Effects of Incorporating Plant and Industrial Waste on the Thermo Physical Characteristics of Fired Earth Bricks

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Abstract
This research aims to contribute to the utilization of local building materials and waste recycling. It focuses on enhancing the thermal properties of fired earth bricks while maintaining their physical characteristics within the recommended range. The study involves incorporating various types of waste powders and granules at a consistent ratio of 10% by weight of the soil matrix, composed primarily of clay and dune sand. The objective is to assess the effectiveness of these additions and compare the results obtained. Additionally, the study explores the potential utilization of the voids created by these additions after the burning process of the samples. The waste materials utilized include synthetic rubber granules, synthetic rubber powder, date palm wood powder, alfa plant powder, glass powder, and polystyrene granules. The research findings indicate that the voids created by burning the different waste additions within the soil matrix significantly contribute to improving the thermal insulation properties of the tested samples. Among the various waste materials, the powders derived from plant wastes exhibited the best performance. The addition of 10% palm wood powder and alfa plant powder resulted in a reduction in thermal conductivity by 19.68% and 28.24% respectively, with corresponding thermal conductivity values of 0.31 W/m.K and 0.277 W/m.K. However, these waste materials had varying negative effects on the physical properties of the bricks. Overall, this study suggests that incorporating different types of waste materials into earth bricks, specifically fired bricks, could lead to the production of environmentally friendly building materials. These materials hold promise for the field of construction engineering.
Keywords: fired brick; thermal insulation; physical properties; waste; recycling

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1.Introduction

When constructing buildings, the use of heat-insulating construction materials is crucial. These materials significantly contribute to ensuring thermal comfort for occupants and reducing excessive energy consumption. Heat-insulating building materials play a crucial role in the summertime by minimizing the entry of excessive external heat, thus enhancing the indoor temperature. In the wintertime, they help prevent heat loss, improving indoor air quality and creating a harmonious and comfortable environment for residents.

The utilization of heat-insulating building materials yields a multitude of significant advantages. First and foremost, it leads to substantial energy cost savings. By maintaining an optimal temperature within the building, the excessive use of heating and cooling appliances is minimized, resulting in significant reductions in utility bills. In addition, employing heat-insulating building materials aids in environmental preservation by promoting efficient use of natural resources and mitigating carbon emissions that contaminate the air and contribute to climate change. By reducing energy consumption, these materials play a vital role in utilizing resources more effectively and minimizing the negative environmental impact associated with excessive energy use.

From this perspective, numerous research studies focus on enhancing the thermal insulation of building walls and roofs. Walls contribute to around 25% of heat transfer between the interior and exterior of buildings, while roofs account for approximately 30% of this heat exchange[1],[2].

Moreover, these studies also aim to identify and select environmentally friendly alternative building materials, including vital composites that are based on raw soil. Raw soil is preferred due to its favorable thermal insulation properties and low cost.

Earth bricks are known for their excellent thermal efficiency. This efficiency is derived from the significant thermal inertia of the raw soil, which is a result of two key factors: the fine network of nanopores and the large specific surface area of the clay component. The nanopores enable the material to effectively adsorb and release moisture, while the clay's extensive specific surface area enhances its capacity to store and release latent heat. These processes contribute to the thermal insulation properties of earth bricks, allowing them to regulate temperature and provide effective heat management [3] .

However, despite its reasonable thermal efficiency, particularly when compared to cement blocks, earth bricks alone may not provide sufficient insulation to meet the desired standards for thermal insulation in buildings. Additional measures and materials may be required to achieve the desired level of thermal insulation and enhance energy efficiency in construction projects.

Numerous research studies have been conducted to enhance the thermal performance of earth bricks by focusing on improving their porous structure. The idea revolves around reducing thermal conductivity by incorporating lightweight and combustible elements within the soil matrix. Additionally, the introduction of certain chemical elements can induce porosity within the brick structure through their interactions.

Research conducted by Velasco, P.M. et al. [4] categorizes these additions into four main groups: ash, sewage sludge, organic waste, and inorganic waste.

Researchers introduced multiple waste and additives with the aim of enhancing the thermal performance of earth brick. In brief, some of the additives included were: the sawdust and natural pozzolana by researcher P. Meukam et al. [5] ; flax fibres, corn starch and polystyrene granules by researcher Faycal El Fgaier [6] ;waste paper by researcher Emmanuel Ouedraogo et al. [7] ; date palm fiber by researchers Chaib, Mekharmech and Hakkoum et al. [8], [9],[10] ; sawdust and Walnut peel powder by researcher Tatane Mohamed et al. [11] ; glass powder by researcher Yuecheng Xin et al. [12] ; walnut peel powder by researcher Aboubakr El Hammouti et al. [13] . Also we can mention the waste: rice husk ash [14];Sewage treatment sludge [15];tea processing waste [16]; marble waste powder [17];olive pomace [18];oily waste [19] and earthen brick waste [20].

Building upon the existing body of research and publications, our work focuses on enhancing the thermal efficiency of raw soils, specifically dune sand and clay, which are readily available in the study area. We aim to utilize these abundant resources to create heat-insulating earth bricks by developing their porous structure. This involves incorporating various types of waste materials into the bricks to enhance their insulation capabilities while ensuring that their physical properties align with recommended standards. Through this approach, we aim to contribute to the development of sustainable and energy-efficient construction materials while utilizing locally available resources.

To achieve our objective, we incorporated five types of waste materials into the clay and sand mixture to enhance the porous structure of the fired brick. This approach aimed to increase the amount of trapped air within the bricks, thereby improving their thermal insulation properties. Additionally, we added lime as a chemical stabilizer in the minimum recommended percentage of 6%. The purpose of lime was to enhance the cohesion between the different components of the mixture and minimize the risk of fissures during the drying process. Lime also played a role in accelerating the melting process during firing and increasing the overall porosity of the final product. Lime was chosen as a stabilizer due to its suitability for cohesive soils, making it an appropriate choice for our study [21],[22],[23].

We used synthetic rubber granules and powders ,we also used date palm wood powder, alfa plant powder, glass powder and polystyrene granules.

The completed samples consisted of solid earth bricks that were compressed using a manual compressor, which was further supported by a hydraulic compressor capable of exerting pressure forces up to 1.2 MPa. These samples were then air-dried for a duration of 30 days. Subsequently, the bricks were fired in an oven at a temperature of 850 °C, utilizing the facilities of a brick factory (STB) located in the state of Touggourt.

To achieve the desired results and observe noticeable differences in the performance of the final products, the waste materials were added in a proportion of 10% of the weight of the soil matrix, comprising clay and sand. This specific ratio was chosen to facilitate the detection of variations in the performance of the bricks, as it can be challenging to observe significant differences when adding smaller proportions of these waste materials.

In our study, we incorporated dune sand at a specific percentage of 25% in the mixture. This percentage was determined based on previous researchs conducted by Chaib, Mekharmech and Hakkoum et al. [8],[9] ,[10] which indicated that a 25% inclusion of dune sand is suitable for achieving desirable thermal and physical performance in the resulting bricks. The addition of sand in the mixture serves multiple purposes in the context of earth brick production. Firstly, sand acts as an inert component that reduces the plasticity of the mixture, making it easier to mix and mold. This is particularly beneficial for the manufacturing process. Additionally, sand acts as a degreasing agent, helping to remove excess moisture during the drying process. Moreover, the presence of sand aids in minimizing shrinkage during both the drying and burning processes. By reducing the shrinkage rate, sand helps to maintain the shape and structural integrity of the bricks, ensuring they retain their desired dimensions[22] .

