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Physical and mechanical properties of locally fabricated geopolymer-plastic ceiling boards

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ABSTRACT

The 21st century has seen a rise in the demand for building materials, which is not unconnected to the rise in population. The high demand has led to an increase in the price of such commodities as well as a strain on environmental resources and the call for more sustainable, and cost-effective alternatives to replace the conventional materials. In this study, waste glass powder was alkali-activated to produce geopolymer, which was combined with both fine and coarse waste polyethylene terephthalate (PET) pulverized plastics (aggregates). The product was then cured to form the ceiling board. The impact of the employed glass, alkaline solution, aggregate size, and aggregate content in the boards were then investigated. Board J with 92.5% PET particles (Coarse and Fine) and 7.5% Glass Particles gave the best water absorption (16.561%), thickness swelling (3.332%) and density test (0.918 g/cm^3) results. It was found that the geopolymer with equal proportions of fine and coarse PET aggregates reduced the material's ability to absorb water and increased its density and swelling thickness. The modulus of rupture and modulus of elasticity of the boards were both enhanced by adding more glass powder and fine PET aggregates. However, it was discovered that the board's mechanical qualities, unlike its physical properties, were not improved by the addition of the geopolymer during manufacture.

1. Introduction

Sustainable building materials refer to products and materials used in construction that are environmentally friendly and promote energy efficiency [1–3]. In today's world, where the effects of climate change are becoming increasingly evident, it is crucial to consider the impact of construction practices on the environment. The need for sustainable building materials has never been greater. One of the main reasons for the need for sustainable building materials is to reduce the carbon footprint of the construction industry [4]. Conventional building materials such as concrete, steel, and asphalt are responsible for a significant portion of global greenhouse gas emissions [5]. By using sustainable building materials, the carbon emissions associated with construction can be reduced, contributing to a cleaner and healthier environment. Another reason for the need for sustainable building materials is to conserve natural resources [6]. Many traditional building materials, such as timber, are becoming scarce and are being extracted at an unsustainable rate [7–9]. By using alternative materials such as bamboo or recycled materials, the depletion of natural resources can be slowed and a more sustainable future can be ensured [10]. Sustainable building materials also contribute to the health and well-being of the occupants of a building [11]. For example, materials such as bamboo, cork, and wool have natural insulation properties that help regulate temperature and improve indoor air quality [12,13]. These materials are free from harmful chemicals and are less likely to emit pollutants, promoting a healthy indoor environment.

Geopolymers are a type of inorganic polymer that is made from naturally occurring aluminosilicates, such as fly ash and slag [14,15]. The production of geopolymers involves a chemical reaction between the aluminosilicates and an alkaline activator solution, which causes the material to solidify and form a polymer-like substance [16–18]. Geopolymers are considered an environmentally friendly alternative to traditional Portland cement-based materials, as they produce fewer greenhouse gas emissions during production and can be made from

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waste materials [19]. Additionally, geopolymers are often stronger and more durable and offer improved environmental sustainability than traditional concrete [20]. They can be used in a variety of applications, including construction, road paving, and water treatment [20]. Geopolymer-plastic ceiling boards, therefore, are composites consisting of a mixture of geopolymers and plastic wastes used as construction materials, to the best of the author's knowledge, there has yet to be any study in the literature that utilized geopolymer for the fabrication of ceiling boards. Due to the properties of the geopolymer alongside the properties of plastic, the geopolymer ceiling board may have better physical and mechanical properties as compared to other materials used to construct ceiling boards, like asbestos and timber, among others. It also significantly reduces the cost of production as wastes which are readily available, and supports sustainable/green technology as it makes use of waste products that do not use excess energy in their production. Geopolymer withstands high temperatures due to its thermal conductivity property and is also able to increase the overall strength of ceiling boards above the normal levels possessed by other types of ceiling boards [21,22].

