, which form the basis of conventional power generation systems are gradually being depleted. Also, nuclear power generation using uranium and plutonium is another potential that can be utilized but it has own limitation because it is very costly, people can be exposed to radiation risks of the nuclear power plant and problems related with nuclear waste disposal are severe threats to living organisms and environment (Dutil & Rousse, 2012; Imran et al., 2020).

Several researches have looked at different other renewable energy sources that may be used to power societies such as solar energy, hydroelectric energy, wind energy, wave energy and bio-fuel energy among others as the word looks for ways to generate increased energy to fuel societies while ensuring the environment is not subject to pollution. Thus, the use of newly renewable energy sources is justified due to the fact that, in contradistinction from the generally employers of fossil and nuclear fuel, they make it possible to obtain an unlimited energy basis. However, its application is still confined to the developing countries mostly due to the higher costs of manufacturing renewable energy technologies (Steiner et al., 2017; Nazi et al., 2015; Gotz et al., 2016).

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The largest consumer of electrical energy is the residential sector because people spend most of their time inside residential buildings more so than in commercial or industrial premises (González-Torres et al., 2022). Consequently, there is a need to determine effective and efficient methods of lowering energy use in dwellings. These solutions should also take into account four of environmental sustainability, that is, avoiding pollution and encouraging environmentally sustainable initiatives (Santamouris & Vasilakopoulou, 2021).

Literature review of electrical energy measurement and control shows that conditioning systems in buildings consume more energy than other electrical appliances including lighting systems. Cooling in some climates, especially those areas that have a high mean annual temperature, can account for up to 60% of a building's electrical energy (Ozel, 2014; Sankar et al., 2010). This high demand is mostly due to thermal loads that are largely dependent on convection, conduction, and radiation through windows, walls, and ceiling respectively (Sahu & Prakash, 1979; Shen & Li, 2016).

In some buildings it has been found that cooling load attributable to the wall can be a substantial part of the overall cooling load, in some cases even higher than other heat loads (Paraschiv et al., 2020). The primary roles of thermal insulation in walls are energy efficiency for cooling and heating to reduce both the energy costs and emissions to the atmosphere (S. Paraschiv & Paraschiv, 2019; Ozel, 2011; Ozel, 2012). An ideal insulation involves the determination of the overall heat transfer coefficient and the heat flow density in the wall in question before and after the insulation (Zhang et al., 2019).

Modifying the physical and structural properties of walls greatly affects the energy consumption of buildings. Heat loss and gain are predominantly influenced by the thermal performance and thickness of the materials used in construction. The thermal mass of a wall is determined by the properties of its constituent materials, the characteristics of the layers comprising the wall assembly, and the placement of these layers within the wall structure (Paraschiv et al., 2020; Nazi et al., 2015).

A novel material was developed using a composite of cement, sand, and palm fibers, designed for application as an insulating building material. Experimental findings proved that through minimizing thermal conductivity, the composite can serve as constructive material without compromising other thermo-mechanical properties (Benmansour et al., 2014). Detailed evaluation suggested that microsphere glass types MGS 38 and MGS 15 have better applicability in thermal insulation when used as lightweight fillers in cementitious systems. In addition, MGS38 was found to have higher average compressive strength than MGS15 thus, in applications where thermal insulation as well as mechanical strength is desirable, MGS38 is more ideal (Hanif et al., 2017). Mechanical and thermal studies on the lightweight concrete using vermiculite gave lower thermal conductivity in comparison to EPS when testing the properties of lightweight concrete. The incorporation of an air-entraining agent further dropped the density of the lightweight concrete and improved its insulating characteristic; but this led to low mechanical strength (Schackow et al., 2014). Light weight concrete also shows that the modulus of elasticity and the thermal conductivity of LWC decreases with the reduction in density of concrete. Nonetheless, the core factors which define the compressive strength of these materials are the microstructure of the material especially when lightweight aggregates such as fly ash balls are used in the lightweight structural concrete (Zhou & Brooks, 2019).

