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Research Article

Impact of Eggshell Powder on the Mechanical and Thermal Properties of Lightweight Geopolymer

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Adopting proper waste management technology in the place of the construction industry to the extent possible to lower the production of new materials and intern reduces the environmental impact pertaining to the industry. In this work, eggshell powder (ESP; waste from the poultry industry) and fly ash (FA; waste from combustion of coal) were utilized as precursors for producing geopolymer and to substitute conventional cement-based construction materials. Three different weight percentage ratios of precursors, namely, 90FA:10ESP, 80FA:20ESP, and 70FA:30ESP were reinforced with two different weight percentages, namely, 15 and 30 wt% of paddy straw in the presence of suitable combinations of sodium silicate and sodium hydroxide to obtain lightweight geopolymer panels. Results received from different analytical tests, namely, density, water absorption, compressive strength, and flexural strength infer that the incorporation of ESP enhances the performance of the geopolymer products to a considerable extent. The specimen sample made using 70FA:30ESP in the absence of paddy straw reinforcement possesses a compressive strength value of 15.64 MPa, which is higher than that of paddy straw reinforced panels. It was observed that there was a reverse trend noticed in the case of flexural behavior on reinforcement of paddy straw, namely, 15 wt% possesses a higher value than that of the panel (70FA:30ESP) made using in the absence of reinforcement. The lowest thermal conductivity value was observed at 0.0633 W/m·K for the sample 90FA:10ESP reinforced with 30% paddy straw. Data from different studies infer that using ESP and paddy straw reinforcement influences strength properties and thermal conductivity. The present study indicates valid information related to the using biowastes for the production of insulation materials and environmental preservation and energy conservation.

1. Introduction

Municipal and industrial waste management possesses a significant concern in developing countries like India. Dumping wastes into landfill is hazardous for the soil environment [1]. Alongside waste disposal, the rapid population growth requires more extensive land space, leading to land scarcity, and higher land costs [2, 3]. In this context, it is essential to encourage the use of such trash in building materials to divert as much waste as possible from landfills. Consequently, the amount of disposal is reduced in landfills and contributes to India's ongoing trash reduction drive [4]. Annually, significant volumes of fly ash (FA) and eggshell are generated [5]. Due to their mineralogical composition, these waste products are utilized in the construction industry [6].

Geopolymers, which exhibit comparable properties to cement, are being explored as a promising substitute due to their environmentally friendly nature. Additionally, these geopolymers are recognized for their impressive initial strength [7, 8] and fast setting [9, 10]. Furthermore, they demonstrate resilience against high temperatures [11, 12], acidic conditions [13], carbonation [14], chloride exposure [15, 16], and sulfate attacks [17].

(a) (b) (c) (d)

Figure 1: (a–d) Raw materials, namely, fly ash, eggshell powder, paddy straw, and alkaline activator, respectively.

It has been found that nearly 1.61 million tons of eggshells are produced [18]. It is easy to generate eggshell powder (ESP) with the minimum required additional energy or manpower. It is estimated that nearly about 94% calcium carbonate is found in eggshells, which can serve as an adequate substitute for lime cement manufacture [19]. This calcium carbonate with an alkaline solution imparts significant improvement in the mechanical strength of geopolymer composites [20]. Finer eggshell particles fill up the voids in the geopolymer composites, which makes the composites denser with higher strength [21]. Further, ESP contains the same amount of CaO as cement. Thus, ESP can be utilized as a partial replacement for any construction materials [22, 23].

FA obtained from coal combustion consists of a high amount of aluminosilicate materials and can be used as a precursor for geopolymer composites production [24]. India produces nearly 100 million tons of FA annually [25]. High silica and alumina in the FA contribute to the high pozzolanic activity, which makes FA a suitable substitute for cement [26]. Similarly, in the case of insulation material used for building construction, natural fibers are considered significant and valuable materials that help to reduce energy conservation [27]. Natural fibers are considered a valuable insulation material for sustainable construction, because of their low carbon emission, high acoustic proof, and low heat conductivity [28]. Paddy straw and wheat straw fibers have been investigated as potential renewable and environmentally friendly materials for building insulation applications [29].

Geopolymers are produced through a polycondensation process involving the dissolution of alumina and silica in the presence of an alkaline activator [30, 31]. Materials containing aluminum silicates are considered geopolymer precursor such as FA, ground granulated blast furnace slag, and so forth [32]. In the case of geopolymerization reaction, alkali activators act as a catalyst that releases metal cations like Na^+, K^+, and these ions balance the negatively charged Al atoms, forming tetrahedrally co-ordinated cementitious materials [33]. Usually, sodium silicate, sodium hydroxide, potassium silicate, and potassium hydroxide are alkaline activators. The alkaline activator leaches the Si and Al, present in the aluminosilicate material during geopolymerization [34, 35]. Although aluminosilicate materials are responsible for geopolymerization, adding ESP increases the calcium content and forms gel. Literature supports the formation of C–S–H, C–A–H, C–A–S–H, and N–A–S–H are included in the study of Li et al. [33], Phummiphan et al. [36], and Cristelo et al. [37]. The prime objective of the present work is to study the physical, mechanical, and thermal performance of lightweight geopolymer composites made with FA and ESP combinations. The elevated temperature has been followed to speed up the rate of reaction as stated in a previous article [31].

2. Materials and Methods

2.1. Materials. The current study involves the preparation of geopolymer composites using FA and ESP as precursor materials. Additionally, paddy straw is employed as a reinforcing component in the composites. Please refer to Figure 1(a)–1(d), for visual representations of the raw materials of geopolymer composites. Waste eggshells contained a large amount of calcium oxide acting as one of the additives collected from local vendors and were cleaned to remove the inner membrane. Collagen found on the inner membrane affects the binding property, hence, it is necessary to remove it before using it [38, 39]. The cleaned eggshells were ground to obtain finer particles of size less than 300 μm [40].

Raw material Class F FA obtained from a thermal power plant as a byproduct of combustion of coal. The chemical compositions of FA and ESP were obtained from energy dispersive X-ray spectroscopy, are presented in Table 1. The specific gravity of FA and ESP is 2.1 and 2.27, much lower than that of cement and soil specific gravity of 2.9–3.1 and 2.7–2.8, respectively, which contributes to the formation of lightweight geopolymer composites. Previous article

Table 1: Chemical composition of ESP and FA.

Chemical compounds	Component (wt%)	
	ESP	FA
CaO	58.89	5.90
SiO_2	0.61	56.18
Al_2O_3	0.53	14.20
Fe_2O_3	0.32	6.70
MgO	0.11	1.12

Table 2: Geopolymer composites mix details.