Polyethylene Terephthalate (PET) is a thermoplastic polymer that is widely used for the production of various consumer goods such as food packaging, beverage containers, and clothing fibres [23–25]. Despite its popularity, PET waste has become a major global environmental problem due to the increasing demand for plastic products and the lack of proper waste management practices [26]. According to a recent report, approximately 23.4 million tons of PET waste were generated worldwide in 2020, and a significant portion of this waste was not properly managed, leading to environmental pollution and harm to wildlife [27]. PET waste is highly persistent in the environment and can take hundreds of years to break down, releasing harmful chemicals and microplastics into the soil and water systems [28,29]. The improper disposal of PET waste contributes to marine litter and plastic pollution, affecting the health of marine ecosystems and wildlife [30]. Marine animals often mistake plastic waste for food, leading to the ingestion of harmful chemicals and possibly leading to injury or death [31,32]. In addition, plastic waste that ends up in the ocean can absorb toxic pollutants and concentrate on them, making them even more dangerous to marine life. One solution to reducing the amount of PET waste generated is to increase recycling efforts [33]. The use of recycled plastic in the production of new products also reduces greenhouse gas emissions, contributing to a more sustainable future [34]. This is the reason why this study is geared towards the recycling of PET waste into geopolymer-based ceiling boards.

The use of PET wastes as aggregates in a geopolymer composite has been previously explored. Ganesh, Deepak [35] utilized ground-granulated blast furnace slag as a precursor for the synthesis of geopolymer and incorporated PET bottles as aggregates in the geopolymer concrete. In another study, Lazorenko, Kasprzhitskii [36] studied the effect of different sizes and shapes of waste PET bottles on geopolymer composites that utilized fly ash as their precursor. Waste PET bottles were also used to replace quartz sand in coal fly ash-based geopolymer mortar [37]. The use of waste PET bottles as aggregates in fly ash-based geopolymer composites has also been explored [38]. Shaikh [39] observed that the compressive, tensile, and flexural strengths of PET-reinforced geopolymer composites are higher than those of cement composites. Even though these studies exist, none of them explored the use of glass wastes as an aluminosilicate source for the production of geopolymer and PET wastes as aggregates for the production of a composite. This is also the first study to the best of the authors' knowledge that utilizes geopolymer for the fabrication of a ceiling board.

In the assessment of other materials used in ceiling board production, it has been realized that the production and usage of some of these materials, like wood, gypsum, glass and metal, among others, have detrimental effects on the environment as well as cost, availability, and production issues [40–43], these negative effects are nullified with the use of geopolymer and plastic wastes. The primary objective of this study is to fabricate ceiling boards primarily from geopolymer and plastic, which can be used as a replacement for other materials currently used in their fabrication, and to evaluate the physical and mechanical properties they possess. This research is justified because it accomplishes three goals: waste management, material development, and environmental sustainability.

2. Methodology

2.1. Materials

The waste glass utilized in this study was obtained from a junkyard in Kwara State, Nigeria, where used car parts are disposed. Polyethylene Terephthalate (PET) packaging bottle wastes were obtained from the table water factory of Landmark University, Omu-Aran. Sodium metasilicate (Eastchem) and sodium hydroxide (Qualikems) were used as received, without further purification.

2.2. Production of the geopolymeric-plastic ceiling boards

The geopolymer was obtained through the alkaline activation of the waste glass. The alkaline solution was prepared by combining a concentration of 2 M sodium metasilicate (Na_2SiO_3) with a 2 M sodium hydroxide (NaOH) solution in a ratio of 2.5:1, respectively. Al Bakri Abdullah, Kamarudin [44] and Nematollahi, Sanjayan [45] have previously established that for optimum geopolymer production, a volume ratio of 2.5:1 for Na_2SiO_3: NaOH should be used. After mixing, the alkaline solution was left for 24 h before usage.

