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Mechanical Testing of Novel and Conventional Geopolymer Brick Dried under Passive Solar Dryer with Ferric Chloride Dihydrate as Phase Change Material

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ABSTRACT

Conventionally, in Geopolymer bricks (GPB), fly ash from power plants and ground granulated blast furnace slag are converted into bricks by chemical treatment. In this work, a novel GPB has been obtained by adding nano silica and rice husk ash to the conventional ingredients of GPB, along with Ferric Chloride Dihydrate, which is used as a phase change material to accelerate the curing time by utilizing its latent heat stored in the form of phase change. This novelty aims at introducing solar dryers with phase change materials in the areas of curing GPB, which have shown competent properties when compared to conventional bricks in the construction sector. It has been experimentally found that the solar drying method with Ferric Chloride Dihydrate (22 hours) utilizes a shorter curing time when compared to an electrical oven (24 hours) and open sun drying (24 hours). The properties of novel GPBs are evaluated by mechanical testing and compared with conventional GPBs. It has been experimentally observed that novel GPB exhibits higher compressive strength of 45 MPa, tensile strength of 4.5 MPa, and flexural strength of 6.5 MPa when compared to compressive strength of 41.5 MPa, tensile strength of 3.35 MPa, and flexural strength of 6.2 MPa as that of conventional GPB. Also in this study, Scanning Electron Microscopy (SEM) images of the damaged surfaces and energy-dispersive X-ray spectroscopy (EDX) analysis of novel GPB obtained from test results have been furnished. Smart quantitative results from EDX analysis show that the Oxygen Potassium content has the highest weight percentage and atomic percentage.

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1. Introduction

Energy from the sun is a potential candidate, compared to other sources, in several areas like agriculture, distillation, construction, and other industries [1]. Greenhouse energy is an open method when compared to other modes of drying [2]. Open sun drying and its risk factors, like excess drying of the substance kept inside the solar dryer, leading to unnecessary thermal expansion and extremely hard surfaces, pose a threat to the drying process [3]. The risk factors of the greenhouse energy method can be eliminated by convection-based solar dryers, which are also safe for the environment [4]. A solar dryer was proposed as a substitute for an electric dryer to prove its efficiency [5]. Solar dryers are subjected to climatic fluctuations, which can be overcome by employing Phase change materials inside the solar dryers. Phase change materials are materials to regulate a bandwidth of temperatures, by utilizing their latent heat, in several applications like buildings to minimize the consumption of energy [6]. Phase change material (PCM) like paraffin wax suffers negligible volume changes during the phase change process, making it easier to incorporate it in equipment [7]. PCM can maintain a hotter environment than the ambiance, at least for a span of five hours after sunset, thereby reducing the curing time [8]. Nano PCMs have found their applications in energy storage under fluctuating loadings in solar PV panels [9]. Paraffin ceramsite composites are used as PCM to tackle massive energy consumption [10]. Solar dryers with PCM can be employed for accelerated curing time of all types of bricks in construction industries, forming a new platform for research by using clean energy to bring down emission levels, when compared to conventional curing methods.

Geopolymer bricks (GPB) were developed by Davidovits in 1978 and are produced by activating high-alumina silica-rich materials in an alkaline solution (consisting of sodium or potassium silicate and sodium or potassium hydroxide). These materials form a basis for the next generation and move towards a sustainable environment, in the construction and building sectors [11,12,13]. A geopolymer is an inorganic polymeric material with a three-dimensional network structure composed of long aluminosilicate chains that are obtained by polymerization (condensation reaction) of an aluminosilicate precursor in an alkaline environment at room temperature [14,15,16]. Geopolymerization usually occurs at ambient or slightly elevated temperatures; the solid aluminosilicate raw materials dissolve into the alkaline solution, then cross-link and polymerize into a growing gel phase, which then continues to set, harden, and gain strength and durability, thereby enabling industrial solid waste management and recycling [17,18,19]. Also, GPB exhibits an amorphous nature at elevated temperatures. It is similar to ceramic composites, with a link between alumina and silica. Further, binding materials like rice husk can be added to enhance the properties of GPB [20,21,22]. Geopolymer-based concrete based on fly ash has the potential to replace ordinary Portland cement (OPC)-based concrete with comparable structural qualities in the construction industry [23,24,25]. GPBs are a potential threat to sand and cement bricks with good particle size distribution and structural properties, economy, and eco-friendliness, even at elevated temperatures [26,27]. Also, in comparison with other conventional bricks, GPB is affordable while economy and eco-friendliness are concerned [28]. Hao Shi et al. investigated the strength, microstructure, and curing time of GPB [29]. Mohammed Rihan Maaze and Sandeep Shrivastava suggested an efficient drying range of temperatures between 40°C to 60 °C for evolving GPB in construction industries. [30]. Polymer composites are finding applications even in construction areas, like the use of polymer in bricks [31,32]. Construction industries need bricks with less energy consumption and pollution, which inculcates hybrid solar dryers in building applications [33]. Rice husk ash is finding applications in the manufacturing of sustainable GPB [34]. Nano clay and granite dust are alternative replacements for cement mortars to bring down carbon dioxide emissions [35]. The use of GPB in terms of strength compared to conventional bricks comes under the modified guidelines of GPB using Indian standards [36, 37]. GPB meets sustainable goals like using clean energy for curing when compared to conventional bricks [38]. The effect of nanoparticles like nano silica can enhance the properties of GPB, thereby increasing the reliability of GPB [39]. Using solar dryers accompanied by PCM for accelerating curing time and enhancing properties of GPB is under investigation, and it forms a new platform for research in building applications [40]. Geopolymer mortar is investigated from industrial waste for a sustainable approach in the Construction sector [41, 42].