New concrete known as oil palm husk foamed geopolymer concrete (OPSFGC) has been produced through the use of low calcium fly ash (FA) and palm oil fuel ash (POFA) as binder and oil palm husk (OPS) as lightweight aggregate (LWA). The concrete with densities at 1300 – 1500kg/m³ is identified as structural and insulating concrete or Class II while that with a density of 1700 kg/m³ is for structural concrete or Class I. The latter reveals a compressive strength of about 30 MPa and thermal conductivity of 0.58 W/m·K, therefore, can be used in structural applications with improved thermal characteristics (Liu et al., 2014).

This paper is based on the use of locally available insulating materials such as saw dust, reeds, corn waste among those that are available in Iraq (Alhwayzee et al., 2020). All these materials were used in mixing cement with sand in different proportions to arrive at unique mortar formulations. The resulting mortars are expected to be applied as construction sealants to diminish heat flows through the building walls and thereby minimize the energy needed for air conditioning of structures, and increase the overall efficiency of utilizing energy in buildings.

2. Materials and Methods

2.1 Portland Cement

The Portland cement that was used in this study was from Karbala Cement Manufacturing Ltd a subsidiary of Lafarge. Herein, a set of examinations in the laboratory was performed for determining its physical and chemical characteristics, which met the necessary requirements of Iraqi standards. Both the chemical and physical properties of cement samples are summarized from the presented **Table 1** and **Table 2**. The chemical analysis helps to determine the chemical characteristics and quality of the cement, whereas the physical tests check specific physical characteristics such as fineness, setting time, and compressive strength that allows making conclusions about its applicability to constructions.

Table 1. Chemical analysis of cement

Item	percentage by weight	Iraqi Specification limits No. 5 /1984
Calcium oxide (CaO)	63.9	-
Silicon dioxide (SiO_2)	21.02	-
Alumina (aluminum oxide) (Al_2O_3)	3.81	-
Iron oxide (Fe_2O_3)	4.65	-
Sulfur trioxide (SO_3)	2.09	2.8 % (Maximum limit)
Magnesium oxide (MgO)	1.00	5.0 % (Maximum limit)
Loss on ignition (L.O.I .)	1.99	4.0 % (Maximum limit)
Insoluble waste	0.85	1.5 % (Maximum limit)
Alkalis (Na2O+0.658K2O)	0.49	-
Lime Saturation Factor (LSF)	0.97	1.02- 0.66
Dicalcium silicate (C_2S)	54.1	Not specified
Tricalcium silicate (C_3S)	22.5	Not specified
Tricalcium aluminate (C_3A)	6.8	5% (Greater than)
Tetracalcium aluminoferrite (C_4AF)	9.5	Not specified

Table 2. Physical properties of cement

Feature	Test result	Iraqi Specification limits No. 5 /1984
Fineness (cm^2/g) Blaine Method	3513	2300 cm^2/g (Minimum limit)
Freezing time by Vicat method:		
1) Initial cohesion per hour	2.35	60 minutes (No less than)
2) Final cohesion per hour	4.30	600 minutes (No less than)
Compressive strength of cement mortar cubes (N/mm2) for ages:		
1) 3 days	20.14	15 (No less than)
2) 7 days	24.28	23 (No less than)
Autocleavage stability	0.18 %	0.8% (No more than)

Fine Sand

For the experimental study, selected washed sand collected from the quarries near Karbala, Iraq at the shores of Lake Razzaza was used. These are quarries located within the Euphrates formation at depths of between 2- 6 meters producing sand with an average grain size of 2-5mm. Nonetheless, the sand found in the region is mainly low in such materials as clay and salts; it has yellow and red tint due to presence of iron oxides. Some of the chemical compositions detected in the sand include occasional gypsum lenses and fine gravel; nevertheless, it has been widely employed in the preparation of the mixtures for industries. These quarries have been exploited since the time the associated manufacturing facilities were put up in 1980.

Water

Water used throughout the washing, mixing and treatment processes was new potable water. Clean water was used to ensure that the mixture was of high quality, and no water interfered with the hydration reaction of the materials.