With the aid of a bore mill machine, the waste glass was pulverized and then sieved using a 100-μm sieve giving a maximum particle size of 1 mm. The PET bottles were melted and then allowed to cool. After cooling, it was pulverized with the aid of the bore mill machine, and the milled plastics were sieved using two different mesh sizes: coarse particles (2.0 mm) and fine particles (1.18 mm). The alkaline solution and the waste glass were introduced into a pan and thoroughly mixed to form the geopolymer. Thereafter, the PET plastics were introduced into the pan and thoroughly mixed (dry-mix). The binder (urea-formaldehyde) was then added to the mix, which was stirred until a homogeneous composition was obtained. By varying the composition of the different constituents, a total of twelve samples were obtained, as shown in Table 1.

The homogeneous mixture was transferred to a metallic mould with dimensions of 350 mm × 350 mm × 12 mm. After which, the mould was covered and pressured under a 100 kg load for 2 h. The samples were then cured at 100 °C for 1 h. After this, the board was de-moulded and returned to the oven at the same temperature for 2 h. After heating, the board was allowed to cool for 72 h. After cooling, the boards were kept wrapped in an airtight polyethylene bag at room temperature for 14 days before the commencement of the various tests.

2.3. Analysis of the ceiling boards

2.3.1. Water absorption test

This test was conducted in accordance with ASTM D570. The sample boards were dried in an oven to eliminate any free moisture inherent in them. After cooling, the weight of the sample was taken before it was immersed in water at room temperature (25 °C) for 2 h and then for 24 h. At the expiration of the individual time, the weight of the sample was obtained. Finally, the water absorption percentage was calculated as stated by Onyekachi and Iwuozor [46] as the ratio of the weight increased to the initial weight of the board. The test was repeated in triplicate for each board.

2.3.2. Thickness swelling test

Just like the water absorption test, the boards were dried, cooled,

Table 1
Experimental mix design.

Samples	Glass Powder (%)	Coarse PET Particles (%)	Fine PET Particles (%)	NaOH	Na_2SiO_3	Urea-Formaldehyde (%)
A	2.5	48.75	48.75	–	–	20
B	2.5	48.75	48.75	Present	Present	20
C	2.5	97.5	0.0	Present	Present	20
D	2.5	0.0	97.5	Present	Present	20
E	5.0	47.5	47.5	–	–	20
F	5.0	47.5	47.5	Present	Present	20
G	5.0	95.0	0.0	Present	Present	20
H	5.0	0.0	95.0	Present	Present	20
I	7.5	46.25	46.25	–	–	20
J	7.5	46.25	46.25	Present	Present	20
K	7.5	92.5	0.0	Present	Present	20
L	7.5	0.0	92.5	Present	Present	20

and their thickness was recorded with the aid of a Vernier calliper. Thereafter, it was immersed in water at 25 °C for both 2 h and 24 h. Thereafter, the surface of the boards was dried with a lint-free cloth, and the final thickness was recorded. The percentage of thickness swelling was then calculated as the ratio of the increase in thickness to the initial thickness of the board. The test was repeated in triplicate for each board.

2.3.3. Mechanical tests

For the mechanical properties of the board, the modulus of rupture (MOR) and the modulus of elasticity (MOE) were determined.

Tensile strength is quantified by the modulus of rupture or flexural strength. It determines how much force and stress a material can bear before failing due to bending [47]. The boards were loaded using the universal testing machine. The board was supported on two rollers at each end of the machine and then loaded at their centres. The machine's forward movement caused a progressive rise in stress in the middle span until failure occurred. At that time, the force applied to the board was measured, and the MOR was computed mathematically as follows:

$$MOR = \frac{3Pl}{2bd^2} \quad (1)$$

Where P is the failing load, l is the distance between the centres of support, and b and d are the width and thickness of the board, respectively.