This work deals with the preparation of a novel GPB, a comparison of drying methods like electrical drying and solar drying with a PCM (Ferric Chloride Dihydrate), in terms of curing time, and a mechanical properties comparison of novel GPB with conventional GPB. Ferric Chloride Dihydrate has been selected as PCM, due to its low cost and comparable properties with other conventional PCMs like Paraffin wax.

2. Materials and Methods

A solar dryer of dimensions (710 * 310 * 310) with all dimensions in millimeters was fabricated as shown in Figure 1.

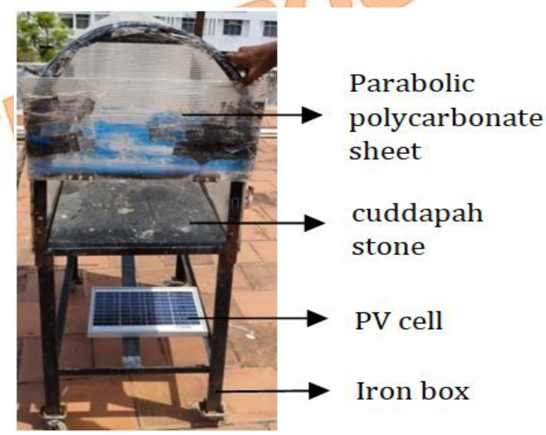


Fig. 1. Solar Dryer

The dryer set up contains an iron stand, drying chamber, and UV-coated parabolic polycarbonate sheets for absorbing incident solar energy. An aluminum frame is used to structurally support the polycarbonate sheet. A Cudappah stone of dimension (695 mm * 295 mm) is kept below the polycarbonate sheet to constrain the transfer of heat in a downward direction to obtain a uniform drying temperature. The dryer shows four nylon wheels at the bottom to move the dryer for convenience. Solar-powered photovoltaic (PV) panel fan is provided to remove saturated air and allow fresh atmospheric air into the chamber. On the basis of the curing temperature, this fan automatically turns on and off during the process. Latent heat storage material like Ferric Chloride Dehydrates, kept in a steel container above the Cudappah stone, has a 57.5 °C melting point temperature. Properties of Ferric Chloride Dihydrate are predicted in Table 1.

Table 1. Properties of Ferric Chloride Dihydrate

PCM	Melting Temperature °C	Density (kg/m³)		Specific Heat (J/Kg-k)		Thermal Conductivity (W/m-K)		Latent Heat of Fusion (kJ/kg)
		1	2	1	2	1	2	
Ferric Chloride Dihydrate	57.5	2900	2810	9630	8650	1.84	1.74	265

In Table 1, 1 implies a solid state and 2 implies a liquid state. The chemical preparation and composition of the ingredients of novel GPB are shown in Figure 2, Table 2, and Table 3.