Sample code	Cement (%)	Fly ash (%)	ESP (%)	Paddy straw (%)	Liquid binder ratio	Curing medium
CP-0	100	0	0	0	0.5	Water
CP-15	85	0	0	15	0.7	Water
CP-30	70	0	0	30	0.7	Water
90FA:10ESP-0P	0	90	10	0	0.7	Heat
90FA:10ESP-15P	0	90	10	15	0.7	Heat
90FA:10ESP-30P	0	90	10	30	0.7	Heat
80FA:20ESP-0P	0	80	20	0	0.7	Heat
80FA:20ESP-15P	0	80	20	15	0.7	Heat
80FA:20ESP-30P	0	80	20	30	0.7	Heat
70FA:30ESP-0P	0	70	30	0	0.7	Heat
70FA:30ESP-15P	0	70	30	15	0.7	Heat
70FA:30ESP-30P	0	70	30	30	0.7	Heat

shows that chemical composition of ESP (58.89 wt% CaO, 0.61 wt% SiO_2, and 0.53 wt% Al_2O_3) is nearly equal to the conventional Portland cement (61 wt% CaO, 20 wt% SiO_2, 6 wt% Al_2O_3, 4 wt% Fe_2O_3, and 2 wt% MgO) [3]. Therefore, FA and ESP-based geopolymer composites are considered potential cement substitutes. The raw paddy straw gathered from a paddy field at Coimbatore, Tamil Nadu, India, was cleaned and dried. The dried paddy straw was treated with an alkaline solution to remove the impurities. The process of alkali treatment of paddy straw is given below.

As per the previous works of literatures [31, 34, 37, 41] 10 M NaOH was used as an alkaline activator, the process of making alkaline solutions is exothermic, and hence the desired amount of NaOH was dissolved into the water slowly to reduce the heat generated during dissolution [42]. Alkaline activator plays essential role in the condensation process of geopolymer composites, as the metal ions from the alkaline solution (NaOH) balances the ions released from aluminosilicate, producing cementitious materials with high mechanical properties [31, 43].

2.2. Experimental Methods

2.2.1. Process of Alkali Treatment. The shredded paddy straw was soaked in the alkaline solution (5% NaOH) for 4 hr. After soaking, the excess alkalinity was removed by rinsing it in water until the pH reached 7 [44]. To remove the moisture from the washed paddy straw was kept in the hot air oven at 45°C for 24 hr. The treated paddy straw having a fiber length of 3–5 mm with 0.5 mm diameter was found to be suitable for making geopolymer composites and was established from previous work [45]. The lignin, hemicellulose, and pectin in the raw paddy straw were intended to be dissolved by the alkali treatment with the NaOH solution. All the impurities were removed completely with this treatment. Further, this treatment helps to break the bundles of fibers into fractions, which produces more surface area and hence the maximum area of contact between fiber and surrounding matrix can be achieved to obtain strong composites [46–49].

2.2.2. Geopolymer Composites Mix. The geopolymer composites mix details are given in Table 2. In this work, FA and ESP were used as precursors with paddy straw as reinforcement. The combinations of samples were made with FA : ESP ratio of 90 : 10, 80 : 20, and 70 : 30 separately reinforced with varying weights of paddy straw, namely, 0, 15, and 30 wt% [40]. The controlled sample mix of cement samples was made with the paddy straw reinforcement of 0, 15, and 30 wt%. The ESP and FA were mixed by a mortar mixer till to reach the uniform consistency. The prepared alkaline solution of 10 M was added with mixed precursor at the desired quantity. The liquid-to-binder ratio was kept constant at 0.7 for geopolymer and 0.5 for neat cement samples. Due to the nature of the finer and large surface area of FA and ESP require an additional quantity of water than that needed for cement samples. The mixing procedure continued until it reached the homogeneous mixes, as reported in a previous article [41]. Figure 2(a)–2(c) illustrates the cube sample of size 50 mm × 50 mm × 50 mm, the beam sample of size 40 mm × 40 mm × 160 mm, and the board of size 300 mm × 300 mm × 10 mm were prepared for the

(a) (b) (c)

Figure 2: (a–c) Geopolymer samples of prism, cubes, and boards.

evaluation of compression, flexure, and thermal characteristics. The prepared samples were kept at room temperature for 24 hr with controlled humidity of 95% + 2% for setting. For each sample combination, triplicates of samples were made to reduce the percentage of errors. Based on ESP, FA, and Paddy straw ratios, nine sample combinations were made. In addition to the above, three more sample combinations were prepared for controlled mixing. According to previous work, a heat curing medium was adopted with a hot air oven at 60°C for 6 hr, later, the samples were kept at ambient temperature till the date of testing [50, 51].

2.2.3. Fresh, Physical, Mechanical, and Thermal Properties of Geopolymer Composites. Subsequent to the mixing process, an ASTM C230 compliant flow test was executed to assess the workability of the geopolymer composites. This involved filling molds, measuring 50 mm in size, with two layers of mortar—each layer being 25 mm thick. Adequate compaction of the geopolymer composites was achieved through tamping. Following thorough compaction, the molds were removed, and the flow table was subjected to 25 drops within a 15 s interval [17, 52].

The dry bulk density of the samples was determined in accordance with ASTM C-642-13. The dry bulk densities were calculated by the ratio of mass to volume, and density variation helps to identify the degree of polymerization occurring on different curing mediums. The water absorption test was carried out in accordance with ASTM C1403-15 and the test results were recorded.

The direct compression test was conducted in accordance with ASTM C-109-20a. This experimental work was carried out with a compression testing machine of capacity 200 kN. The samples of size 50 mm × 50 mm × 50 mm were tested at the age of 28 days of casting. The rate of loading of 0.34 MPa/s was applied to the sample reaches the peak load. Three identical specimens from each mix were taken for testing and the mean values of the samples were recorded.

The flexural test was carried out at ambient temperature in accordance with ASTM C 348. The samples from all the mix of size 160 mm × 40 mm × 40 mm were allowed for three-point bending. The bending test was carried out with Instran 500 testing machine at a rate of displacement (Strain) 0.5 mm/min. All the specimens were kept at the orientation of tensile surface perpendicular direction of lamination and the maximum load under failure condition was recorded. The testing setup for compression and flexure are shown in Figures 3(a) and 3(b), respectively, for reference.