This work seeks to truly evaluation of the effect of waste additives on the thermal and physical properties of manufactured fired earth bricks. The work also aims to compare the behavior of various waste additives. The samples were subjected to experiments bulk density, longitudinal shrinkage ,thermal conductivity ,specific heat ,thermal diffusivity , total water absorption and capillary water absorption.

This work aims to discover construction products that offer environmental solutions by reducing energy consumption and environmental impacts (The emissions). These products can also have an economic impact by investing in the field of cheap building materials and dispensing with expensive industrial materials.

2.Materials and experiments

2.1. Material

2.1.1. Clay

Fig.1. Clay powder used making samples

The used clay is a clay extracted from one of the quarries from Balidat Ameur, Touggourt state, Algeria.(Fig.1)
The bulk and absolute density were evaluated by the standards NF P 94-053; NF P 94- 054 [24]
The granular structure of this soil was evaluated using the granular analysis and sedimentary analysis experiments based on the standards NFP94-056; NFP94-057[24] .
This soil was also subjected to Atterberg limits experiments in order to determine the liquidity limit, the plasticity limit and the plasticity index in order to know the type of soil based on the standards NFP94-051, NFP94-052[24] .

2.1.2.Dune sand

Fig.2. Used dune sand to making samples

The used sand is dune sand extracted from El Oued state desert , Algeria (Fig.2).
The bulk and absolute density were evaluated by the standards NF P 94-053; NF P 94 – 054 [24] .
The granular structure of this soil was evaluated using a granular analysis experiment, based on the standards NFP94-056 [24].
The fineness modulus was evaluated based on the standards NFP18-304[24].
The sand equivalent was evaluated based on the standards NFP18-598[24].
The total water absorption was evaluated based on the standards NF P18-554 [24].

2.1.3. Lime

Fig.3. Used slaked lime to making samples

The used lime is slaked lime $Ca(OH)_2$ (Fig.3). The data sheet of the chemical and physical properties of lime was taken by the importing company.

2.1.4.Waste additives

We used five types of waste in two forms, powders and granules,where we used the following waste

2.1.4.1. Granules and powder of synthetic rubber

Obtained through tire recycling in one of the recycling workshops have been combined in two forms, granules and powder (Fig.4) .

Fig.4. Synthetic rubber granules and powder

2.1.4.2.Date palm wood powder

The dry head of the tree branches, which is typically removed during the cleaning process of date palms, was utilized. This source of palm wood is readily available in the region. The dry head of the tree was crushed using an electric millstone to obtain the desired palm wood powder (Fig.5) .

Fig.5. Date palm tree and date palm wood powder

2.1.4.3.Alfa plant powder

Alfa plant[25] which is found in abundance in the desert of the region, the alfa fibers were crushed by an electric millstone (Fig.6).

Fig.6. Alfa plant and alfa plant powder

2.1.4.4.Glass powder

obtained from the waste of transparent glass household utensils after crushing. The glass elements were crushed after small fragments were broken by an electric millstone (Fig.7) .

Fig.7. Glass waste and glass powder

2.1.4.5.Polystyrene granules

obtained from the protective plates attached to many household electrical appliances. We used electric millstone that for this purpose (Fig.8) .

Fig.8. Polystyrene waste and polystyrene granules

The bulk and absolute density of these wastes was evaluated by the standards NF P 94-053; NF P 94-054[24].

The total water absorption was determined based on the standards NF P18-554 [24].

The granular structure of these wastes was evaluated using a granular analysis experiment based on the standards NFP94-056[24].

2.1.5. Mix proportions

The samples of fired earth solid brick were prepared to be made with scales 22*10.5*6 cm^3 which were based on the standards EN 771-1 and NF P13-305 [24] .A mixture was prepared to produce four models of witness samples and seven models of samples containing various wastes. The table 1 shows the components and their ratios to the soil matrix weight, except for the percentage of polystyrene which was added accordingly to the ratio of the total volume. The percentage of polystyrene was evaluated by the size corresponding to the average volume of the added other fibers to the total volume of the sample, which was about 30% of the volume of the manufactured brick.

With the exception of only one sample, we added 3% of glass powder, in addition to the 10% of palm wood powder, in order to investigate the extent to which the two powders complement each other to get better results than if they were alone. This form was added after a preliminary reading of the results of previous samples.

Table1:Percentages of sample composition

sample	Clay (%)	Sand(%)	Lime(%)	Additive waste (%)
Witness1 not burned	100	0	0	0
Witness2 not burned	75	25	0	0
Witness3	75	25	0	0
Witness4	75	25	6	0
Rubber aggregate	75	25	6	10
Rubber powder	75	25	6	10
Alfa powder	75	25	6	10
Date palm wood powder	75	25	6	10
Glass powder	75	25	6	10
Polystyrene aggregate	75	25	6	w=7grame (30% by total volume)
Glass powder+ DPW powder	75	25	6	3% Glass powder +10% DPWP

2.1.6. Sample preparation

During the initial stage of the process, the clay was crushed using an electric millstone to ensure a uniform consistency when combined with the other ingredients. The additional wastes were soaked in water for 24 hours to reach the saturation level. Next, a preliminary mixture comprising crushed clay, sand, and lime was prepared. The dry components were manually mixed until a homogeneous blend was achieved. Following this, the saturated fibers were added to the mixture, and water was introduced in a ratio equal to the average sum of the plasticity and liquidity limit (LL+ PL)/2 [23]. The mixture was thoroughly mixed until reaching its homogeneous form. The mixture was placed in the piston mold, then the sample was pressed by a hydraulic manual piston, which applies a stacking force of up to a maximum of 1.2Mpa (Fig.9) . After extracting the samples, they were left to dry naturally in a shaded area away from direct sunlight for a period of 30 days. This duration was necessary to allow for the completion of the lime reaction process [21]. Once the drying phase was completed, the samples were transported to the brick factory (STB) located in Touggourt state for the subsequent burning process. In the brick factory, the samples were subjected to the burning process using a tunnel oven. The oven was operated at temperatures reaching up to 850 °C (Fig.10). To conduct comprehensive experiments and ensure accuracy in the results, a total of forty-four (44) earth brick samples were prepared, divided into eleven (11) different models. For each model, four samples were completed, resulting in a total of four samples per model. This approach allowed for the calculation of the arithmetic mean of the results obtained for each model, enhancing the accuracy and reliability of the experimental data.

Fig.9. Pressure device used to perform samples.

Fig.10. Burning samples in a tunnel furnace

2.2. Experimental procedures

2.2.1 Shrinkage measurement experiment

In this experiment, we calculated the percentages of longitudinal shrinkage of fired brick samples after the burning process that is, after reaching its final shape and dimensions. This measurement process is carried out according to the standards NF P15-433 (1994) and ASTM C326-09 (2014) . [24],[26].

2.2.2 Thermal conductivity and specific heat determination experiment

The CTmétre device was used to determine the thermal conductivity and specific heat of the manufactured fired brick blocks. This device was developed by CSTB (Grenoble). It is based on the transient state method via hot wire technology (fig 11) .The standards adopted in this experiment are NF EN 993-15 and ISO 8894-1 [24].