Insulated Material

Sawdust Particles

The sawdust used in this investigation was locally produced by carpentry workshops of which the particles have been screened through a 5mm mesh size. Thus, ensuring its suitability, the sawdust was thoroughly cleaned to exclude excessive tree bark as high organics affect the hydration reactions and the performance of the material. Also, the sawdust was chemically treated with pesticides sphenic in order to have possible negative impacts on concrete cohesion and cement hydration. This treatment was intended to serve as a contribution to providing a new method of enhancing the integrity of the concrete and the use of sawdust additive to the mixture.

Corn Cobs Particles

Maize cobs of yellow colour particles were used in this study and they came from farms in the Karbala desert. The local corn cobs were harvested, dried, sliced and then milled using a particle mill with particle sizes ranging from 5mm. Adverse effects of addition of corn cob on concrete cohesion and cement hydration in extreme cases were avoided by chemically treating the corn cob particles with pesticides such as sphenic. It proved important for managing the workability for sweeping the concrete and adding corn cobs as a green material in the mix.

Reed Stalks Particles

Reeds have been of great importance to inhabitants of ancient Iraq in general and the Sumerians more specifically because, together with clay, they were the available raw materials in southern Mesopotamia. Being easily accessible and possessing satisfactory mechanical characteristics, reeds were often applied in building the residential houses: they helped to strengthen the walls of houses and provide insulation in the climate of the hot region. For this study, the local dry reed stem particles were sourced through cutting and grinding with a particle mill and a 5mm mesh sieve. In order not to negatively affect the cohesiveness of concrete or enhance the rate of cement hydration, the reed particles used in this study were first coated with pesticides such as sphenol, to make the reed particles fit for use in construction materials.

Blend Particles

They used sawdust, chemically treated reed stalk particles and corn cob in a ratio of 1: 1: 1 but all the materials were reduced to 5mm particle size. Previously, each component was treated in order to improve compatibility to cement matrix and avoid negative impact on concrete cohesiveness and hydration. This formulation was designed to investigate the combined effects of these sustainable materials as additives in the composite mixture.

Fig. 1 illustrates the morphology of the individual particles, including sawdust particles, corn cob particles, reed stalk particles, and the blended particles.

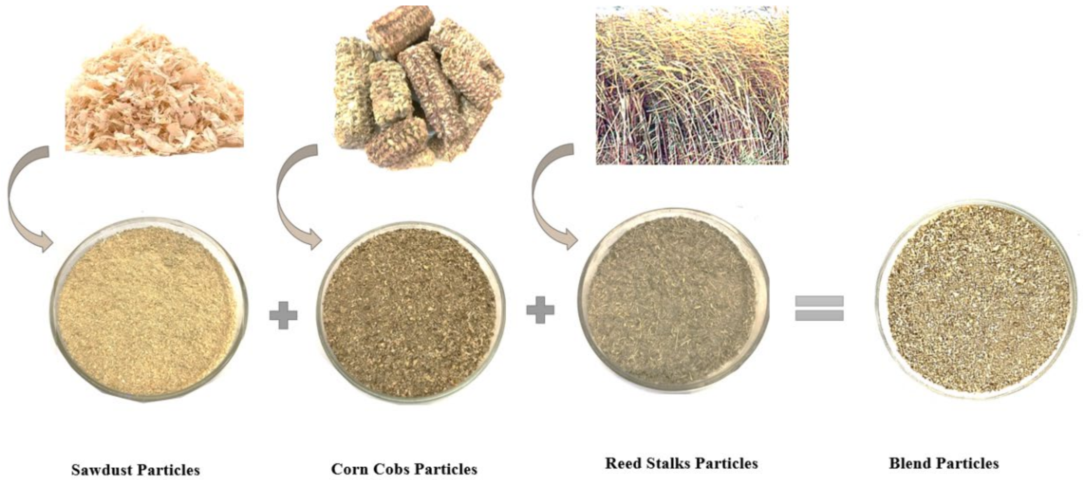

Fig. 1. Sawdust Particles, Corn Cobs Particles, Reed Stalks Particles, and Blend Particles.