The particle size for fly ash, ground granulated blast furnace slag (GGBS), nano silica, and rice husk ash was 43 µm, 11 µm, 75 nm, and 50 µm, respectively. The ignition loss data for fly ash and GGBS, nano silica, and rice husk ash were 0.69%, 0.70%, 1%, and 1.7%, respectively. Sodium hydroxide solution of 97% purity was mixed with distilled water, and the sodium silicate solution acts as an alkaline activator. The morality of the sodium hydroxide solution was kept at 12 M for all specimens. The precursors of this novel GPB are fly ash, GGBS, nano silica, and rice husk ash, whose chemical composition is shown below in Table 3. A sodium hydroxide (NaOH) and distilled water mixture was kept for 24 hours in the bowl. After which, sodium silicate (Na_2SiO_3) solution was added. After 60 minutes, fly ash, GGBS, nano silica, and rice husk mixed with coarse and fine aggregate sand were added to a solution containing NaOH and Na_2SiO_3. M sand is used for creating a mortar mixture. In this mixture, alkali metal sodium, the primary activator, exhibits binding action in the process of polymerization. The role of SiO_2 and Al_2O_3 in this polymerization process is to form the microstructure of GPB. Figure 3 shows what the mixture looks like after all ingredients are well stirred. Figure 4 shows the cubic, cylindrical, and rectangular prism specimens prepared for the curing and testing process. Figures 5 and 6 depict specimens placed in the oven and dryer, respectively. Solar energy is captured and converted into heat energy in the solar dryer by convection and radiation, in which convection plays an active role, while radiation plays a passive role. The Ferric Chloride dihydrate was kept in a solid state in an insulated steel container over the Cudappah stone. The curing process of GPB is accompanied by charging and discharging of PCM, after which the mass of the dried brick was determined by an accurate weighing machine. The curing process of bricks was carried out with a PCM and without a PCM. For mechanical testing, the specimen details based on ASTM standards are shown in Table 4 [40]. Each test was performed on two specimens for the sake of consistency and accuracy of readings. Figures 7, 8, and 9 show the experimental setup used for mechanical testing, respectively. After testing, the components were examined under Scanning Electron Microscopy to show the images of damaged surfaces under the following specifications (2µm, 5 KX), (3µm, 4 KX), (10µm, 1 KX), (20µm, 500X), (100µm, 250 X). EDX analysis was performed to find the highest weight and atomic percentage.

Fig. 2. Photos of ingredients of Novel GPB.

Table 2. Mixed Design table for GPB.

Material	Weight in kg/m³	LOI (Loss of Ignition)
Fly ash	286	0.69 %
GGBS	166	0.70 %
M sand	580	1 %
Coarse aggregate 20 mm	865	1.7 %
Alkaline activated solution	336	-
Sodium silicate solution Na_2SiO_3	240	-
NaOH	96	-
NaOH molarity	12	-
Alkaline/binder ratio	0.61	-
Rice husk ash	82.5	-
Nano silica	16.5	-

Table 3. Chemical composition of GPB.

Precursor	SiO_2	Al_2O_3	CaO	MgO	K_2O	Fe_2O_3	TiO_2	Na_2O	SO_3
Fly Ash	52	27	3.5	9.25	7.5	1.55	0.845	0.725	0.545
GGBS	35	14	36	7.5	0.545	0.45	0.725	0.25	1.65
Nano silica	90.5	0.082	0.059	0.081	0.011	0.02	-	0.89	0.23
Rice husk ash	85.85	0.19	1.95	0.375	1.98	0.09	-	0.39	-

Table 4. Specimen Standards (Dimensions in cm)

Test	Geometry	Length	Breadth	Height	Diameter	STANDARD
Tensile strength	Cylindrical	20			10	ASTM C496-96
Compressive strength	Cubic	10	10	10	-	ASTM E9-19
Flexural strength	Rectangular	50	10	10	-	ASTM D790-17

Fig. 3. (a) Final mixture, (b) mixture poured into mold.

Fig. 4. (a) Specimen for tensile (cubic) & compressive (cylindrical) testing, (b) Specimen for flexural testing

2.1. Electric Oven Drying

Specifications: Power rating = 3600 Watts, Voltage rating = 225 V, and Frequency = 50 Hz.
At the beginning of the curing process, the GPB exhibits fluctuations in weight. As it gets stabilized, the moisture content is completely cured. The time consumed for drying the moisture content is 24 hours. Further, the GPB was allowed to develop proper strength at room temperature for 28 days. This same procedure was applied for all curing methods mentioned below.

2.2. Solar Drying (PCM)

The drying process took 22 hours.

2.3. Open-Sun Drying

The drying process took 24 hours

Fig. 5. Novel GPB (cubic and cylindrical) specimen kept in an electric oven.

Fig. 6. Novel GPB along with (PCM) Ferric Chloride Dihydrate in a solar dryer

Fig. 7. GPB under tension test.

Fig. 8. GPB under compression test.

Fig. 9. GPB under flexural test.

3. Results

Results of the mean value of two specimens in each test have been established in Figures 10, 11, 12, and 13 with the following inference: Electric oven drying operates around 65°C while solar drying operates around 60°C, with variations depending on atmospheric conditions. As per the observations from Figure 10, it is understood that solar drying with a PCM consumes almost two hours less curing time among all curing methods for novel GPB [5, 38].