According to ASTM-C518 2010, thermal conductivity test was performed with HFM-436 Lamda series instrument. Thermal conductivity of paddy straw fiberboard with varying weight percentages of ESP with 30% paddy straw reinforcement has been investigated. The working principle of an instrument is shown in Figure 4. The board was placed between the hot and cold plate and the temperature differences were maintained at 30°C, and the heat flow transferred through the board was measured by the heat flux sensor. The test was conducted with 300 mm × 300 mm with 10 mm thick board was used for this test. The transducer with integrated micrometer scale was used to measure the exact thickness of the sample. The tolerance limit for the thermal conductivity results are kept at 0.5% (error bars), and the reading accuracy for temperature was kept at ±0.01°C and the accuracy of thermal conductivity was ±1%–3% W/m·K.

2.2.4. Thermogravimetric Analysis of Treated Paddy Straw. Thermo gravimetric analysis (TGA) has been employed to assess the performance against an increase in temperature and to predict the impact of thermal stability and degradation of untreated paddy straw fiber and treated paddy straw fiber. The paddy straw was shredded to have a fiber of length 3–5 mm with 0.5 mm dia tested by TGA scan at 25–1,200°C under a heating rate of 2°C/min. The test was conducted in nitrogen atmosphere. The instrument model used for the study was NETZSCH STA 449F3. The untreated paddy straw was weighed 2.171 mg in an AL-203 crucible. During the entire heating operation, the mass loss of the material was studied and recorded at regular time intervals.

(a) (b)

Figure 3: (a, b) Images of compression test and flexural test.

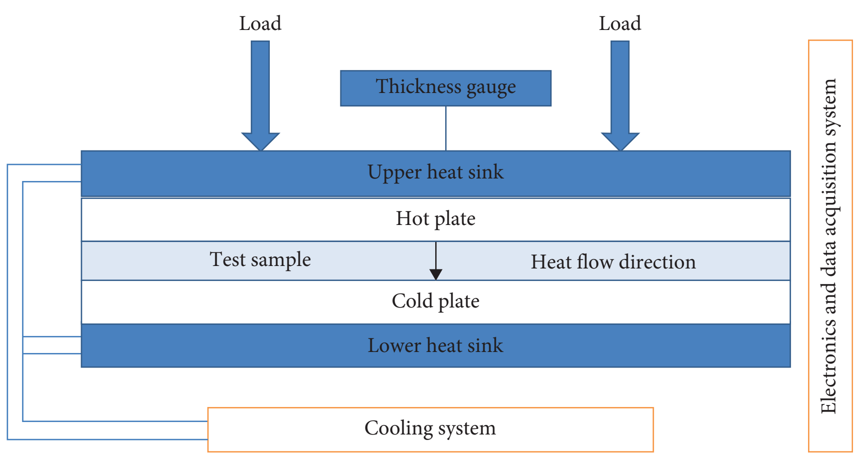

Figure 4: Working principles of NETZSCH–heat flow meter–LAMDA 436.

3. Results and Discussion

3.1. Fresh and Physical Properties. The results obtained from the flow table test were shown in Figure 5. It's noteworthy that the flow diameters corresponding to the specimens labeled as C-0P, 90:10-0P, 80:20-0P, and 70:30-0P were measured at 97, 92, 86, and 71 mm, respectively. The graphical illustration indicates that the progressive increment in the proportion of ESP content reduces its workability. This outcome is in concurrence with the evident property of ESP, which, functioning as a prospective filler within the geopolymer matrix, imparts a restrictive influence on flow characteristics [5, 53]. As is evident, the inherent porous fibrous structure of paddy straw allows for a higher water uptake from the geopolymer slurry, resulting in reduced workability. This effect becomes more pronounced with increased replacement levels, ultimately leading to a complete absence of workability at higher replacements. Consequently, this investigation

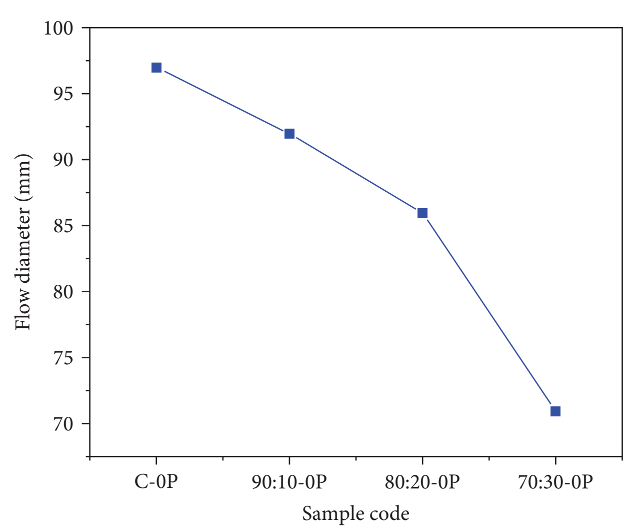

Figure 5: Flowability of cement and geopolymer composites without paddy straw inclusion.

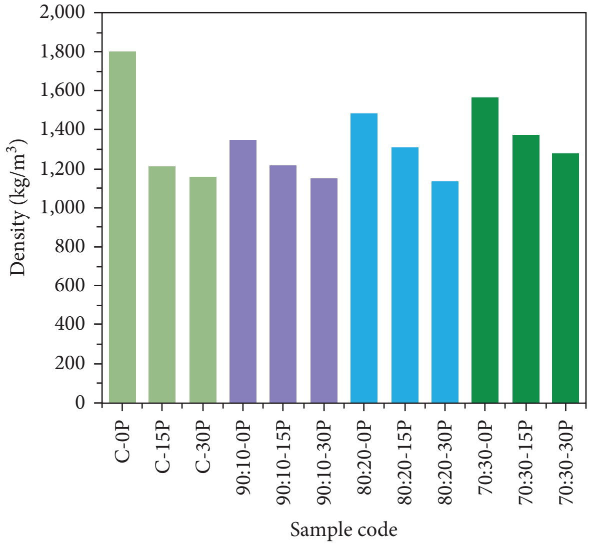

FIGURE 6: Dry density of geopolymer composites.