Mixture Proportions

Several concrete mix ratios were designed to meet the specific objectives of the experimental framework, with the selection criteria focused on evaluating diverse performance parameters. Each mix was tailored to investigate critical factors, including insulation-material type, insulation-material ratio, sand ratio, water-to-cement ratio, density, and compressive strength. Following initial testing, the results of these preliminary mixtures facilitated the identification of an optimized set of mixes for in-depth analysis of the specified variables.

The cement-to-sand ratio in the mixtures was maintained at 6:1 by volume. Additionally, the impact of varying the type of insulation material was investigated. Insulation materials, characterized by their lightweight properties, were incorporated across all cement-to-sand ratios, with varying content levels to assess their influence on the overall performance of the mixtures.

The properties of the various mixtures were systematically compared to identify the optimal formulations for the research objectives, ensuring that the desired characteristics were achieved. Compressive strength tests were conducted using cubic molds with dimensions of 100×100×100 mm^3 at different curing ages. Additionally, wet and dry densities were measured for the samples. For thermal conductivity assessments, threshold molds measuring 50×100×200 mm^3 were employed, in accordance with the specifications required by the thermal conductivity testing apparatus. For each mixture sample, five cubic specimens were tested, and the average of the results was calculated to ensure accuracy and consistency in the data.

Fig. 2. The blend of individual particles for mortar under the microscope, including Insulated Material, Portland Cement, Fine Sand, and Water.

Fig. 2 presents the microscopic view of the blended mortar components, comprising insulating materials, Portland cement, fine sand, and water. The Figure highlights the distribution, particle morphology, and interaction between these constituents, which collectively influence the mortar's mechanical strength, thermal conductivity, and overall performance.

Concrete mixing and modeling method

Following the preparation of materials in their designated volumetric proportions, the essential components—cement, sand, water, insulating materials, and additives—were carefully measured and accurately prepared. The dry ingredients were thoroughly mixed prior to the gradual incorporation of water and additives, ensuring uniform hydration and a homogeneous mixture. A conventional mixing method was employed, selected for its practicality and effectiveness in achieving the desired concrete properties, particularly in terms of density and thermal conductivity. The mixing and pouring of the concrete were conducted in accordance with American standard procedures (ASTM C-192 - 02), utilizing manual mixing and adhering to specified guidelines to ensure material consistency and structural durability.

Once a cohesive and workable concrete mixture with controlled flow properties was achieved, the concrete was poured into the pre-prepared iron molds. To make the concrete molds easier to demold, the inner surfaces of the molds were greased and the concrete was cast in lifts corresponding to the thickness of the molds. Vibrating table was used in compacting and the time taken to compact depends on the mixing ratio and size of the mold. While pouring the concrete, and after compaction, the surface was smoothed using a metal trowel to afford the flat surface that was necessary. Last, the molds were tagged to know which products went to which department or customer, and then the curing process was set.

Fig. 3. The sequential process of concrete preparation including (pouring, specimen modeling, numbering, curing, and final result).

Fig. 3 shows the flow chart for concrete pouring, specimen modeling and numbering, curing of specimens and final result evaluation. Such systematic procedures make the experimentation more accurate and standardized in manner to provide correct stats of the mechanical and thermal characteristics of the tested concrete samples.

3. Testing methodology

3.1 Thermal conductivity test

In this study, the thermal conductivity of rectangular concrete slab specimens of 50 × 100 × 200 mm^3 was measured after 28 days of curing. This thermal conductivity assessment was done to reveal the efficiency of this material at transferring heat as a way of identifying how it is likely to perform under thermally critical operations.

The panels were oven-dried to a constant temperature of 105 ± 5°C for a period of 24 hours to remove any moisture content. Following this, thermal conductivity measurements were conducted using a thermal conductivity tester from a specified manufacturer (PA Hilton- Thermal Conductivity of Building Material Unit H112N). This device is an available asset of the laboratory devices for the College of Engineering - Department of Mechanical Engineering - University of Karbala.