The device used in the experiment operates based on a simple principle. It involves placing a probe inside two identical samples of the material for which the thermal conductivity is to be measured. The probe consists of a wire with a known thermal resistance that emits a specific amount of heat, denoted as Q, into the samples. Additionally, the probe includes a heat collector that measures the temperature changes occurring in the samples over a specific period of time. Through this process, the device provides a quantitative measurement of the thermal conductivity, which is a crucial parameter for assessing the insulation properties of the material. (fig11) [27].

Fig.11. The CT meter and its probe

2.2.3 Thermal Diffusivity

of the samples was then deduced by the relation **$D=\lambda/(SH*\rho)$** . SH is the specific heat of the sample , ρ the bulk density of the sample and λ is the thermal conductivity, the unit of diffusivity is m^2 / s [28].

2.2.4 Total water absorption experiment

The water absorption coefficient plays a vital role in determining the quality and durability of fire brick blocks. This coefficient quantifies the amount of water that the bricks can absorb when exposed to moisture. A high water absorption coefficient can have adverse effects on the durability of the bricks. When water is absorbed, it can cause expansion and contraction during freeze-thaw cycles, leading to cracking, spalling, or deterioration of the bricks over time. This can compromise their structural integrity and reduce their lifespan. Moreover, the water absorption coefficient also impacts the thermal properties of the fire brick blocks. If the coefficient is large and the bricks absorb significant amounts of water, it can impair their ability to provide effective thermal insulation. Water has higher thermal conductivity compared to the brick material itself, which means it can conduct heat more readily. As a result, the thermal insulation properties of the bricks may be compromised when they come into contact with water. Therefore, maintaining a low water absorption coefficient is essential to ensure the durability and thermal insulation capabilities of fire brick blocks. The total absorption experiment was adopted based on the standards NF P 18-555 and BS3921[24],[29] (fig 12) .This experiment is to determine the water content of a sample of bricks after immersion in water for 24 hours at a moderate temperature, where **$TWA=((Wh-Ws)*100)/Ws$**

Wh: the weight of the brick is wet after immersion

Ws: the weight of the brick is dry before immersion

TWA: total water absorption coefficient(%)

2.2.5 Capillary water absorption experiment

This experiment was carried out based on the standards NF XP P 13-305 [24]. (fig 12) The aim of this experiment is to determine the ability of fired brick blocks to absorb water through the capillary property by drawing water into the sample, where the samples are dried up to 65 °C. Then we weighed it. Then it immersed in water through a very thin layer with a thickness of 5 mm for ten minutes. Then the wet sample is weighed. The coefficient of water absorption through the capillary property is given by the relation: **CWA=((W1-W0).100)/(S .√t)**

W1, W0: the mass of water before and after immersion (gram)

CWA: water capillary absorption coefficient (g / cm^2.min $^{1/2}$)

S: surface area submerged in water (cm^2)

t: immersion time per minute (ten minutes)

Fig.12. Total and capillary water absorption test

3.Results and discussion

3.1. Material properties

3.1.1.Physical properties of Clay

The Table .3 and figure 13 shows that the used clay consists of 2% sand, 20% fine sand, 42% silt and 36% clay of its weight. We also note that the granulate gradient curve of this soil consist within the recommended range in the achievement of fired earth brick.

According to the results of the Atterberg Limits experiments, it shows that the soil has a liquidity limit of about 67.75%, a plasticity limit of 23.98% and a plasticity index of 43.77%. Depending on the Casagrande curve, the soil is a very plastic clay. The used clay has a bulk density of 1258 kg / m3 and an absolute density of 2828.57 kg/m3.(Table.2)

Table.2. Physical properties of clay

Property	Apparent density	Absolute density	Liquidity limit	Limit plasticity	Plasticity index	Type of soil
Value	1258 kg/m³	2828.57 kg/m³	%67.75	23.98%	43.77%	Very plastic clays

Table.3 The Granular and sedimentary analysis of clay

Particle size (mm)	2≥D≥0.2	0.2≥D≥0.02	0.02≥D≥0.002	0.002≥D
Percentage (%)	2	20	42	36

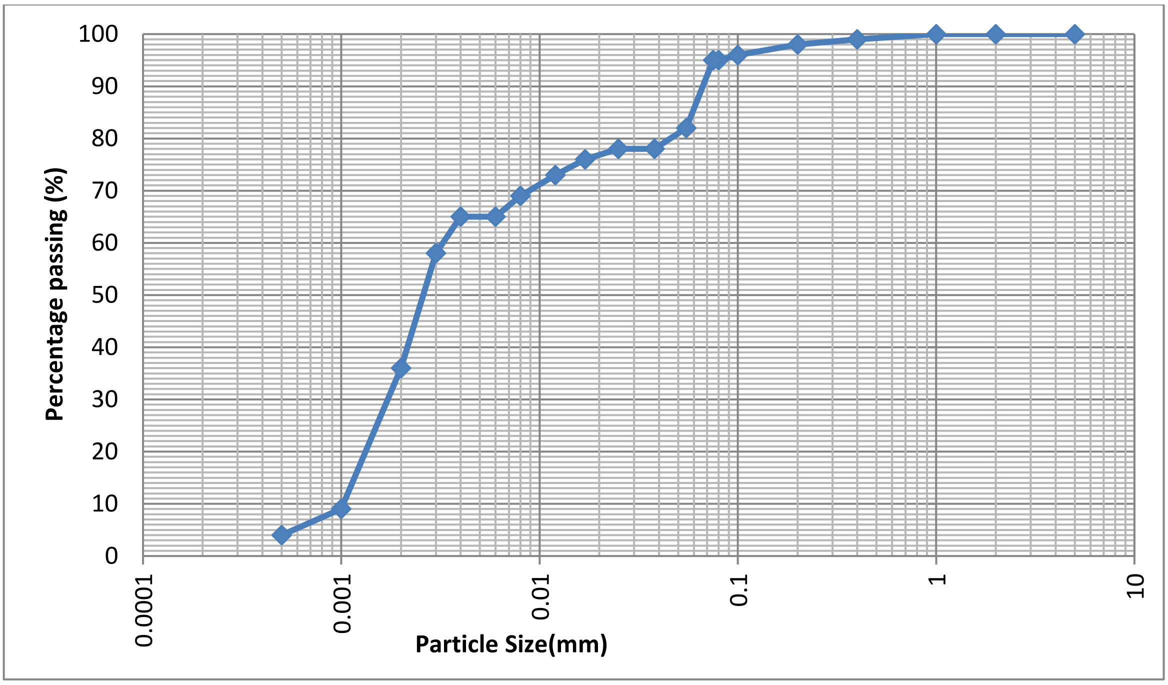

Fig.13. Curve of the granular and sedimentary analysis of clay

3.1.2.Physical properties of dune sand

The Table .5 and figure14 shows that the used sand consists mainly of approximately 92% fine sand and 8% medium sand of its weight. It has an apparent density of 1732 kg / m³ and an absolute density of 2511.09 kg / m³ . The obtained results from the sand equivalent experiment show that this sand has an equivalent of Es=95.12%, which means that it is a very clean sand. As it shows through the fineness modulus MF=0.95 which means that this sand is very fine and has a narrow grain gradient and has a weak water absorption of 0. 91% (Table.4).