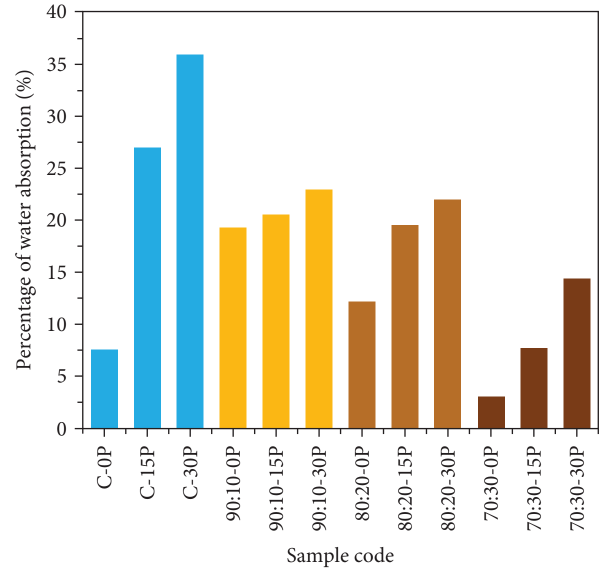

FIGURE 7: Water absorption of geopolymer and cement samples.

refrained from conducting workability assessments on samples incorporating paddy straw due to these observed characteristics [54].

According to ASTM C140 standard, the sample volume and weights were measured after 28 days of curing. Figure 6 illustrates the density variation among the samples. The test results clearly exhibit the geopolymer sample has lower density than that of the neat cement sample. Utilization of lightweight materials like ESP, FA, and paddy straw contributes to lower density of resulting geopolymer composites. According to ACTM C90 standards, the density between 1,680 and 2,000 kg/m^3 are considered as medium density and lower than that of the value considered for lightweight materials. The highest density of 1,560 kg/m^3 was observed for the sample 70FA:30ESP-0P and the lowest density of 1,128 kg/m^3 was obtained for the sample 90FA:10ESP-30P. From the test results, increase in the percentage weight of ESP content increases the density, whereas the reverse trend was noticed when increase in the percentage weight of paddy straw. These results well explained about the contribution of precursor (ESP) on density development and the same was confirmed from the reported literature [40, 53, 55–57].

The higher specific gravity of ESP gives rise to a proportionally increased maximum dry density. Since FA exhibits a lower density compared to ESP, the elevation in ESP content corresponds to a surge in the maximum dry density of the material [40, 55]. Moreover, the microstructural analysis outlined in the previous articles [58] provides validation for the presence of crystalline-phase CaO within the ESP. This presence plays a pivotal role in enhancing short-term strength development, primarily attributed to a calcium-based geopolymeric gel. This gel is synthesized in limited proportions through the activation of ESP within the matrix of the FA-based geopolymer [59].

Figure 7 depicts the water absorption percentages of both geopolymer composites and cement samples. The graphical representation highlights that the highest water absorption occurred in the case of specimens reinforced with 30 wt% paddy straw. The fiber content present in the samples was responsible for water absorption, the same was confirmed from the literature reported [60]. The geopolymer sample 90FA:10ESP-30P and cement sample C-30P attained the higher water absorption of 22% and 36%, respectively. As reported in the literature, the geopolymer sample had lesser water absorption than that of cement sample [61]. Further, increase in the percentage weight of ESP content reduces the water absorption rate. The lowest water absorption of 3.07% was observed for the sample 70FA:30ESP-0P, whereas 90FA:10ESP-0P exhibits significantly higher water absorption of 19.3%. The phenomenon behind this variation of water absorption was finer particles of ESP reduce the amount of pores present in composites [55].

According to the code ASTM C55, permissible water absorption rate for normal, medium, and lightweight masonry blocks are 10.4%, 13%, and 17.14%, respectively. The lowest value of 3.07% found for the geopolymer composites was much lesser than that of the standard, and hence geopolymer composites are more feasible lightweight materials when compared to that of cement-based lightweight materials.

3.2. Mechanical Properties

3.2.1. Compressive and Flexural Strength. During the process of geopolymerization, the reaction occurs between the CaO, silica, and alumina from ESP, FA, and alkaline activators are responsible for strength development [21]. Figure 8 represents the compressive strength of cement and geopolymer composites with varying combinations of binder and paddy straw. Among these, the highest value of compressive strength was observed for cement and geopolymer samples is ranged between 19.60 and 15.64 MPa (70:30-0P). An increase in ESP content, namely, 10%, 20%, and 30% increases the value of compressive strength by 10.12, 12.08, and 15.64 MPa, respectively. The finer surface area of ESP is more reactive with

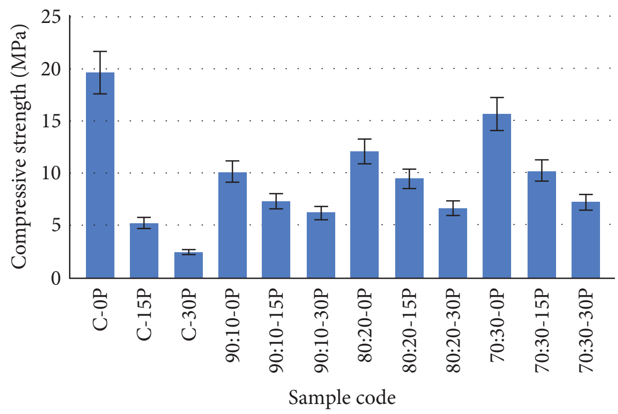

Figure 8: Compressive strength of geopolymer and cement samples.

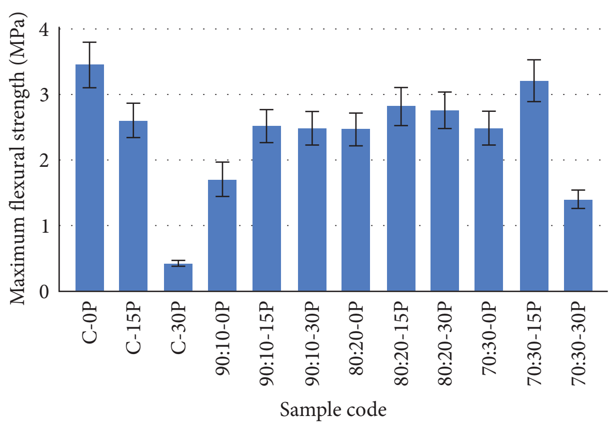

Figure 9: Flexural strength of geopolymer and cement samples.

activator particles [55]. The previous article ensures the high calcium oxide present in the ESP gives early strength to the geopolymer composites [55]. The incorporation of paddy straw significantly reduces its compressive strength [62]. That is the reinforcement of 30% paddy straw for the cement sample reduces its compressive strength value by 87.7%, whereas for the geopolymer sample (70FA:30ESP), the value was decreased to 53.96% [59]. It shows that the paddy straw reinforcement significantly reduces the value of compressive strength of the cement sample when compared with that of the geopolymer sample. The bond occurred between paddy straw fiber and geopolymer composites is evident from the improved geopolymer performance with cement samples [63–65].