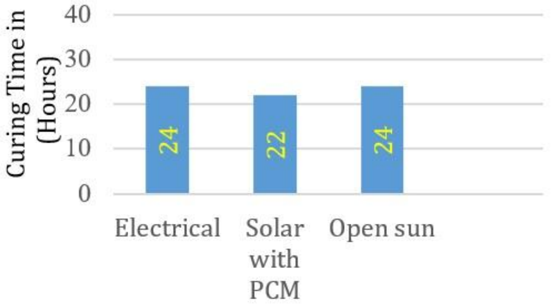


Fig. 10. GPB curing time comparisons

According to Indian standards, compressive strength for conventional GPB is around 30 MPa [36, 37]. In this work, the compressive strength from the experiment predicts a value of 45 MPa for novel GPB in solar drying with a PCM, as shown in Figure 11. Also for novel GPB, the tensile strength of 4.5 MPa and flexural strength of 6.5 MPa were obtained in solar drying with a PCM [40], as illustrated in Figures 12 and 13, respectively. Experimentally, it is evident from figures 11, 12, and 13 that novel GPBs under solar drying with a PCM exhibit 4.65 % and 9.76 % higher compressive strength when compared to electrical drying and open sun drying, respectively [40]. From Figure 12, it is clear that novel GPB under solar drying with a PCM shows 5.88 % and 12.5 % higher tensile strength when compared to electrical drying and open sun drying, respectively [40]. From Figure 13, it is evident that novel GPB under solar drying with PCM shows 4.84 % and 8.33 % higher flexural strength when compared to electrical drying and open sun drying, respectively [40]. The specimen under the solar dryer with PCM has been selected for SEM and EDX analysis. Specimen and surface topographical images of the tensile strength test, compression test, and flexural test captured by SEM have been shown below in Figures 14, 15, 16 and 17, 19, and 21, respectively, to have an idea of the microstructure. An EDX analysis of specimens under tensile strength, compression test, and flexural test has been illustrated in Figures 18, 20, and 22, which predicts Oxygen Potassium as the highest by weight and atomic percentage in all three tests.

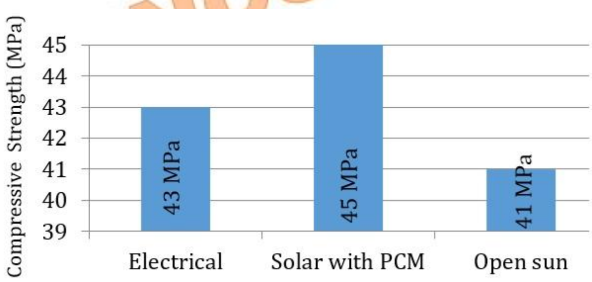


Fig. 11. Compressive strength comparison

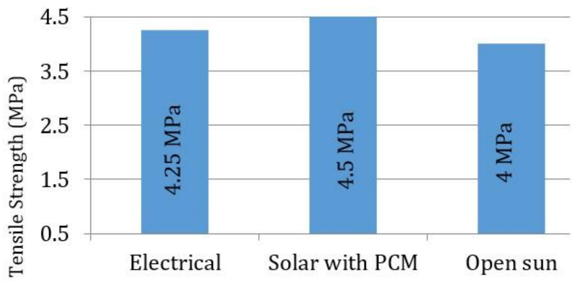


Fig. 12. Tensile strength comparison.

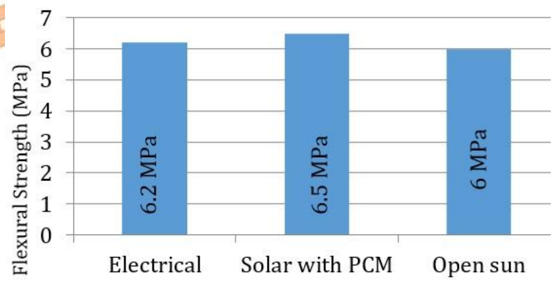


Fig. 13. Flexural strength comparison

4. Discussion

From Table 5, novel GPB under solar drying with PCM is the most efficient with 22 hours of curing time due to latent heat storage [5, 38]. It is evident from Tables 6, 7, and 8 that novel GPB exhibits higher mechanical properties when compared to conventional GPB for all the curing methods [39, 40]. This is due to the presence of Nano silica and Rice Husk Ash in the novel GPB. Rice Husk Ash, which gives a better bonding effect, and Nano silica give rise to a denser microstructure with good interlocking, which is evident from SEM images shown in Fig. 17 (500X), Fig. 19 (250X), and Fig. 21 (500X). The particles are uniformly distributed when compared to each other, which makes this novel GPB yield higher properties when compared to conventional GPB [39, 40]. In addition, we have added Nano silica by 3%(weight percentage), which increases the mechanical properties of this novel GPB, according to the literature [39]. Also, for novel GPB, solar drying with a PCM shows higher mechanical properties when compared to electrical drying and open sun drying due to higher latent heat storage [39, 40].