Table.4. Physical properties of dune sand

Property	Apparent density	Absolute density	Sand equivalent	Fineness module Type of sand	Water absorption rate
Value	1732 kg/m^3	2511.09 kg/m^3	95.12% very clean sand	0.95 The sand is very fine and has a narrow grain gradient	0.91%

Table.5 .The Granular analysis of dune sand

Particle size (mm)	0.8≥D≥0.4	0.4≥D≥0.2	0.2≥D≥0.1	0.1≥D≥0.08	0.08≥ D
Percentage (%)	8.06	79.5	11.93	0.51	00

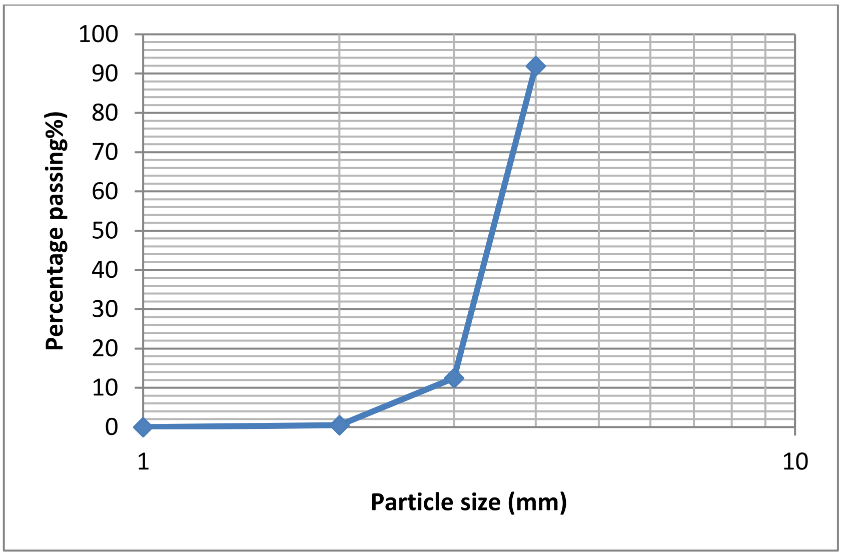

Fig.14. Curve the granular analysis of dune sand

3.1.3.Physical and chemical properties of lime

The used lime is slaked lime and its data sheet is summarized in the table 6.a and table 6.b

Analysis bulletin of slaked air lime [30]

Table.6.a Physical analysis

FINENESS (% by Weight)	Apparent density (ρ_{app})
98% passing 0.2mm	555 kg/m^3

Table.6.b Chemical analysis

Element	CaO	CO2	K2O+NaO	SiO2	Al2O3	Fe2O3	SO3	H2O
Percentage (%)	73.12	15.23	0.05	0.32	0.05	0.06	0.02	0. 3

The lime used in the study was found to have a high quality due to its significant content of quicklime. Overall, the high-quality lime, enriched with quicklime, used in the study has beneficial effects on the hardness, melting speed, and porosity of the fired bricks, contributing to their overall quality and thermal insulation capabilities.[31],[4],[22].

3.1.4. Properties of waste additives

The physical characteristics of used waste are shown in the table .7 and table .8.

Table.7. Physical properties of waste additives

The Wastes additives	Apparent density	Absolute density	Water absorption rate
Rubber granules	480 kg/m3	666.67 kg/m3	negligible
Rubber powder	460 kg/m3	500 kg/m3	negligible
Alfa plant powder	490 kg/m3	1594.59 kg/m3	140%
Date palm wood powder	155 kg/m3	588.26 kg/m3	243.13%
Glass powder	1540 kg/m3	1925 kg/m3	negligible
Polystyrene granules	14 kg/m3	20.59 kg/m3	negligible

Table.8.Granular analysis of waste additives

	Percentage of weight (%)						
Particle size (mm)	**5≥D≥2.5**	**2.5≥D≥0.8**	**0.8≥D≥0.4**	**0.4≥D≥0.2**	**0.2≥D≥0.1**	**0.1≥D≥0.08**	**0.08 ≥ D**
Rubber granules	1.2	83.33	15.47	00	00	00	00
Rubber powder	00	1.5	73.2	18.1	5.2	1.6	0.4
Alfa plant powder	00	00	67.66	16.32	6.24	5.42	4.36
Date palm wood powder	00	82.13	10.62	5.32	1.93	00	00
Glass powder	00	11.16	40.42	38.32	8.84	00	1.26
Polystyrene granules	100 (3.15≥D≥2.5)	00	00	00	00	00	00

3.2.Test results

We list the results obtained from various tests in the table 9

Table.9. Experimental results of all tests

Sample	Diagonal shrinkage(%)	Capillary water absorption ($g/cm^2.min^{0.5}$)	Total water absorption (%)	Bulk density(kg/m^3)	Thermal conductivity(w/m k)	Specific heat (kj/m^3k)	Thermal diffusivity ($x10^{-7}m^2/s$)
uncooked witness 1	7.247	Great water sensitivity	Great water sensitivity	2129.14	0.82733	1854.1	4.46
uncooked witness 2	6.056	Great water sensitivity	Great water sensitivity	2024.79	0.764	1822.65	4.19
witness 3	7.617	25.627	12.321	1836.67	0.48833	1322.67	3.68
witness 4	7.511	56.744	23.0094	1547.81	0.386	1188.87	3.25
Glass powder	7.511	61.244	20.886	1567.12	0.42067	1151.83	3.65
Alfa powder	7.31	160.561	39.885	1243.31	0.277	970.267	2.85
Date palm wood powder	8.612	102.581	40.524	1211.16	0.31067	942.067	3.29
Glass powder+ DPW powder	6.408	114.396	34.241	1338.09	0.317	1071.17	2.96
Rubber aggregate	6.953	89.949	29.356	1376.8	0.324	1064.97	3.04
Rubber powder	8.4	72.658	29.879	1378.6	0.33867	1125.4	3
Polystyrene aggregate	8.043	77.084	24.712	1352.8	0.33033	1074.63	3.07

The uncertainty was determined and included in the diagrams.