Figure 9 presents the values of flexural strength of geopolymer composites prepared with varying ratios of precursors with different weight percentage of reinforcement of paddy straw. Data resulted infer that the reinforcement of paddy straw gradually reduces the value of flexural strength of cement samples, whereas in the case of geopolymer samples, the reinforcement of paddy straw up to 15% improves the flexural strength significantly. In detail, the cement sample with 15% paddy straw content reduces its flexural strength by 24.63%, whereas in the case of geopolymer (70FA:30ESP-15P) the values of flexural strength found to

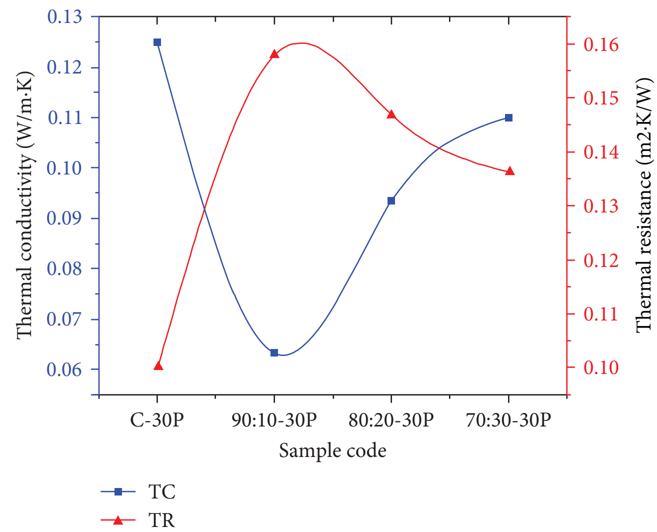

Figure 10: Comparative plot for thermal conductivity and thermal resistance.

be increased about 160%. The reason behind such increment is treated paddy straw fiber has efficient adhesion and good bonding with surrounding geopolymer composites. The reinforcement of paddy straw supports the flexural stress transferred from composites to fiber and thereby improving the flexural strength [66, 67]. Even though the reinforcement of paddy straw enhances the value of flexural strength, beyond 15 wt% of reinforcement of paddy straw, the reverse trend was noticed. The reason behind such reduction is increasing in paddy beyond the desired limit may be due to nonuniform distribution, and agglomeration paddy straw fibers, thereby reducing the flexural strength [68]. Therefore, geopolymer composites made with 70FA:30ESP and 15 wt% of reinforcement of paddy straw were found to be the optimum to achieve maximum value of flexural strength.

3.3. Thermal Properties

3.3.1. Thermal Conductivity Measurement. In Figure 10, the thermal conductivity values of both cement and geopolymer composites are presented. The cement particle board with 30% replacement of paddy straw exhibited a thermal conductivity of 0.124943 W/mK, whereas the geopolymer composite (90FA:10ESP:30P) possessed a thermal conductivity of 0.063285 W/mK, indicating a 49.34% reduction in thermal conductivity.

When focusing specifically on the geopolymer composites, the highest thermal conductivity was observed in the sample 70FA:30ESP:30P (0.110023 W/mK). This value is 73.85% higher than that of the 90FA:10ESP:30P composite (0.063285 W/mK), and it is 11.94% lower than the thermal conductivity of the cement particle board (0.124943 W/mK).

The reason behind the above observation is the maximum replacement of ESP with FA influencing the efficient formation of denser composites by closely filling all the voids due to its finer surface area [21]. Previous literature has provided evidence supporting a direct relationship between the density and thermal conductivity of composites. It has

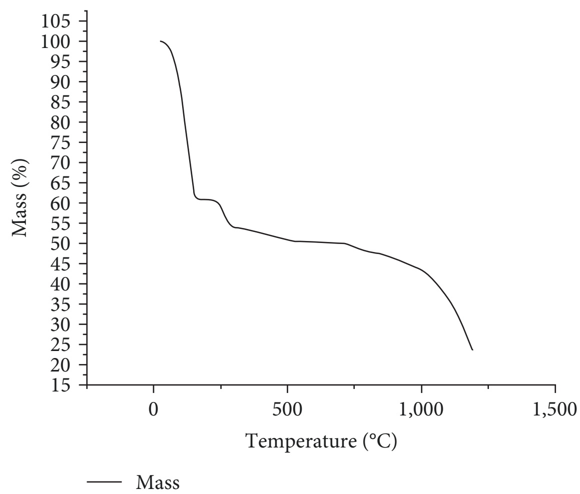

FIGURE 11: Thermogravimetric analysis of treated paddy straw.

been established that composites with lower density tend to exhibit lower thermal conductivity [69]. Further, it is well known that there is an inverse relationship between thermal resistance and thermal conductivity. In this particular scenario, a reduction of 49.34% in thermal conductivity resulted in a corresponding increase in thermal resistance by 57.92%. Upon analyzing the aforementioned results, it can be observed that reducing the replacement of ESP in the composites leads to a decrease in composite density, which consequently results in lower thermal conductivity. This observation indicates the paddy straw fiber-reinforced particle board can be considered as a cost competitive material for thermal insulation application. As the thermal conductivity of sample wall panel boards developed in the present work is within the acceptable limit, these boards can be considered as possible and promising thermal insulation materials [70, 71].

3.3.2. Thermo Gravimetric Analysis of Treated Paddy Straw. The thermogram obtained for the treated paddy straw is shown in Figure 11. The graph infers that the degradation temperature of the treated sample of paddy straw rises significantly after the treatment. As from the previous research, it was found that an increase in temperature, increases the deterioration also increased [72]. Temperature ranges from 235 to 255°C were found to be the decomposing temperature for the treated paddy straw. This results explicit higher degree of thermal stability achieved for treated paddy straw. The presence of carbonaceous elements in the paddy straw under nitrogen atmosphere is indicated by the fiber residue that remains after heating of 530°C [73]. The amount of residue in the fibers obtained after treatments was quite low because calcium oxalate crystals of lignin and other sources of ash were removed during the high-pressure and temperature procedure. These results suggest that hemicellulose and lignin were removed in part, leading to a decreased residual mass of paddy straw fibers, which in turn increased the temperature at which they decomposed. All these point to a noticeable improvement in the thermal resistance of treated paddy straw fibers, when using with geopolymer composites.

4. Conclusion

The present work deals with the development of treated paddy straw reinforced ESP blended FA-based hybrid geopolymer lightweight composite panels for possible thermal insulation application. The hybrid composite panels developed with conventional dimensions were studied for their strength-related properties such as density, water absorption, compression, and flexural performance according to standard methods and the results are discussed.