This device facilitates the measurement of thermal conductivity in a variety of building materials, including both solid and granular types. The H112N operates using a relative method in accordance with ISO 8301 standards for thermal conductivity measurement. It is equipped with a PID-controlled electric flat heater and a water-cooled flat plate, featuring an integrated, highly sensitive heat flow meter. The test specimen is placed between the heated and cooled plates within a thermally insulated chamber to minimize heat losses. Specially calibrated thermometers are positioned to record intermediate temperatures on either side of the specimen, allowing for precise determination of the temperature gradient across the material and, consequently, its thermal conductivity.

This method provides a reliable framework for evaluating heat conduction through the material under steady-state conditions.

3.2 Compressive strength test

The compressive strength was assessed using a testing device of type (ADR Touch SOLO 1500 Compression Machine with Digital Readout) with a capacity of (1560 kN/350 000 lbf), in accordance with the Standard specification (Calibration accuracy to BS EN ISO 7500-1; ASTME4), as shown in **Fig. 4**. This device is an available asset of the laboratory devices for the College of Engineering - Department of Civil Engineering - University of Karbala. Samples aged 7 and 28 days were subjected to compressive strength tests. The cubic specimens were positioned within the testing apparatus with one side face placed perpendicular to the casting direction. A gradually increasing load was applied until failure occurred, and the applied load was recorded. The device measured the compressive strength by dividing the recorded load by the area of the loaded face, which had dimensions of 100 × 100 mm.

Fig. 4. Compressive strength tester (ADR Touch SOLO 1500 Compression Machine with Digital Readout)

3.3 Density measurement

The density of concrete mixtures in both wet and air-dry states was determined by measuring the dimensions of the test samples using a Vernier caliper and an electronic balance with an accuracy of ±0.10 g. Cube specimens with dimensions of 100 × 100 × 100 mm were employed to calculate the total wet and air-dry densities. Sample preparation and storage were conducted in accordance with the requirements outlined in (ASTM C-567). For each mixture examined in this research, five samples were tested to ensure reliable results.

4. Results And Discussion

The primary objective of this research is to develop a heat-insulating mortar that minimizes heat transfer while providing an aesthetic finish for buildings. This is achieved by incorporating locally available insulating materials in Iraq, such as reeds, corn, and sawdust with mortar. The main aspects of the experimental program included measurement of the compressive strength of the mortar and identification of the – Wet and Dry densities after (7 and 28) days. Furthermore, the thermal conductivity of all mortar models have also been determined. The results obtained were further compared to arrive at the right blend to enhance thermal conductivity; mechanical properties; and density of the resulting mixture.

4.1 Mechanical Properties

4.1.1 Compressive Strength

Fig. 5 and **Fig. 6** present the results of the compressive strength tests conducted at 7 and 28 days for the specified mortar models. It is well-established that the compressive strength of concrete and mortar specimens at 28 days is significantly higher than the values observed at 7 days. This increase is attributed to the continued hydration of cement over time, leading to the progressive development of the material's microstructure and improved mechanical properties. The data indicate a gradual reduction in compressive strength as the proportion of insulating materials increases across the different mortar compositions. Among the tested materials, corn cobs resulted in the lowest compressive strength, while sawdust achieved the highest compressive strength within the tested range of insulating material proportions.

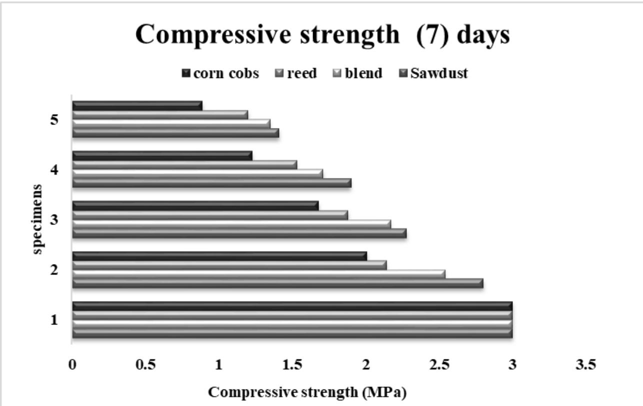

Fig. 5. Compressive strength tests (MPa) conducted at 7 days for corn cobs, reed, sawdust, and blend materials.