3.2.1. Bulk density

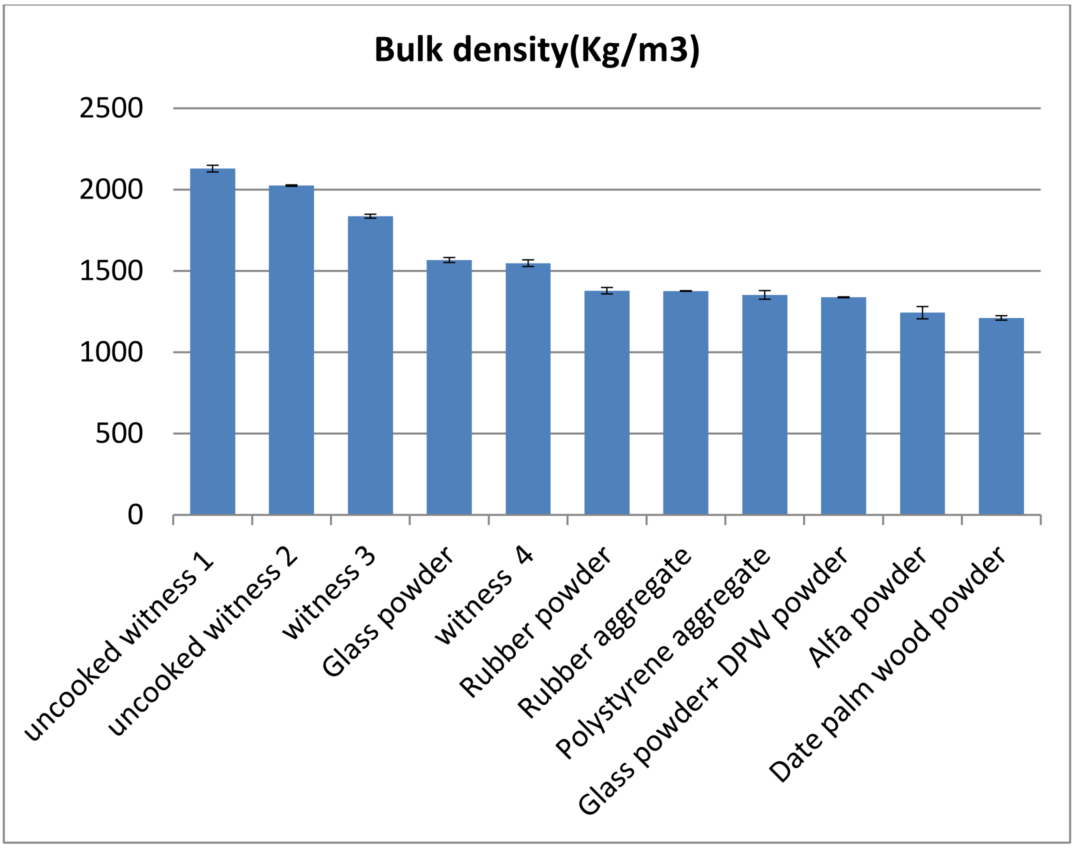

Fig.15 Bulk density

The diagram shown in Figure 15 clearly illustrates the impact of adding sand to the clay mixture. This addition results in a decrease in the density of the sample by approximately 5%. The lower density makes the building blocks lighter, as sand has a lower absolute density compared to clay. Furthermore, the addition of lime and the subsequent burning process lead to a significant decrease in density, reducing it by over 23% compared to the weight of the second witness sample. This decrease in density attributed to various factors related to the burning process, such as the melting of the mixture, decomposition of organic matter, destruction of clay minerals, evaporation of residual water, and decomposition of calcium carbonate. These observations align with the findings of previous researchers [22].

The addition of lime also plays a role in increasing the melting speed during the burning process and enhancing the porosity of the final product. These effects have been confirmed by researchers [22] [23].

It is worth noting that all the added granules and powders from waste materials contribute to reducing the density of the final product to varying degrees. The reduction in density reaches a value of up to 1243.31 kg/m3 and 1211.155 kg/m3, which corresponds to a decrease of more than 19.67% and 21.75% compared to the weight of the fourth witness sample when adding alfa plant powder and date palm wood powder, respectively. This attributed to the ease of burning and decomposition of these two elements during the burning process. On the other hand, despite the low density of rubber granules, the density of the final product is higher due to the incomplete decomposition of this waste. Plant fibers, in general, have lower burning temperatures and produce light ash.

Almost all the samples containing additives exhibited lower density compared to the range specified for commercial fired solid bricks, which typically falls within the range of ρϵ[1600;2000] kg/m3 [32];[33].

3.2.2. Longitudinal shrinkage

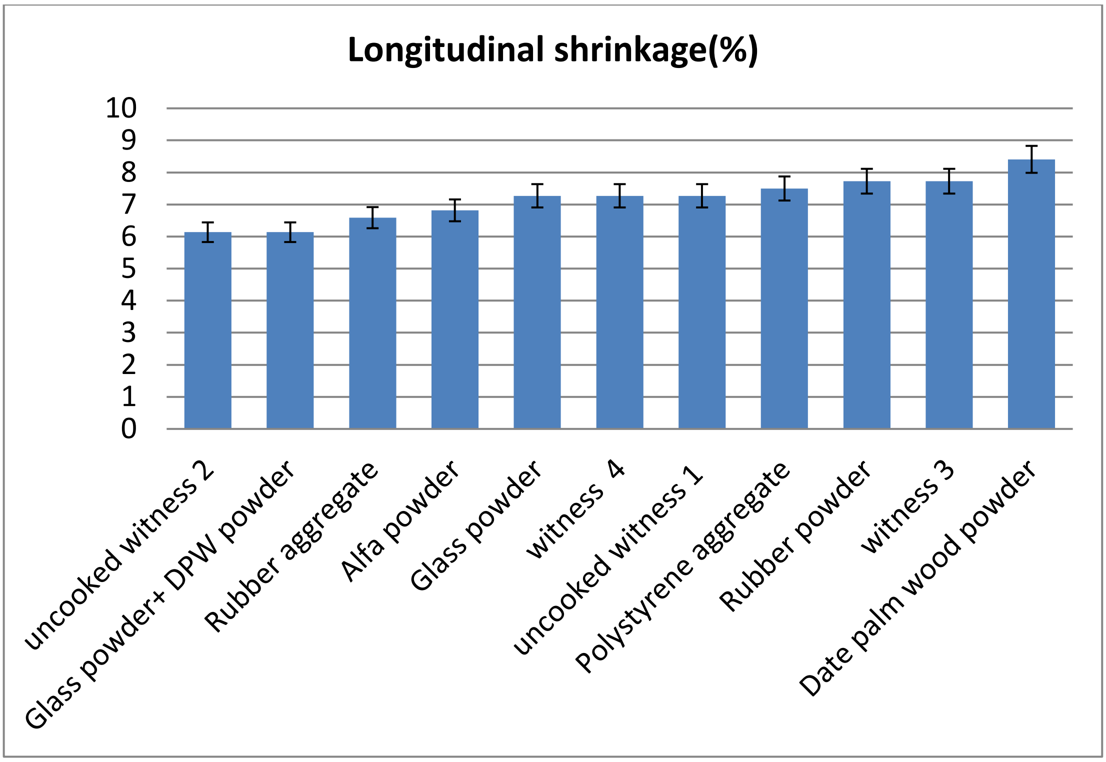

Fig.16 . The longitudinal shrinkage

From the diagram in Figure 16, it is evident that adding sand to the sample reduces the shrinkage value. This is clearly observed in the shrinkage ratio of the second witness sample, attributed to the lower water absorption rate of sand. Conversely, samples with powders having a higher water absorption rate exhibited significant shrinkage. This explained by the increased volume and swelling of the fibers when saturated with water during the sample preparation. As water evaporates during the drying process, the volume of the fibers decreases significantly.

Interestingly, the burning process did not significantly increase the shrinkage rate, as a large percentage of the water had already left the sample during the drying process.

The shrinkage rates for all the samples were observed to range from 6.056% to 8.612%. These values fall within the permissible range specified for longitudinal shrinkage, which should typically be between 5% and 8% according to previous research [22].