A material's modulus of elasticity is its mechanical ability to endure compression or elongation concerning its length. It is a material's normal stress to longitudinal strain ratio. The MOE of the boards was determined in accordance with ASTM D2344 [48]. The board was bent by loading it into a universal testing machine with a bend fixture and creating a concave surface at the midpoint with a set radius of curvature. The load value was recorded in relation to the deflection value. Mathematically, it is represented as follows:

$$MOE = \frac{P_1 l^3}{4bd^3 H} \quad (2)$$

Where P_1 represents the load at the proportional limit, l is the distance between the centres of support, b and d are the width and thickness of the board, respectively, and H is the increase in deflection.

3. Results and discussion

3.1. Water absorption test

The mechanical properties and dimensional stability of boards are affected by water absorption, which is an essential physical property. It shows the relationship between the geopolymer and urea-formaldehyde-bonded plastic boards and their reactions to humidity conditions. The amount of water and moisture that the ceiling board can absorb within a given period is determined via the water absorption test. For this test, samples from the overall boards were cut out and completely submerged in water at room temperature for a short period of 2 h and a long period of 24 h to adequately determine the rate of water absorption for each sample. From the mean values obtained from all board samples as shown in Fig. 1, it was observed that after 2 h of immersion, sample J, which was composed of 46.25 g coarse PET bottle particles, 46.25 g fine PET bottle particles, and 7.5 g waste glass powder with the presence of alkaline solution, had the least value (12.564%) for the water absorption test, while sample C, which contained 97.5 g coarse PET bottle particles and 2.5 g waste glass powder with the presence of alkaline solution, had the highest value (33.712%) of water absorption. It was also observed that after 24 h of immersion, sample J (46.25 g coarse PET, 46.25 g fine PET, and 7.5 g waste glass powder with alkaline solution present) had the least value (16.561%) of water absorption, while sample I (46.25 g coarse PET, 46.25 g fine PET, and 7.5 g waste glass powder without alkaline solution) had the most value (35.412%) of water absorption recorded from the test. Board sample J had the best water resistance characteristics for both the 2-h and 24-h immersion times as compared to the other board samples.

It was also observed that all boards with an equal proportion of fine and coarse PET bottle particles and waste glass in an alkaline solution (geopolymer) had relatively lower water absorption values than the other board samples tested. Moreso, it was observed that with the increase in geopolymer in each board sample, water absorption decreased. This may be due to the low water absorption of glass present in the geopolymer as reported by Albidah, Alsaif [49]. Looking at the results obtained from the water absorption test, it was observed that the presence of geopolymer in the particle boards had an increasing influence on their water resistance characteristics as the amount of geopolymer increased. In the samples with equal proportions of fine and coarse particles (board samples A, B, E, F, I, and J), the boards with geopolymer present (board samples B, F, and J) have the lowest water absorption values as compared to the boards without the geopolymer present (board samples A, E, and I). This implies that the water absorption property of the board reduces with an increase in its geopolymeric content. This is due to the water-resistant nature of the waste glass particles used in the production of the geopolymer. Thus, the water resistance characteristics of the boards are more efficient in boards with equal proportions of fine and coarse PET bottle particles and with a significant amount of geopolymer as a binder as the properties increase with an increase in geopolymer than other boards without geopolymer.

The effect of the particle size used in making the boards on their water absorption was also significant, as the board samples with equal proportions of fine and coarse PET bottle particles (i.e., boards A, B, E, F, I, and J) showed higher water resistance properties as compared to the boards with only fine or coarse PET bottle particles (i.e., boards C, D, G, H, K, and L). Looking at other board samples with only fine PET particles or only coarse PET particles and geopolymer present, it is observed that the presence of geopolymer has a larger effect on the water resistance characteristics of the finer particles than on the coarse particles. But this is lower than the boards with an equal proportion of fine and coarse PET bottle particles. Therefore, boards with only fine or only coarse PET