Fig. 14. Specimen (Solar dried with PCM) after Tensile test

Fig. 15. Specimen (Solar dried with PCM) after Compression Strength test.

Fig. 16. Specimen (Solar dried with PCM) after Flexural Strength test

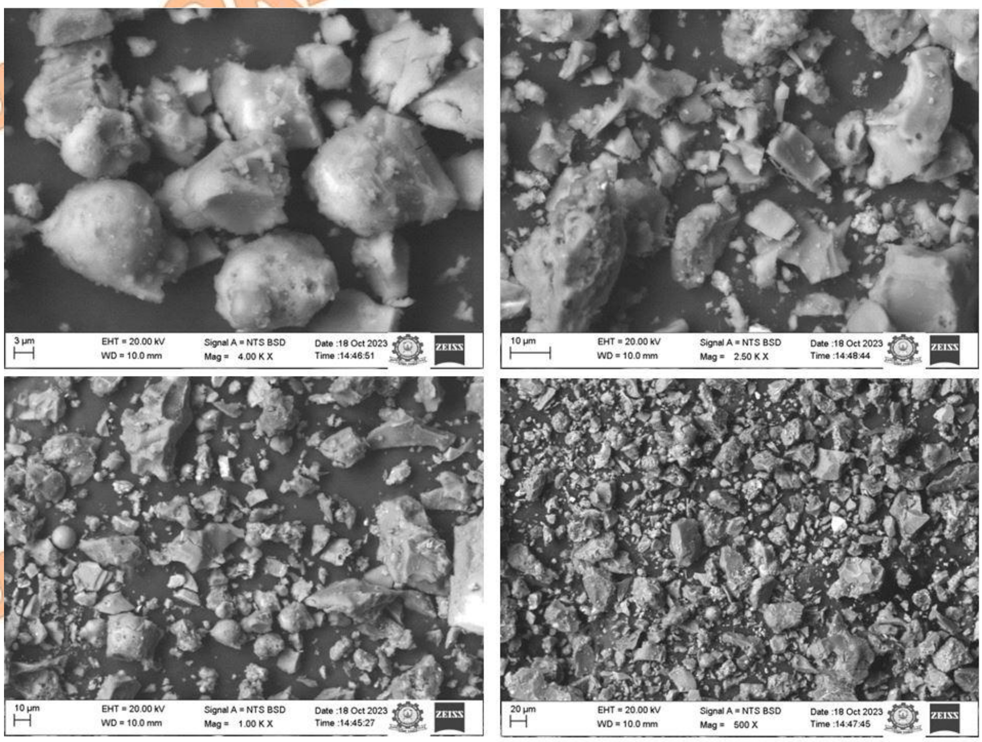
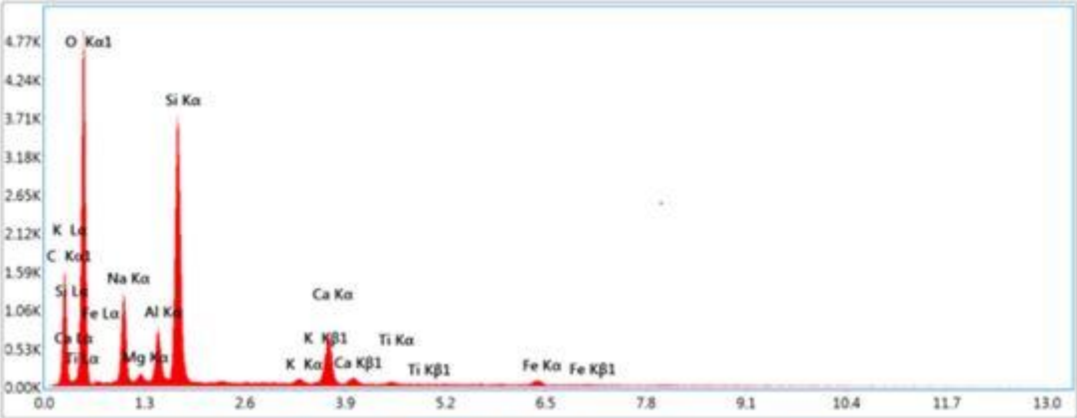


Fig. 17. Surface Topography of Specimen (Solar dried with PCM) under Tensile Strength test.