3.2.3. Thermal conductivity (λ)

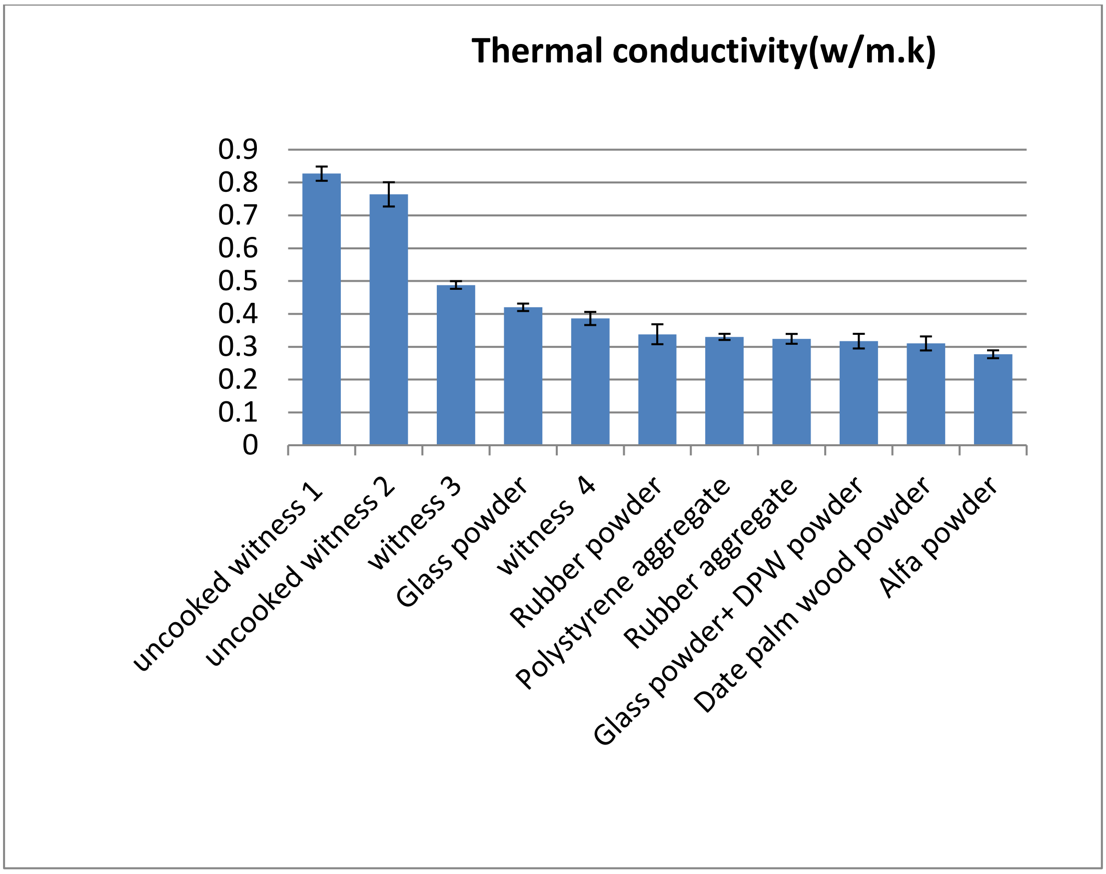

Fig.17. Thermal conductivity

From the diagram in Figure 17, it is evident that the second witness sample, which contained sand, exhibited a decrease in thermal conductivity by approximately 7.61% compared to the first witness sample. This attributed to the lower thermal conductivity of sand compared to clay.

The burning process significantly contributed to reducing the thermal conductivity of the samples by up to 36.12%. This attributed to the structural transformation of the sample during fusion, mineral breakdown, and the removal of all water content.

The addition of lime also played a role in reducing the thermal conductivity by up to 20.9%. This attributed to its effect on increasing the melting speed and enhancing the porosity of the final product, as mentioned earlier. These results differ from those obtained by other researchers [34], [35] et al., which may be due to the influence of the lime burning process .

The addition of glass powder increased the thermal conductivity of the final product due to its relatively high conductivity compared to other components of the mixture. However, the thermal conductivity of the sample with 10% glass powder was found to be 0.420 W/m.K, which is better than the results obtained by the researcher [12] et al.

Furthermore, the other samples containing various wastes exhibited decreased thermal conductivity in varying proportions. The thermal conductivity of these samples ranged from

0.277 to 0.488 W/m.K (excluding unburned samples), which is lower than the thermal conductivity range of commercial fired solid bricks which states that λϵ[0.7 ; 0.73] W/m.K [33] . The percentage decrease was highest for the samples containing palm wood powder and alfa plant powder, with a decrease of 19.68% and 28.24%, respectively, compared to the fourth witness sample, with corresponding thermal conductivity values of 0.31 W/m.K and 0.277 W/m.K. These results attributed to the voids created by these wastes during the burning process, resulting in a favorable porous structure in terms of thermal performance.

3.2.4.Specific heat

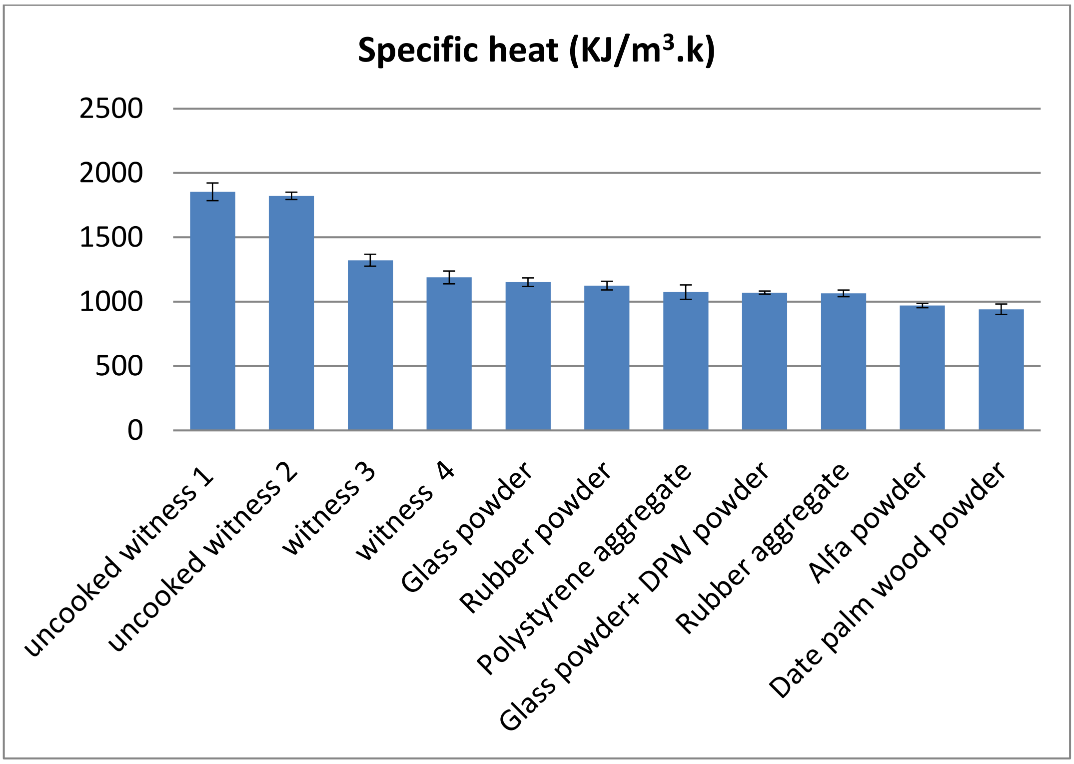

Fig.18.Specific heat

In Figure 18, it is observed that the specific heat results are consistent with the thermal conductivity results. The addition of fibers and powders to the samples led to a decrease in specific heat. This attributed to the increased air trapped inside the samples as a result of the burning process and the presence of these additives. The air component has a lower specific heat compared to the main components of the soil matrix (sand and clay). The specific heat of air is approximately 1006 J/kg.K. [28].