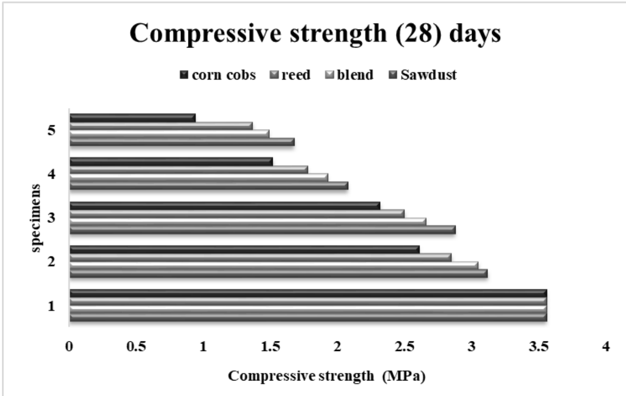

Fig. 6. Compressive strength tests (MPa) conducted at 28 days for corn cobs, reed, sawdust, and blend materials

The incorporation of insulating materials, along with the gradual increase in their proportions, results in a reduction in compressive strength, albeit within the permissible limits for this mortar. Notably, the fifth group exhibited the lowest compressive strength, attributed to the absence of fine sand particles in the mortar composition. It is important to highlight that compressive strength is influenced by various factors, including mixing proportions, aggregate and gradation, cement type, and compaction method. These factors collectively contribute to the observed variations in compressive resistance.

4.1.2 Density

Wet density and dry density are two major factors normally measured in other construction materials like concrete or mortar which give useful information about the constituent and behavior of the material. Wet density reflects the density of the material which incorporated the mass of water trapped inside pores. It is always higher than dry density because dry density has the water content that was not evaporated. On one hand, there exists what is termed dry density that gives the state of the material after all the water has been evaporated and what remains is the real density of the material, by this it means the solid components of the material that includes the aggregates and cement. These measurements are important in evaluating the performance of materials, since density relates to strength, porosity, and heat capacity. Moreover, the ratio between the two densities adds useful information of the ability of the material to retain water and the level of porosity.

From the wet and dry densities of the samples, it was deduced that wet densities of samples bore higher values relative to the specimens because of water retained in the specimens which did not evaporate as noted in **Fig. 7** and **Fig. 8**. Moreover, when all the augmenting components in the make-up of the mixtures are left to be in a solid or dry state, then the new mortar with saw dust had the highest density. This result suggests that wood chips have a higher intrinsic density as compared to the other insulating materials that may be used in the mixtures.

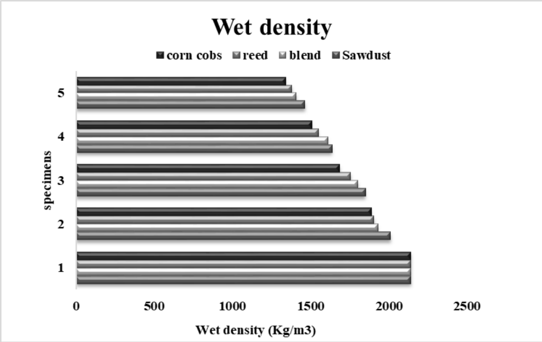

Fig. 7. Wet density (kg/m^3) for corn cobs, reed, sawdust, and blend materials.

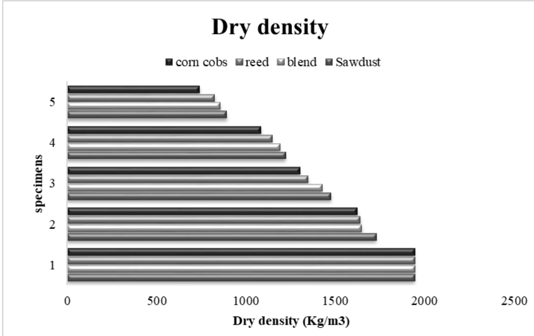

Fig. 8. Dry density (kg/m^3) for corn cobs, reed, sawdust, and blend materials.