Element	Weight %	Atomic %	Error %	Kratio
C K	22.6	32.2	10.0	0.0548
O K	45.1	48.2	9.1	0.1119
NaK	8.9	6.6	8.3	0.0319
MgK	0.8	0.5	12.2	0.0034
AlK	3.0	1.9	6.7	0.0173
SiK	12.7	7.7	4.4	0.0858
K K	0.5	0.2	17.3	0.0039
CaK	4.8	2.0	3.4	0.0418
TiK	0.4	0.1	23.6	0.0032
FeK	1.2	0.4	11.4	0.0105

Fig. 18. EDX analysis of Specimen (Solar dried with PCM) under Tensile strength test

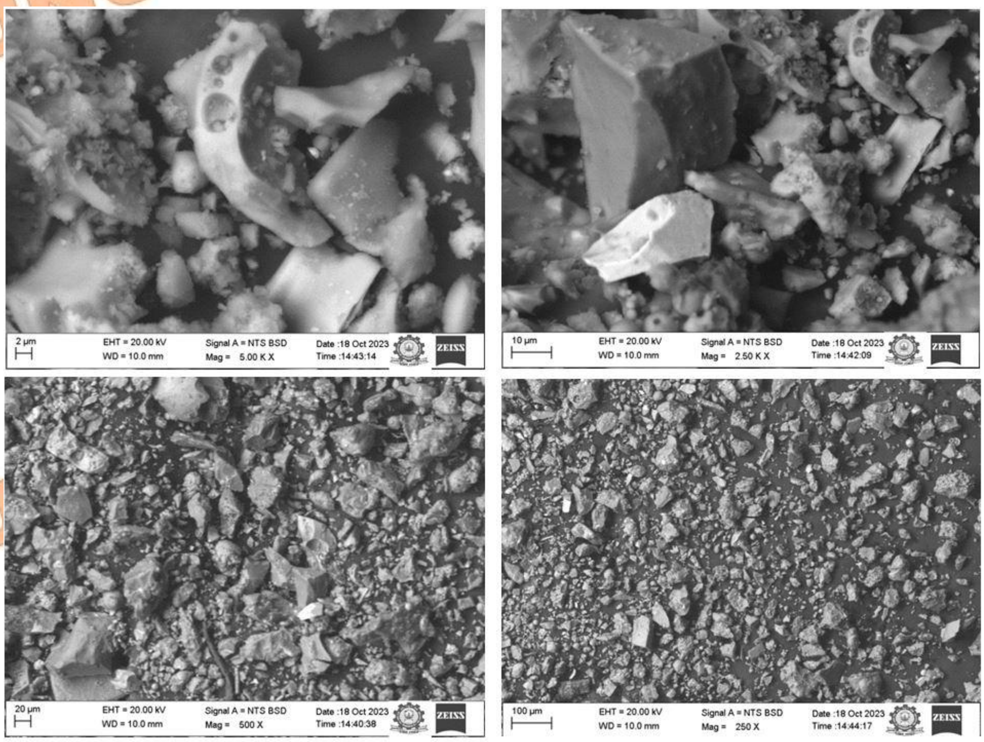
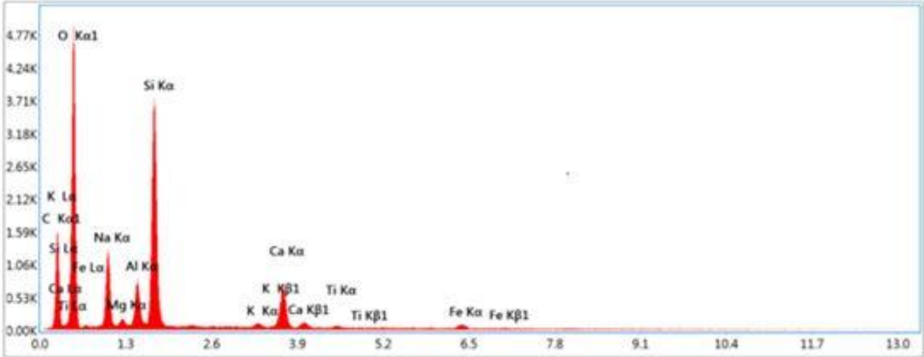


Fig. 19. Surface Topography of Specimen (Solar dried with PCM) under Compression Strength test.