The specific heat values for the samples containing alfa plant powder and palm wood powder are lower compared to other wastes. This can be explained by the lower density of these elements compared to other additives. The lower density allows them to occupy a larger volume within the samples, resulting in more trapped air during the burning process. The presence of additional trapped air reduces the specific heat of the samples. Overall, the results show that the addition of various wastes and the burning process have an impact on the specific heat of the samples, primarily through the alteration of the air content within the samples.

3.2.5.Thermal diffusivity

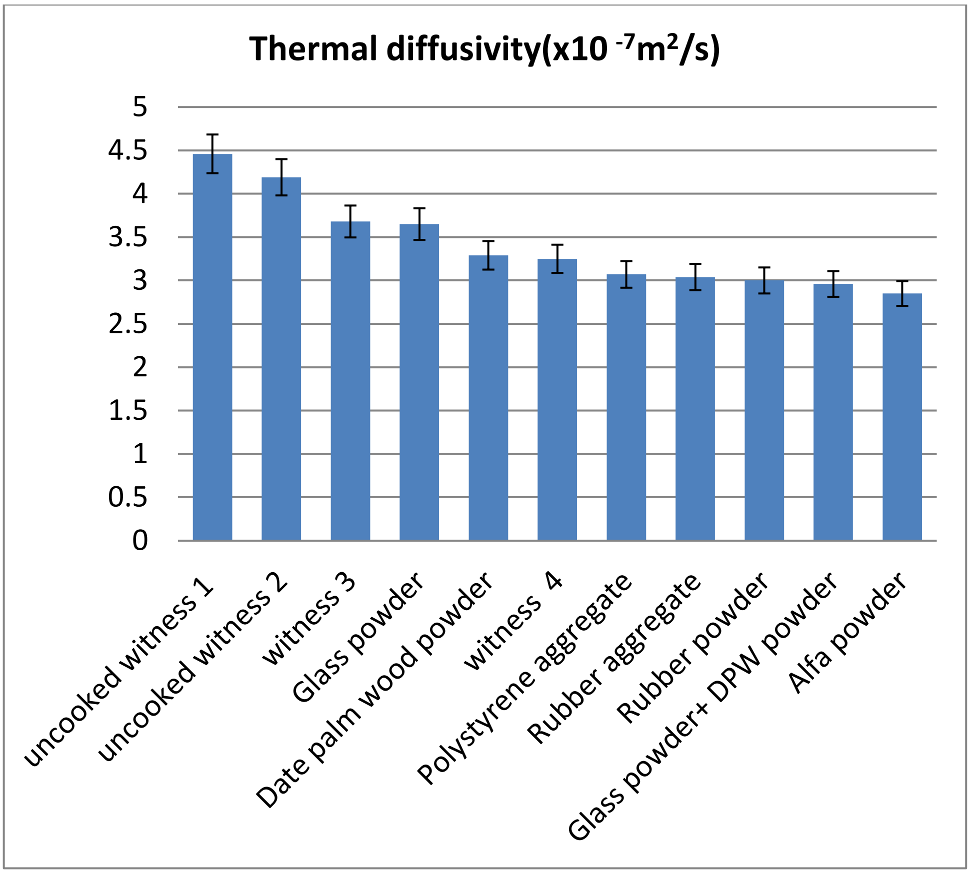

Fig.19. Thermal diffusivity

In Figure 19, it is evident that the various fibers used in the samples have played a significant role in reducing thermal diffusivity. The lowest value was observed in the sample containing alfa powder, with a reduction percentage of approximately 12.3% and a thermal diffusivity value of $2.85x10^{-7}$ m^2/s. This indicates that the presence of alfa powder has a notable effect in enhancing the thermal insulation properties of the sample.

The addition of lime to the samples also contributed to a decrease in thermal diffusivity, with a reduction percentage of 12.6%. This attributed to the role of lime in increasing the melting speed, increasing porosity, and altering the sample's structure during the burning process, resulting in improved thermal insulation.

The burning of samples further reduced the thermal diffusivity by 9.27%. The third witness sample recorded a thermal diffusivity of $3.68x10^{-7}$ m^2/s. This reduction attributed to the structural transformation and elimination of water content during the burning process, leading to a less dense and more thermally insulating material.

Additionally, the inclusion of sand in the samples resulted in a 6% reduction in thermal diffusivity. The observed results in thermal diffusivity experiments align with the findings from thermal conductivity experiments, indicating that the samples exhibit improved thermal insulation efficiency.

3.2.6.Total water absorption

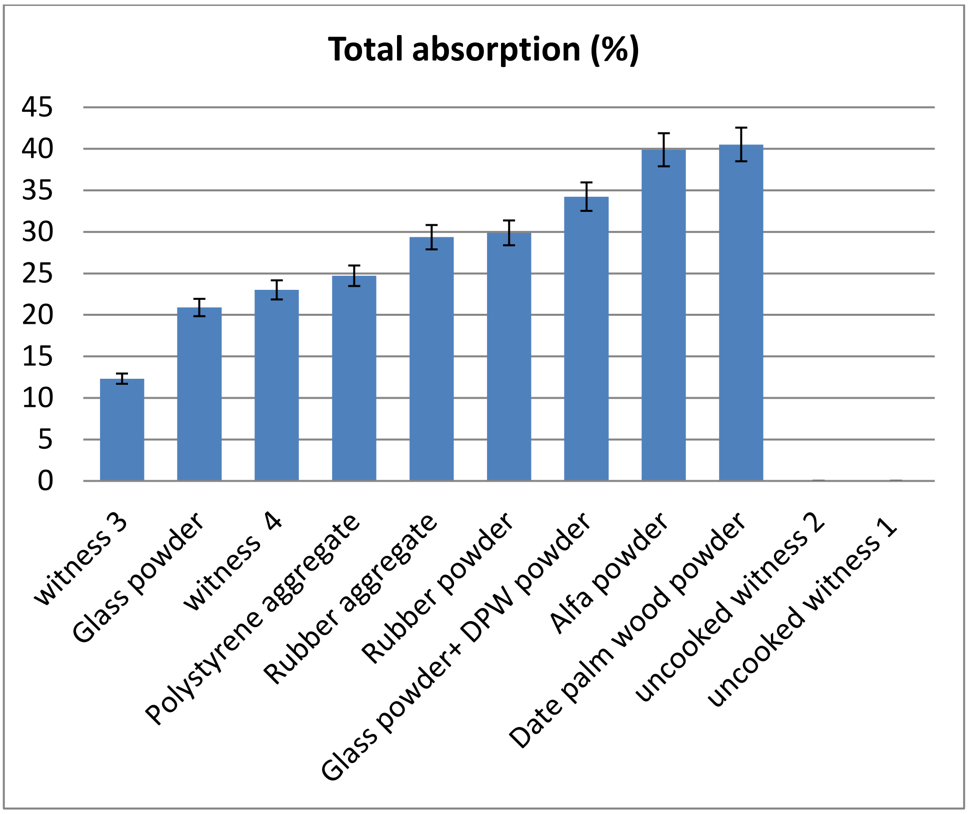

Fig.20. Total water absorption

From Figure 20, it can be observed that the addition of lime to the samples has significantly increased the percentage of total water absorption by approximately 86.74%. This attributed to the increased porosity of the samples resulting from the addition of lime, which allows for greater water absorption.