When compared to the plain geopolymer, the composite samples containing ESP exhibit enhanced compression and flexural performance. This improvement can be attributed to their effective interaction and the formation of robust chemical bonds. The paddy straw reinforcement influences the reduction of density and facilitates the formation of lightweight composites with improved flexural behavior. When considering mechanical properties, the sample prepared with a composition of 70% FA and 30% ESP without any paddy straw (70FA:30ESP-0P) demonstrates the highest compressive strength of 15.64 MPa. By contrast, the sample developed with a mixture of 70% FA, 30% ESP, and 15% paddy straw reinforcement (70FA:30ESP-15P) exhibits the maximum flexural strength of 3.21 MPa. Additionally, the sample prepared with a blend of 90% FA and 10% ESP, along with 30% paddy straw reinforcement (90FA:10ESP-30P), showcases the lowest thermal conductivity of 0.0633 W/mK. This value is 49.32% lower than the thermal conductivity of the cement board (C-30P) reinforced with 30 wt% paddy straw, which has a thermal conductivity of 0.1249 W/mK. Data resulting from various studies suggest that the incorporation of paddy straw, ESP, and FA in geopolymer composites can be utilized to create effective lightweight wall panels with good insulating properties.

Data Availability

The original contributions presented in this study are included in the article, further inquiries directed toward the corresponding and submitting author.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Sharholy, K. Ahmad, G. Mahmood, and R. C. Trivedi, "Municipal solid waste management in Indian cities—a review," *Waste Management*, vol. 28, no. 2, pp. 459–467, 2008.

[2] N. Singh and S. P. Singh, "Validation of carbonation behavior of self compacting concrete made with recycled aggregates using microstructural and crystallization investigations," *European Journal of Environmental and Civil Engineering*, vol. 24, no. 13, pp. 2187–2210, 2020.

[3] N. Singh and S. P. Singh, "Carbonation resistance of self-compacting recycled aggregate concretes with silica fume," *Journal of Sustainable Cement-Based Materials*, vol. 7, no. 4, pp. 214–238, 2018.

[4] A. Pappu, M. Saxena, and S. R. Asolekar, "Solid wastes generation in India and their recycling potential in building materials," *Building and Environment*, vol. 42, no. 6, pp. 2311–2320, 2007.

[5] M. Dhanalakshmi, N. J. Sowmya, and A. Chandrashekar, "A comparative study on egg shell concrete with partial replacement of cement by fly ash," *International Journal of Engineering Research & Technology (IJERT)*, vol. 4, no. 5, pp. 12–20, 2015.

[6] H. M. Hamada, B. A. Tayeh, A. Al-Attar, F. M. Yahaya, K. Muthusamy, and A. M. Humada, "The present state of the use of eggshell powder in concrete: a review," *Journal of Building Engineering*, vol. 32, Article ID 101583, 2020.

[7] K. Korniejenko, P. Kejzlar, and P. Louda, "The influence of the material structure on the mechanical properties of geopolymer composites reinforced with short fibers obtained with additive technologies," *International Journal of Molecular Sciences*, vol. 23, no. 4, Article ID 2023, 2022.

[8] X. Guo, J. Yang, and G. Xiong, "Influence of supplementary cementitious materials on rheological properties of 3D printed fly ash based geopolymer," *Cement and Concrete Composites*, vol. 114, Article ID 103820, 2020.

[9] H. M. Yang, S. M. Zhang, L. Wang et al., "High-ferrite Portland cement with slag: hydration, microstructure, and resistance to sulfate attack at elevated temperature," *Cement and Concrete Composites*, vol. 130, Article ID 104560, 2022.

[10] P. Zhang, W. Wang, Y. Lv, K. Wang, and S. Dai, "Effect of polymer coatings on the freezing–thawing and carbonation resistances of nano-SiO_2 and polyvinyl alcohol fiber-reinforced cementitious composites," *Journal of Materials Research and Technology*, vol. 21, pp. 69–83, 2022.

[11] C. Wen, P. Zhang, J. Wang, and S. Hu, "Influence of fibers on the mechanical properties and durability of ultra-high-performance concrete: a review," *Journal of Building Engineering*, vol. 52, Article ID 104370, 2022.

[12] P. Zhang, X. Han, J. Guo, and S. Hu, "High-temperature behavior of geopolymer mortar containing nano-silica," *Construction and Building Materials*, vol. 364, Article ID 129983, 2023.

[13] G. Zhang, C. Wu, D. Hou, J. Yang, D. Sun, and X. Zhang, "Effect of environmental pH values on phase composition and microstructure of Portland cement paste under sulfate attack," *Composites Part B: Engineering*, vol. 216, Article ID 108862, 2021.

[14] G. L. Golewski, "An extensive investigations on fracture parameters of concretes based on quaternary binders (QBC) by means of the DIC technique," *Construction and Building Materials*, vol. 351, Article ID 128823, 2022.

[15] L. Kan, F. Wang, Z. Zhang, W. Kabala, and Y. Zhao, "Mechanical properties of high ductile alkali-activated fiber reinforced composites with different curing ages," *Construction and Building Materials*, vol. 306, Article ID 124833, 2021.

[16] P. Zhang, X. Sun, F. Wang, and J. Wang, "Mechanical properties and durability of geopolymer recycled aggregate concrete: a review," *Polymers*, vol. 15, no. 3, Article ID 615, 2023.

[17] P. Zhang, S. Wei, Y. Zheng, F. Wang, and S. Hu, "Effect of single and synergistic reinforcement of PVA fiber and nano-SiO_2 on workability and compressive strength of geopolymer composites," *Polymers*, vol. 14, no. 18, Article ID 3765, 2022.

[18] A. Bhartiya and M. Dubey, "Replacement of cement with coconut shell ash and egg shell powder for preparation of fresh concrete," *International Research Journal of Engineering and Technology (IRJET)*, vol. 05, no. 6, pp. 1272–1275, 2018.

[19] M. Mohamed Ansari, M. Dinesh Kumar, J. Milan Charles, and G. Vani, "Replacement of cement using eggshell powder," *International Journal of Civil Engineering*, vol. 3, no. 3, pp. 1-2, 2016.

[20] A. S. Sauffi, W. M. W. Ibrahim, M. M. A. B. Abdulla et al., "A review of carbonate minerals as an additive to geopolymer materials," *IOP Conference Series: Materials Science and Engineering*, vol. 551, Article ID 12084, 2019.