Element	Weight %	Atomic %	Error %	Kratio
C K	22.6	32.2	10.0	0.0548
O K	45.1	48.2	9.1	0.1119
NaK	8.9	6.6	8.3	0.0319
MgK	0.8	0.5	12.2	0.0034
AlK	3.0	1.9	6.7	0.0173
SiK	12.7	7.7	4.4	0.0858
K K	0.5	0.2	17.3	0.0039
CaK	4.8	2.0	3.4	0.0418
TiK	0.4	0.1	23.6	0.0032
FeK	1.2	0.4	11.4	0.0105

Fig. 20. EDX analysis of Specimen (Solar dried with PCM) under compression strength test

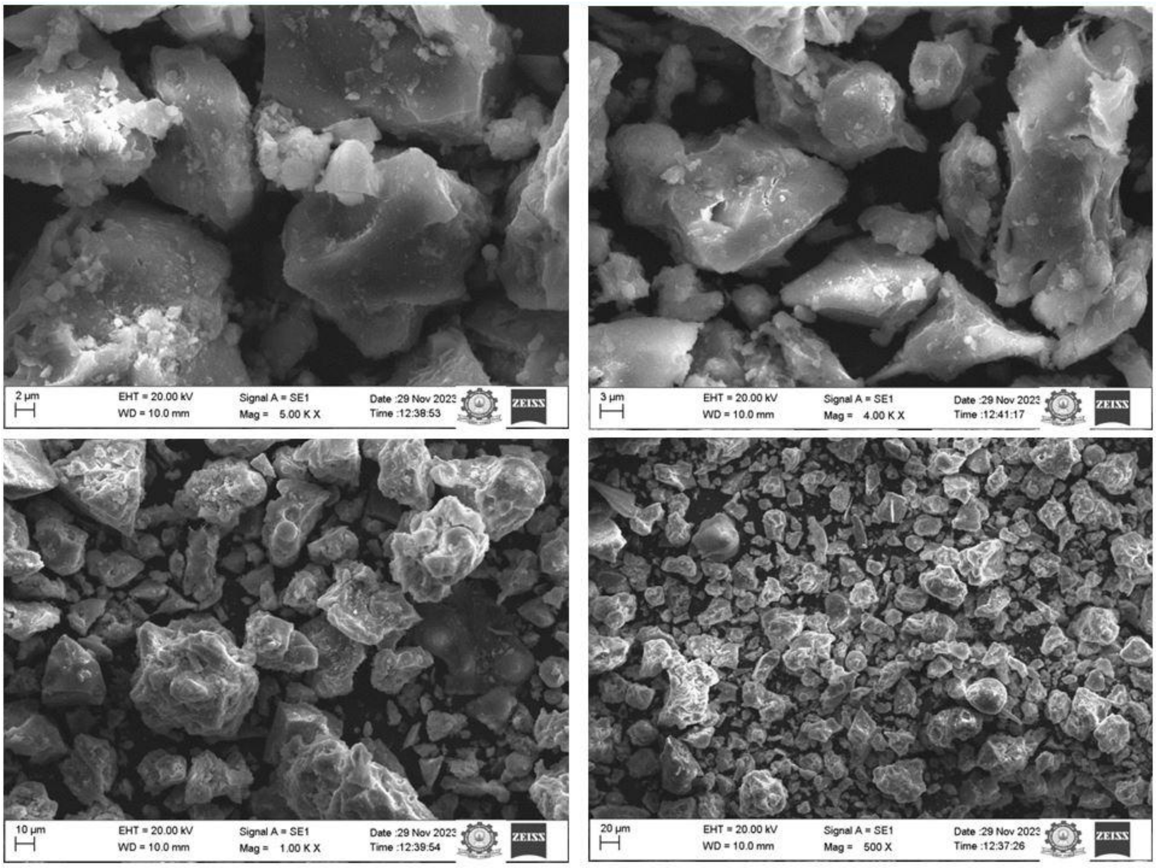
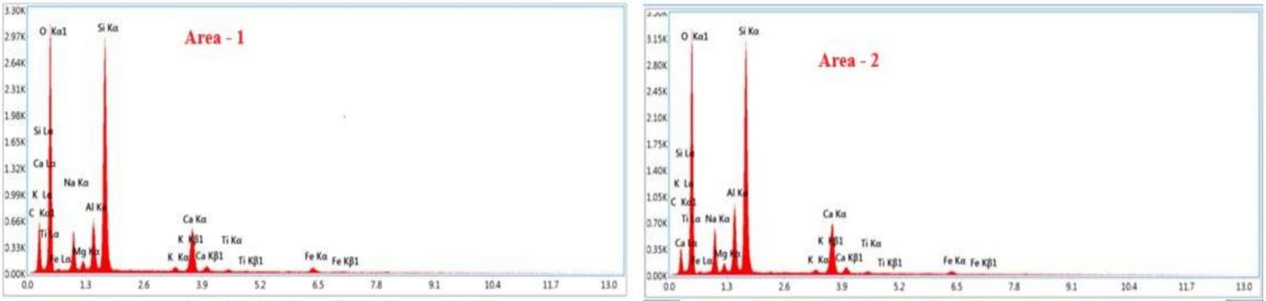


Fig. 21. Surface Topography of Specimen (Solar dried with PCM) under Flexural Strength test.