However, the sample to which glass powder was added exhibited a decrease in the percentage of total water absorption by approximately 9.22%, despite the presence of lime. This is due to the role of glass powder in contributing to the closure of pores after melting, resulting in reduced water absorption. Glass powder has low water absorption characteristics, as indicated by previous research [36] et al.

The remaining samples containing various wastes showed an increase in the percentage of total water absorption, with the highest values observed in the samples containing alfa powder and palm wood powder, with absorption values reaching 39.885% and 40.524%, respectively. These values exceed the recommended range for water absorption in fired earth bricks (WA ϵ [15;25%]) [4].

Furthermore, the samples exhibited higher water absorption compared to commercial bricks, absorbing water at a rate nearly five times higher. This attributed to the porous structure left by the incinerated wastes as well as the difference in compressive strength when manufacturing samples, which negatively affects the physical properties of the samples . [37];[38].

The significant increase in total water absorption attributed to the porous structure created by the combustion of fibers within the samples.

Interestingly, the sample to which 3% of glass powder was added, despite containing the same percentage of palm wood fibers, exhibited a lower total water absorption rate with a decrease of 15.5%. This demonstrates the role of glass powder in reducing water absorption in the samples.

It is worth noting that the first and second witness samples were not subjected to the water absorption experiment due to their high sensitivity to water.

3.2.7.Capillary water absorption

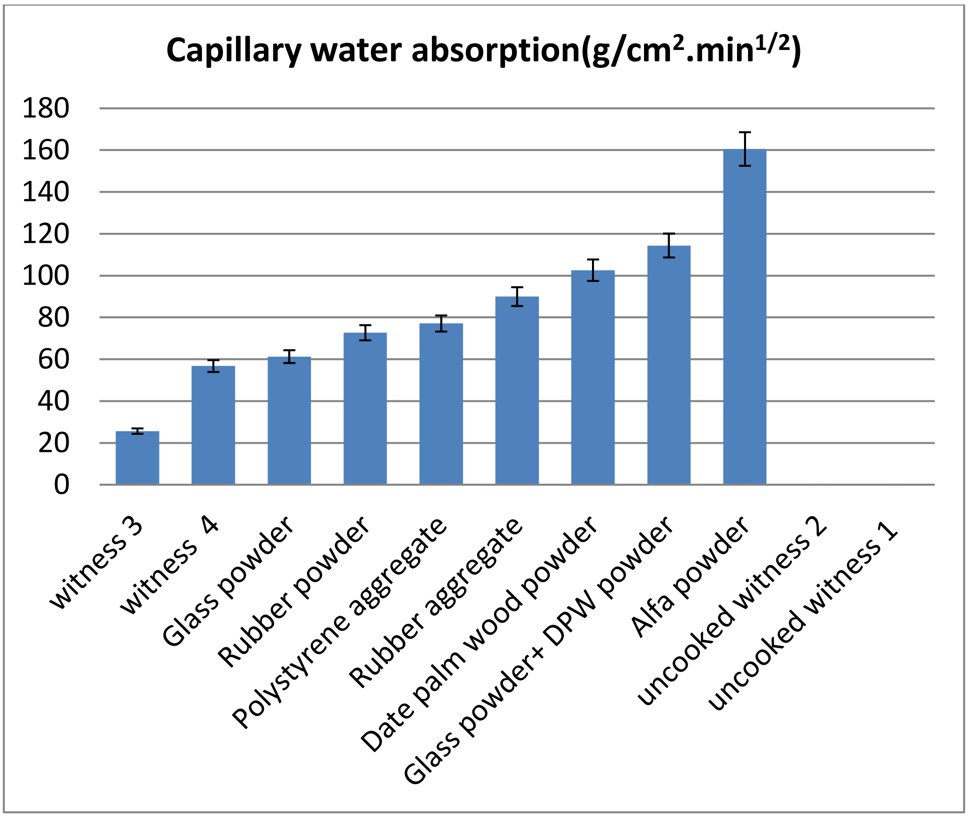

Fig.21. Capillary water absorption

From the observations in Figure 21, it is evident that the capillary water absorption of the samples to which various wastes and powders were added exceeded the recommended range for solid fired bricks, which is typically between 30 $g/cm^2.min^{1/2}$ to 80 $g/cm^2.min^{1/2}$ [22].

The samples containing alfa plant powder exhibited a capillary water absorption of 160.561 $g/cm^2.min^{1/2}$, while the samples with palm wood powder reached 102.581 $g/cm^2.min^{1/2}$. These values indicate a high capillary water absorption rate, which attributed to the porous structure created by the addition of these wastes.

Additionally, the added lime contributed to an increase in the amount of absorbed water, further enhancing the capillary water absorption of the samples.

Interestingly, increasing the amount of glass powder in the palm wood powder sample did not have a positive effect on reducing capillary water absorption, as expected. This suggests that the addition of glass powder did not significantly impact the capillary water absorption properties of the samples.

As previously mentioned, the first and second witness samples were not included in the water absorption experiment due to their high sensitivity to water.

4.Conclusion

Based on the results and observations of this research, the following conclusions can be drawn:

- The addition of waste materials, both industrial and plant-based, to the earth-fired brick mixture has a positive impact on the thermal and physical properties of the bricks.
- The incorporation of waste materials such as alfa plant powder, palm wood powder, and rubber granules contributes to reducing the density of the final product, making it lighter and potentially more suitable for certain applications.
- The burning process of the samples plays a significant role in reducing the density and improving the porosity of the bricks, thereby enhancing their thermal insulation properties.
- The addition of lime to the mixture helps increase the melting speed during the burning process and increases the porosity of the final product. This further improves the thermal properties of the bricks.
- The addition of sand to the clay mixture reduces shrinkage and water absorption, which positively affects the durability of the bricks during freeze-thaw cycles.
- The thermal conductivity of the bricks is influenced by various factors, such as the composition of the mixture and the burning process. The addition of certain waste materials can decrease thermal conductivity, making the bricks more efficient in terms of thermal insulation.
- The specific heat and thermal diffusivity of the bricks are influenced by the presence of waste materials and the burning process. The incorporation of fibers and powders contributes to lower specific heat and thermal diffusivity values, indicating improved thermal performance.
- The water absorption properties of the bricks are affected by the addition of waste materials. The use of certain waste materials, such as alfa plant powder and palm wood powder, significantly increases water absorption, while the addition of glass powder can reduce water absorption due to its ability to close pores.
- The capillary water absorption of the bricks with waste materials exceeds the recommended range for solid fired bricks, highlighting the need for further optimization in this aspect.
- The study demonstrates the potential of utilizing waste materials in the manufacturing of ecological building materials with improved thermal properties. Further research and optimization are needed to enhance other mechanical and durability properties of these bricks.

In conclusion, this research highlights the positive impact of incorporating waste materials in the production of earth-fired bricks, leading to the development of new eco-friendly building materials with improved thermal performance.

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