[21] I. C. Moison, L. Gungat, H. Asrah, and F. H. Chiew, "A review of eggshell powder and fly ash-based geopolymers concrete," *IOP Conference Series: Materials Science and Engineering*, vol. 1229, Article ID 12011, 2022.

[22] A. A. Jhatial, W. I. Goh, K. H. Mo, S. Sohu, and I. A. Bhatti, "Green and sustainable concrete—the potential utilization of rice husk ash and egg shells," *Civil Engineering Journal*, vol. 5, no. 1, pp. 74–81, 2019.

[23] S. Kamaruddin, W. I. Goh, A. A. Jhatial, and M. T. Lakhiar, "Chemical and fresh state properties of foamed concrete incorporating palm oil fuel ash and eggshell ash as cement replacement," *International Journal of Engineering & Technology*, vol. 7, no. 4.30, pp. 350–354, 2018.

[24] K. Somna, C. Jaturapitakkul, P. Kajitvichyanukul, and P. Chindaprasirt, "NaOH-activated ground fly ash geopolymer cured at ambient temperature," *Fuel*, vol. 90, no. 6, pp. 2118–2124, 2011.

[25] M. Sivakumar and N. Mahendran, "Strength and permeability properties of concrete using fly ash (FA), rise husk ash (RHA) and egg shell powder (ESP)," *Journal of Theoretical and Applied Information Technology*, vol. 66, no. 2, pp. 489–499, 2014.

[26] H. M. Giasuddin, J. G. Sanjayan, and P. G. Ranjith, "Strength of geopolymer cured in saline water in ambient conditions," *Fuel*, vol. 107, pp. 34–39, 2013.

[27] Y. Huang, J. Tan, X. Xuan et al., "Study on untreated and alkali treated rice straw reinforced geopolymer composites," *Materials Chemistry and Physics*, vol. 262, Article ID 124304, 2021.

[28] L. Savio, R. Pennacchio, A. Patrucco, V. Manni, and D. Bosia, "Natural fibre insulation materials: use of textile and agri-food waste in a circular economy perspective," *Materials Circular Economy*, vol. 4, Article ID 6, 2022.

[29] A. Thomson and P. Walker, "Durability characteristics of straw bales in building envelopes," *Construction and Building Materials*, vol. 68, pp. 135–141, 2014.

[30] J. Davidovits, "Geopolymers: inorganic polymeric new materials," *Journal of Thermal Analysis and Calorimetry*, vol. 37, no. 8, pp. 1633–1656, 1991.

[31] A. Palomo, M. W. Grutzeck, and M. T. Blanco, "Alkali-activated fly ashes: a cement for the future," *Cement and Concrete Research*, vol. 29, no. 8, pp. 1323–1329, 1999.

[32] N. B. Singh and B. Middendorf, "Geopolymers as an alternative to Portland cement: an overview," *Construction and Building Materials*, vol. 237, Article ID 117455, 2020.