Element	Weight %	Atomic %	Error %	Kratio
C K	16.6	24.8	11.2	0.0357
O K	46.5	52.4	9.2	0.1185
NaK	6.0	4.7	9.5	0.0211
MgK	1.1	0.8	11.6	0.0053
AlK	4.2	2.8	6.6	0.0244
SiK	16.3	10.5	4.5	0.1106
K K	0.6	0.3	17.2	0.0048
CaK	6.5	2.9	3.7	0.0562
TiK	0.5	0.2	21.7	0.0042
FeK	1.7	0.6	10.4	0.0148

Element	Weight %	Atomic %	Error %	Kratio
C K	9.8	15.5	12.6	0.0192
O K	47.6	56.6	9.1	0.1276
NaK	7.0	5.8	9.3	0.0250
MgK	1.1	0.9	11.8	0.0053
AlK	6.0	4.2	6.2	0.0348
SiK	18.0	12.2	4.7	0.1193
K K	0.5	0.2	21.4	0.0040
CaK	8.2	3.9	3.4	0.0711
TiK	0.6	0.2	19.0	0.0050
FeK	1.3	0.4	15.6	0.0112

Fig. 22. EDX analysis of Specimen (Solar dried with PCM) under Flexural strength test.

Table 5. Curing time comparison for Novel GPB and Conventional GPB.

Drying Method	Conventional GPB	Novel GPB
	Curing Time (Hours)	Curing Time (Hours)
Electrical drying	24	24
Solar drying (PCM)	22	22
Open-sun drying	24	24

Table 6. Compressive Strength Comparison for Novel GPB and Conventional GPB

Drying Method	Conventional GPB	Novel GPB	Percentage Difference
	Compressive Strength (MPa)	Compressive Strength (MPa)	
Electrical drying	38.5	43	11.68
Solar drying (PCM)	41.5	45	8.43
Open-sun drying	37	41	10.81

Table 7. Tensile Strength Comparison for Novel GPB and Conventional GPB.

Drying Method	Conventional GPB	Novel GPB	Percentage difference
	Tensile Strength (MPa)	Tensile Strength (MPa)	
Electrical drying	3.10	4.25	37.09
Solar drying (PCM)	3.35	4.5	34.32
Open-sun drying	2.9	4	37.93

Table 8. Flexural Strength Comparison for Novel GPB and Conventional GPB.

Drying Method	Conventional GPB	Novel GPB	Percentage difference
	Flexural Strength (MPa)	Flexural Strength (MPa)	
Electrical drying	4.95	6.2	25.25
Solar drying (PCM)	6.20	6.5	4.83
Open-sun drying	6.70	6	10.5

5. Conclusions

- Novel GPB in a solar dryer with a PCM consumes 22 hours of curing time, which is less than other methods.
- As per Indian standards, the compressive strength for conventional GPB is 30 MPa. In this work, for novel GPB under a solar-dried with PCM, the experimental value shows 45 MPa, which is favorable for building applications in the construction industry.
- The presence of nano silica and rice husk ash proves that novel GPB exhibits higher mechanical properties when compared to conventional GPB for all curing methods, due to the better bonding effect of Rice Husk Ash and the interlocking effect of Nano silica gives rise to a denser structure.
- Novel GPB, under solar drying with a PCM, shows higher mechanical properties when compared to electrical and open sun drying, which promotes the use of PCM-based solar dryers in curing bricks and enhancing the strength of bricks in construction industries on a large-scale basis.
- Also, Solar dryers with PCM can extend the curing process for a few hours after sunset due to their latent heat storage capability, which relieves us from emissions in conventional brick industries, and hence, we employ clean energy to achieve sustainability goals.
- Due to the important contribution of silica in construction industries, nano-silica has been used as a target by adding it in a small percentage (0.65 kg/m3) to predict its contribution to the strength of GPB.
- For the electrical drying of GPB, the electric oven consumes 84 units of power supply. As per the carbon footprint calculator, 84 units of power are equal to 78.12 kg of Carbon dioxide. If we quantify this in terms of per annum, it is equal to 28513 kg of Carbon dioxide emission per year. So, for the curing of GPB by using a solar dryer aided by PCM, we are almost preventing the entry of 28513 kg of Carbon dioxide emission per year into the environment, thereby significantly reducing the impact on the atmosphere.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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