4.2 Thermal Properties

The main conclusions, derived from this work, concern the influence of the thermal conductivity coefficient on the density of the concrete models. The investigation also reveals that thermal conductivity coefficient increases with density. This behavior is attributed to the reduced presence of insulating materials within the concrete matrix, which facilitates the propagation of heat waves through the mass. The insulating materials embedded within the aggregate act as barriers to heat transfer. However, as these materials are replaced by the primary components of the mortar, such as sand or cement, the overall thermal conductivity of the material increases. This underscores the critical role of insulating materials in impeding heat transfer within concrete structures.

The results indicate that the mortar containing corn cobs exhibits the most effective heat insulation properties when compared to the other materials tested, making it the optimal choice for heat-insulating mortar. **Fig. 9** illustrates the results of thermal conductivity tests conducted on selected mortar samples. The data show a consistent decrease in thermal conductivity as the proportion of insulating materials in the mortar compositions increases. On the other hand, the mortar with sawdust exhibited the highest thermal conductivity within the examined range of insulating material ratios.

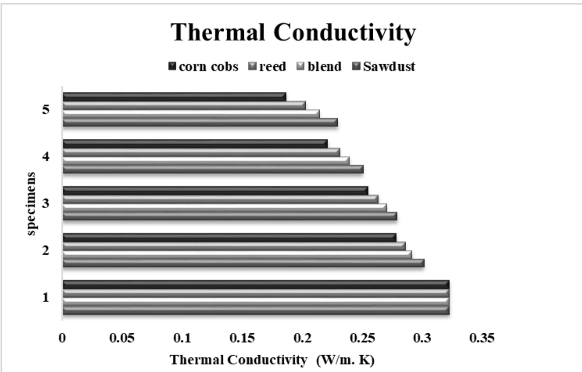

Fig. 9. Thermal conductivity test (W/m.K) for corn cobs, reed, sawdust, and blend materials

These results indicate that the developed mortar is highly suitable for building applications, particularly as an exterior wall covering. It provides excellent thermal insulation, enhances the structural protection of building walls, and is cost-effective, presenting a practical and economical solution for modern construction needs. This also greatly reduces the amount of heat transfer through the thickness of the walls, so that air conditioning systems need not run constantly, thus resulting in a reduction in electrical energy use.

5. Conclusion

The inaugural work of this research is an experimental study examining thermal and mechanical characteristics of a new mortar material which was prepared using Iraqi agricultural bio-materials like sawdust, reeds, and corn cobs. These bio-materials, readily available in Karbala- Iraq were blended at different ratios with sand and cement to formulate different types of mortars. The goal of this study was thus to compare the viability of these materials for use in providing a degree of insulation to external building walls to minimize heat flow from the exterior environment. Compressive strength at 7 and 28 days, thermal conductivity, and both the wet and dry densities of the developed mortars were measured experimentally.

From the average of the compressive strength on the mortar samples for 7 and 28 days the highest compressive strength was attained by mortar with saw dust however for the thermal insulation property the mortar prepared with corn cob achieved the best result as compared to the other mortar mixtures. These results provide clues to improvement of application of available agricultural wastes in improving the thermal properties of building materials.

The experimental results of wet and dry approach densities indicated that the mortar including sawdust reached the highest density in the dry state as compared with other mixtures, which means that the sawdust has the greater intrinsic density than other insulation materials used in the compositions.

With regards to thermal insulation the results indicate that the mortar incorporating corn cobs provided the best heat insulation compared to the other materials and thus recommended for heat insulating mortar. In addition, analysis on the results indicated that the thermal conductivity was decreasing as the percentage of insulating materials in the mortar mixtures were also enhanced. Conversely, the mortar containing sawdust exhibited the highest thermal conductivity within the evaluated range of insulating material ratios.

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