[33] Y. Li, X. Min, Y. Ke, D. Liu, and C. Tang, "Preparation of red mud-based geopolymer materials from MSWI fly ash and red mud by mechanical activation," *Waste Management*, vol. 83, pp. 202–208, 2019.
[34] P. Sukmak, S. Horpibulsuk, and S.-L. Shen, "Strength development in clay–fly ash geopolymer," *Construction and Building Materials*, vol. 40, pp. 566–574, 2013.
[35] M. S. Morsy, S. H. Alsayed, Y. Al-Salloum, and T. Almusallam, "Effect of sodium silicate to sodium hydroxide ratios on strength and microstructure of fly ash geopolymer binder," *Arabian Journal for Science and Engineering*, vol. 39, pp. 4333–4339, 2014.
[36] I. Phummiphan, S. Horpibulsuk, P. Sukmak, A. Chinkulkijniwat, A. Arulrajah, and S.-L. Shen, "Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer," *Road Materials and Pavement Design*, vol. 17, no. 4, pp. 877–891, 2016.
[37] N. Cristelo, S. Glendinning, L. Fernandes, and A. T. Pinto, "Effect of calcium content on soil stabilisation with alkaline activation," *Construction and Building Materials*, vol. 29, pp. 167–174, 2012.
[38] P. Pliya and D. Cree, "Limestone derived eggshell powder as a replacement in Portland cement mortar," *Construction and Building Materials*, vol. 95, pp. 1–9, 2015.
[39] O. O. Amu, A. B. Fajobi, and B. O. Oke, "Effect of eggshell powder on the stabilizing potential of lime on an expansive clay soil," *Journal of Applied Sciences*, vol. 5, no. 8, pp. 1474–1478, 2005.
[40] P. Shekhawat, G. Sharma, and R. M. Singh, "Potential application of heat cured eggshell powder and flyash-based geopolymer in pavement construction," *International Journal of Geosynthetics and Ground Engineering*, vol. 6, Article ID 28, 2020.
[41] C. Suksiripattanapong, S. Horpibulsuk, S. Boongrasan, A. Udomchai, A. Chinkulkijniwat, and A. Arulrajah, "Unit weight, strength and microstructure of a water treatment sludge–fly ash lightweight cellular geopolymer," *Construction and Building Materials*, vol. 94, pp. 807–816, 2015.
[42] R. M. Hamidi, Z. Man, and K. A. Azizli, "Concentration of NaOH and the effect on the properties of fly ash based geopolymer," *Procedia Engineering*, vol. 148, pp. 189–193, 2016.
[43] J. Davidovits, "Properties of geopolymer cements," in *Proceedings of First International Conference on Alkaline Cements and Concretes*, pp. 131–149, Kiev State Technical University, Kiev, Ukraine, 1994.
[44] M. G. Jackson, "Review article: the alkali treatment of straws," *Animal Feed Science and Technology*, vol. 2, no. 2, pp. 105–130, 1977.
[45] K. Korniejenko, E. Frączek, E. Pytlak, and M. Adamski, "Mechanical properties of geopolymer composites reinforced with natural fibers," *Procedia Engineering*, vol. 151, pp. 388–393, 2016.
[46] S. Mishra, A. K. Mohanty, L. T. Drzal, M. Misra, and G. Hinrichsen, "A review on pineapple leaf fibers, sisal fibers and their biocomposites," *Macromolecular Materials and Engineering*, vol. 289, no. 11, pp. 955–974, 2004.
[47] F. Pacheco-Torgal and S. Jalali, "Cementitious building materials reinforced with vegetable fibres: a review," *Construction and Building Materials*, vol. 25, no. 2, pp. 575–581, 2011.
[48] P. Duxson, A. Fernández-Jiménez, J. L. Provis, G. C. Lukey, A. Palomo, and J. S. J. van Deventer, "Geopolymer technology: the current state of the art," *Journal of Materials Science*, vol. 42, pp. 2917–2933, 2007.
[49] D. Sedan, C. Pagnoux, A. Smith, and T. Chotard, "Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction," *Journal of the European Ceramic Society*, vol. 28, no. 1, pp. 183–192, 2008.
[50] P. Zhang, Y. Zheng, K. Wang, and J. Zhang, "A review on properties of fresh and hardened geopolymer mortar," *Composites Part B: Engineering*, vol. 152, pp. 79–95, 2018.
[51] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, "On the development of fly ash-based geopolymer concrete," *Materials Journal*, vol. 101, no. 6, pp. 467–472, 2004.
[52] S. E. Wallah and B. V. Rangan, *Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties*, Curtin University of Technology, 2006.
[53] D. S. Ing and C. S. Choo, "Eggshell powder: potential filler in concrete," in *Malaysian Technical Universities Conference on Engineering and Technology*, Research Gate, 2014.
[54] T. Bezabih, C. Kanali, and J. Thuo, "Effects of teff straw ash on the mechanical and microstructural properties of ambient cured fly ash-based geopolymer mortar for onsite applications," *Results in Engineering*, vol. 18, Article ID 101123, 2023.
[55] P. Shekhawat, G. Sharma, and R. M. Singh, "Strength behavior of alkaline activated eggshell powder and flyash geopolymer cured at ambient temperature," *Construction and Building Materials*, vol. 223, pp. 1112–1122, 2019.
[56] C. Phetchuay, S. Horpibulsuk, C. Suksiripattanapong, A. Chinkulkijniwat, A. Arulrajah, and M. M. Disfani, "Calcium carbide residue: alkaline activator for clay–fly ash geopolymer," *Construction and Building Materials*, vol. 69, pp. 285–294, 2014.
[57] P. Sukmak, P. De Silva, S. Horpibulsuk, and P. Chindaprasirt, "Sulfate resistance of clay-portland cement and clay high-calcium fly ash geopolymer," *Journal of Materials in Civil Engineering*, vol. 27, no. 5, Article ID 4014158, 2015.
[58] P. Shekhawat, G. Sharma, and R. M. Singh, "Morphology and microstructure of waste material-based geopolymer with flyash, eggshell powder, and soft soil," *Materials Letters*, vol. 334, Article ID 133621, 2023.
[59] P. Shekhawat, G. Sharma, and R. M. Singh, "Strength characteristics of hazardous wastes flyash and eggshell powder-based geopolymer-stabilized soft soil cured at ambient temperature," *Arabian Journal of Geosciences*, vol. 16, Article ID 127, 2023.
[60] Ö. Andiç-Çakir, M. Sarikanat, H. B. Tüfekçi, C. Demirci, and Ü. H. Erdoğan, "Physical and mechanical properties of randomly oriented coir fiber–cementitious composites," *Composites Part B: Engineering*, vol. 61, pp. 49–54, 2014.
[61] X. Xie, Z. Zhou, M. Jiang, X. Xu, Z. Wang, and D. Hui, "Cellulosic fibers from rice straw and bamboo used as reinforcement of cement-based composites for remarkably improving mechanical properties," *Composites Part B: Engineering*, vol. 78, pp. 153–161, 2015.
[62] P. Zhang, X. Han, S. Hu, J. Wang, and T. Wang, "High-temperature behavior of polyvinyl alcohol fiber-reinforced metakaolin/fly ash-based geopolymer mortar," *Composites Part B: Engineering*, vol. 244, Article ID 110171, 2022.
[63] M. Chougan, S. H. Ghaffar, P. Sikora, E. Mijowska, W. Kukułka, and D. Stephan, "Boosting Portland cement-free composite performance via alkali-activation and reinforcement with pre-treated functionalised wheat straw," *Industrial Crops and Products*, vol. 178, Article ID 114648, 2022.

[64] L. Zhu, J. Qiu, W. Liu, and E. Sakai, "Mechanical and thermal properties of rice straw/PLA modified by nano attapulgite/PLA interfacial layer," *Composites Communications*, vol. 13, pp. 18–21, 2019.

[65] R. Scaffaro, A. Maio, E. F. Gulino, and G. Pitarresi, "Lignocellulosic fillers and graphene nanoplatelets as hybrid reinforcement for polylactic acid: effect on mechanical properties and degradability," *Composites Science and Technology*, vol. 190, Article ID 108008, 2020.

[66] L. Yan, N. Chouw, and X. Yuan, "Improving the mechanical properties of natural fibre fabric reinforced epoxy composites by alkali treatment," *Journal of Reinforced Plastics and Composites*, vol. 31, no. 6, pp. 425–437, 2012.

[67] R. A. J. Malenab, J. P. S. Ngo, and M. A. B. Promentilla, "Chemical treatment of waste abaca for natural fiber-reinforced geopolymer composite," *Materials*, vol. 10, no. 6, Article ID 579, 2017.

[68] T. Alomayri, F. U. A. Shaikh, and I. M. Low, "Characterisation of cotton fibre-reinforced geopolymer composites," *Composites Part B: Engineering*, vol. 50, pp. 1–6, 2013.

[69] M. G. Ranjithkumar, P. Chandrasekaran, and G. Rajeshkumar, "Characterization of sustainable natural fiber reinforced geopolymer composites," *Polymer Composites*, vol. 43, no. 6, pp. 3691–3698, 2022.

[70] P. Zhang, Q. Han, J. Wu, Y. Zhang, and T. Zhang, "Mechanical properties of nano-SiO_2 reinforced engineered cementitious composites after exposure to high temperatures," *Construction and Building Materials*, vol. 356, Article ID 129123, 2022.

[71] P. V. Domke and V. D. Mude, "Natural fiber reinforced building materials," *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, vol. 12, no. 3, pp. 104–107, 2015.

[72] X. Chen, J. Yu, Z. Zhang, and C. Lu, "Study on structure and thermal stability properties of cellulose fibers from rice straw," *Carbohydrate Polymers*, vol. 85, no. 1, pp. 245–250, 2011.

[73] B. Xiao, X. F. Sun, and R. C. Sun, "Chemical, structural, and thermal characterizations of alkali-soluble lignins and hemicelluloses, and cellulose from maize stems, rye straw, and rice straw," *Polymer Degradation and Stability*, vol. 74, no. 2, pp. 307–319, 2001.