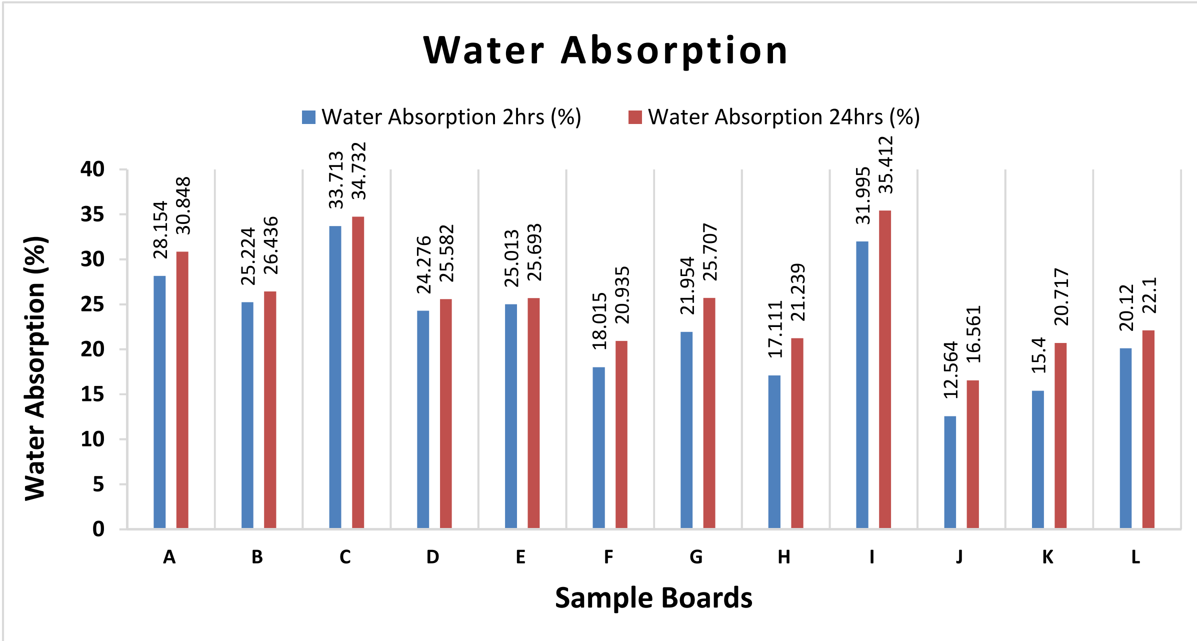

Fig. 1. Chart showing the water absorption properties of the boards at 2 h and 24 h.

particles have relatively higher values for the water absorption test, which goes to indicate that they absorb more water and have poorer water resistance properties than the boards with both fine and coarse PET particles. This observation is in agreement with that obtained by Albidah, Alsaif [49] that observed that the geopolymer-based concrete made from the combination of equal amounts of coarse and fine aggregates was higher than that from different amounts of both coarse and fine aggregates. It was also observed that the presence of fine aggregates has a lower water absorption percentage than that of coarse aggregates alone which is in agreement with the findings of Shalbafan, Nadali, and Thoemen [50].

3.2. Thickness swelling test

The result of the thickness swelling test is shown in Fig. 2. It was observed that after immersing the board samples in water for 2 h, board sample L had the least value (3.118%) of thickness swelling, followed by samples J (3.136%), H (3.315%), K (3.574%), D (3.655%), F (4.267%), B (4.569%), G (5.336%), C (5.454%), A (6.020%), and I (6.261%), while board sample E had the highest value (6.462%) of thickness swelling. After 24 h, the board samples immersed in water experienced only very minor changes in swelling, which indicated that the absorption of water that causes swelling is very fast. This means that water absorption to saturation can be achieved very quickly. The sample with the least value

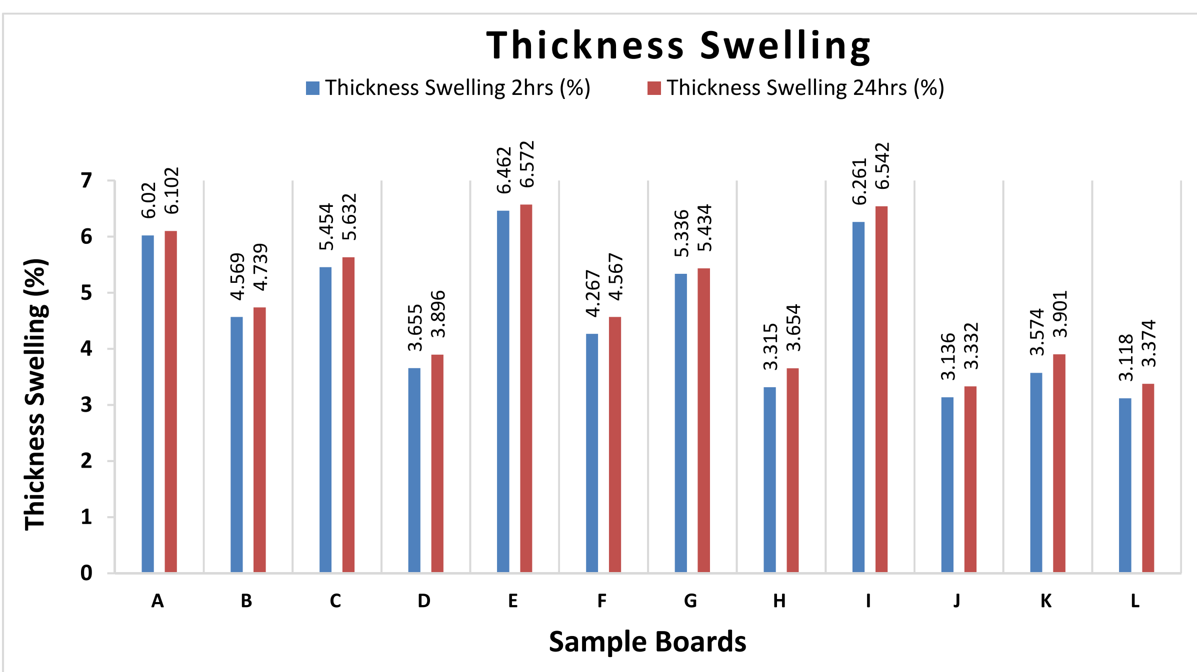

Fig. 2. Mean Values of Thickness Swelling for the ceiling boards.

after soaking for 24 h remained sample L (3.374%), and the sample with the highest value remained sample E (6.572%). An increase in thickness swelling with time was also observed by Bahrami, Shalbafan [51].

The effect of geopolymer was quite significant because, from the results obtained, it can be observed that the presence of geopolymer reduces the thickness swelling of boards as an increase in the amount of geopolymer added causing a decrease in the value of thickness swelling, with the least value of thickness in the boards with geopolymer being board sample J (3.136% for 2 h and 3.332% for 24 h) and the highest being board sample B (4.569% for 2 h and 4.739% for 24 h). It was also observed that the boards without geopolymer had higher values of thickness swelling as compared to the boards with geopolymer with the highest being sample I and the least, being sample A. This observation may be due to the hydrophobic nature of the glass precursor used in the production of the geopolymer, which limits the absorption of water as it contains limited hydrophilic functional groups [45]. This, in turn, doesn't improve the porosity of the geopolymer in the ceiling boards and therefore affects the thickness swelling property adversely. The effect of the particle size and combination on the thickness swelling was also observed visibly as the board samples with only finer PET bottle particles (sample C, sample G, sample K) had higher values as compared to other boards. The boards with coarse PET bottle particles (sample D, sample H, sample L) also had lower values as compared to boards with an equal proportion of both large and small particles (sample B, sample F, sample J).

3.3. Density test

Density is a physical property of various boards. The density of each ceiling board produced was determined and recorded for samples of each board, and then the mean value of density was obtained and recorded as shown in Fig. 3. It was observed that board D had the lowest mean density value (0.606 g/cm^3), followed by samples A, E, H, C, L, I, B, G, F, and K, respectively, while sample J had the highest mean density value (0.918 g/cm^3), as shown in Fig. 3. From Fig. 3, the ceiling boards with geopolymer present had higher values of density as compared to the boards without geopolymer present. It was also observed that the boards with equal proportions of fine and coarse PET bottle particles fared significantly better than boards with only one type of particle present. Singhal, Junaid [52] observed that the presence of glass fibre in a geopolymer-based composite improved its density in comparison to that without it.

3.4. Mechanical properties of the ceiling boards

Modulus of elasticity (MOE) and modulus of rupture (MOR) are the mechanical properties of the boards produced, which were tested and the various values were recorded to obtain the mean MOE and MOR. The ability of a material to resist being deformed elastically when subjected to stress is known as the modulus of elasticity, while the stress applied to the material and structural components just before it yields in a flexural test is known as the modulus of rupture. The mean values for MOE and MOR are shown in Table 2.

It can be observed in Table 2 that the mean values of the modulus of elasticity for the boards produced varied from 2.736 to 34.098 N/mm^2. Of the entire boards fabricated, sample D had the lowest MOE with a value of 2.736 N/mm^2, while sample I had the highest MOE value of 34.098 N/mm^2. An increase in the amount of glass powder used for the production of the geopolymer improved the MOE of the boards. Since the waste glass is the source of aluminosilicate in the geopolymer, this observation may be due to the fact that an increase in the alumina and silica concentrations affected the polymerization reactions, thereby affecting the MOE [53]. Another reason could be that as the concentration of the glass powder increased, the volume of fine glass particles

Table 2
Mean values for modulus of elasticity and modulus of rupture.

Board Type	Modulus of Elasticity (N/mm^2)	Modulus of Rupture (N/mm^2)
A	8.518	0.00951
B	4.273	0.00467
C	5.349	0.00507
D	2.736	0.00603
E	10.017	0.00767
F	17.243	0.00435
G	3.784	0.00429
H	18.636	0.00465
I	34.098	0.00565
J	11.131	0.00277
K	11.913	0.00283
L	21.828	0.00392

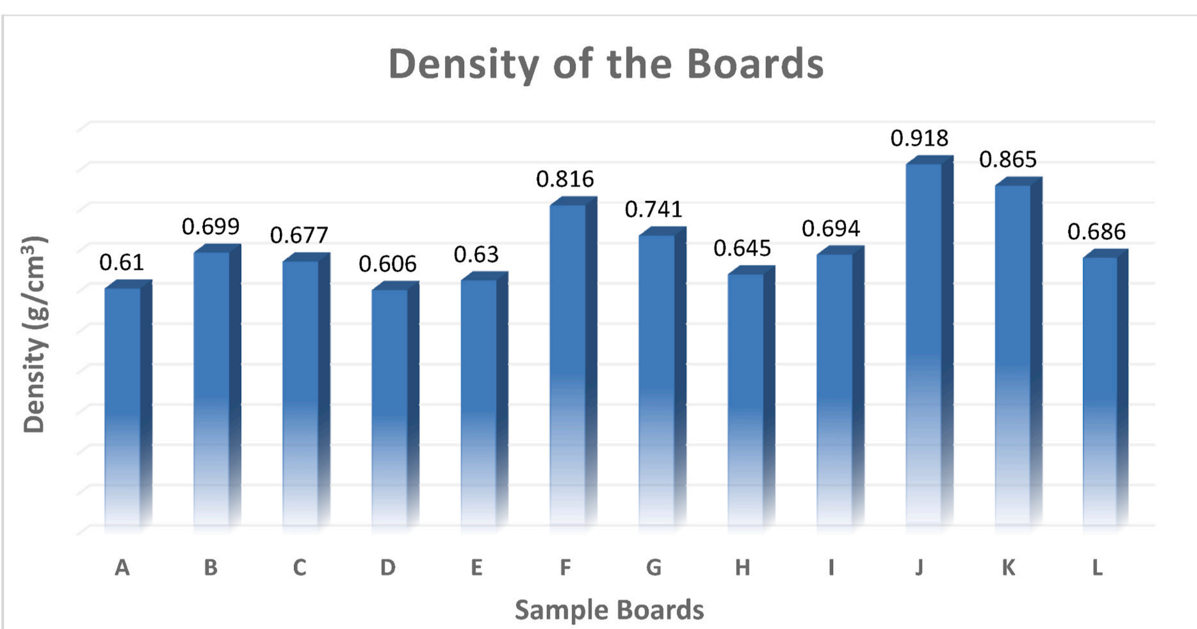

Fig. 3. Mean density values of geopolymer-plastic ceiling boards.

increased, thereby filling any remaining void between the aggregates and the geopolymer [36]. This could also be the reason why the presence of finer aggregates (PET) affected the MOE more than the coarse aggregates. Ahmed, Mohammed [54] also made a similar observation. An interesting trend in the result that was observed was that the boards without the presence of the alkaline solution, i.e., the non-geopolymer boards, had a higher MOE than the geopolymer boards. This could be due to the presence of moisture in the alkaline solution, which causes an increase in the friction between the particles [55]. Shaikh [39] obtained a similar result in the production of geopolymer from the alkaline activation of lignite bottom ash.

The MOR of the boards ranged from 0.00277 N/mm^2 for sample J to 0.00951 N/mm^2 for sample A. The results showed that the MOR decreased as the concentration of the geopolymer's precursor (glass powder) increased. Another observation that was made is that the finer the aggregates, the higher the MOR value. Fine PET particles led to an increase in the MOR value more than that of the coarse PET particles. This could be due to an increase in the PET volume fractions inherent in the pores of the composite [45]. Nematollahi, Sanjayan [45] observed that the higher the concentration of glass fibre in a geopolymer-based composite, the higher the flexural strength of the material. In addition, the samples without the alkaline solution showed improved MOR compared to the samples with the alkaline solution. The MOR of samples A, E, and I clearly depicts this observation.

4. Conclusion

In this study, geopolymer was synthesized from the alkali-activation of waste glass powder. The synthesized geopolymer was also combined with both fine and coarse waste polyethylene terephthalate (PET) bottles, which served as aggregates for the fabrication of ceiling boards. It was observed that the presence of the geopolymer as well as equal amounts of both the fine and coarse PET aggregates decreased its water absorption capacity, thickness swelling, and density. The water resistance characteristics of the boards are more efficient in boards with equal proportions of fine and coarse PET bottle particles and with a significant amount of geopolymer as a binder. Also, the boards without geopolymer had higher values of thickness swelling as compared to the boards with geopolymer with the best board giving a minimum thickness swelling value of 3.332%. An increase in the amount of glass powder, and fine PET aggregates improved both the modulus of elasticity and modulus of elasticity of the boards. However, it was observed that the addition of the geopolymer in the production of the board enhanced its physical properties but not its mechanical properties. This research work has offered the construction society an option of producing ceiling boards from geoplymer generated from waste materials and it can be concluded that this locally fabricated geopolymer-plastic boards can be efficiently used as suspended ceiling boards which requires less mechanical efficiency, exploring its good durability and physical properties. Furthermore, new researches can be done to improve its mechanical properties.

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors have unanimously decided that this manuscript be sent for possible publication.

Consent to publish

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Author contribution

Atoyebi Olumoyewa D. – Conceptualization, Methodology, Supervision, Writing-review, Iwuozor Kingsley O. – Writing-Original Draft & review, Emenike Ebuka C. - Writing-Original Draft & review, Anamayi David S. – Invesitigation, Methodology, Writing-original draft, Adeniyi Adewale G. – Writing-review & editing.

Declaration of competing 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.

Data availability

Data will be made available on request.

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