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Evaluation of Polymer Interlocking Paver Blocks Made of Waste Plastic Polyethylene Terephthalate and Sand Modified with Nano-Sized Palm Kernel Shells

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Demand for sustainable construction materials has driven research into utilizing waste in innovative ways. This paper focused on incorporating Nano-sized palm kernel shell with recycled waste plastic and sand to produce a Polymer Interlocking Paver blocks using a mixed ratio of 1: 2, respectively. The chemical composition of Nano-sized palm kernel shell was examined with X-ray fluorescence Analysis. Effects of Nano-sized palm kernel shell at various percentages, 5, 10, 15, 20, and 25% as filler in the composite, were determined by performing compressive strength, flexural strength, water absorption, and abrasive resistance tests. The micro-structural analysis was done with a Scanning Electron Microscope. The X-ray fluorescence Analysis revealed Iron (III) Oxide and Silicon Oxide as dominant oxides. The addition of Nano-sized palm kernel shell in Polymer Interlocking Paver blocks increased the compressive strength by 14.26%, 24.94%, and 75.67% for 7, 21, and 28 days, respectively, and flexural strength at 5%. Reduction in water absorption, and abrasion index with uniform distribution of particles was observed. Conclusively, 5% Nano-sized palm kernel shell gave better resistance to wear of the modified sample, and is considered a reasonable alternative material for Polymer Interlocking Paver blocks production to promote sustainable construction practices.

1. Introduction

Interlocking Paver blocks (IPBs) are an integral part of the pavement infrastructure in developing countries. They served as an alternative to concrete and asphalt pavements, widely used in the field of construction as pedestrian walkways, garage floors, road pavements, yards and intersections among other types of pavement design because of their quality, ease of installation, maintenance which is relatively inexpensive in terms of cost and added aesthetic and toughness values (Djamaluddin et al., 2020; Gencel et al., 2012; Atoyebi et al., 2020; Rath, 2022). Besides, they are used in areas where conventional types of construction are less durable due to many operational and environmental constraints. IPBs are pre-cast solid products which are made of cement, aggregates and water.

However, the high demand of cement has led to an increase in the cost of cement, high energy expense, and Carbon (IV) Oxide (CO2) emissions into atmosphere which associated with cement manufacture.

Pressures have been brought about to reduce cement consumption and sustain conventional construction materials which are depleting as a result of high demanding arising from an increase in population, socioeconomic activities, and infrastructural development (Karak, et al., 2012; Wilson and Webster, 2018). Industrial and agricultural wastes which are locally available and cheaper materials are used to replace concrete materials, and improve their properties (Wonorahardjo et al., 2019; Liu et al., 2017; Rojas et al., 2019; Gómez-Meijide et al., 2015 and Usman et al., 2012).

Aside the conservation of conventional resources, it reduces the amount of waste generated, and provide solutions to the negative environmental impact of inappropriate wastes disposal (Jony et al., 2011; Aziz et al., 2014; Ike et al., 2018). Hence, this research is motivated towards the need to find sustainable abundant and cheap agricultural, and industrial wastes produced locally in construction industry. PKS and wastes plastic are examples of agricultural and industrial wastes, respectively, which constitute major fraction of total solid wastes because they exist in abundance globally. They have received a lot of attention among other wastes for conventional aggregate replacement. PKS are materials recovered as residual waste in the extraction of the kernel from the nut, after palm oil had been removed from the mesocarp of the oil palm fruit but not optimally used. In Africa and South East Asia, PKS are one of the most quantitative waste materials produced due to its favourable climatic condition for palm tree cultivation, hence produce in large quantity. Plastics are synthetic materials derived from fossil fuel used in a wide variety of forms in our everyday lives both in developed and developing countries (Gilbert 2016; Palm and Myrin 2018, and Vaverkova 2019). Plastics can be categorized into two main types based on their response when heat is applied: namely thermoplastic and thermosets. Thermoplastics are plastics that can be melted and remolded repeatedly when heat is applied, whereas thermosets undergo irreversible chemical changes when heat is applied, thus cannot be reheated and remolded (Brouwer et al., 2018 and Post et al., 2020).

According to Plastics, 2013 report, the world's annual consumption of plastic material was 204 million tons in 2002, and increased to 300 million tons in 2013. In 2015, it was 407 million tons (Geyer 2017) while about 400.3 million tons was recorded in 2023 (Plastic Waste Worldwide, 2025). It was affirmed by d'Ambrieres, 2019 and UNEP, 2015 that only 9% of the used plastic ended up in landfills and are recycled while 4 to 12 million metric tonnes of waste plastic ended up in the oceans annually. In addition, Eriksen et al., 2014 stated that 5 trillion of plastic pieces floating on the ocean would take about one year for the ocean to degrade these wastes, yet not completely. Besides, harmful chemicals like bisphenol A (BPA) are released into the water during this degradation process, which is dangerous for marine organisms. Also, according to reports given by Alabi et al., 2019; Klemes et al., 2020, and Pan et al., 2020, waste plastic dumped into landfills have the possibility of causing biotic and abiotic plastic degradation that eventually leach and contaminate nearby ecosystems.

In addition, gases like methane and Carbon (IV) Oxide are released into the environment when plastic waste decomposed in landfills, and contributes to the greenhouse gas emission (Alabi et al., 2019; Vishwakarma, 2020, and Yadav et al., 2020). Several researchers have investigated and established the use of PKS and waste plastic as part of construction materials in construction industries to enhance the engineering properties of the composite materials (Corinaldesi et al., 2015; Mir, 2015; Rajput and Yadav 2016, and Rokdey et al., 2015).

PKS have the potential to replace conventional aggregates for road construction (Ogundipe et al., 2021). Zarina et al., 2016 and Ezekiel et al., 2017, worked on the feasibility of PKS as a replacement for coarse aggregate in lightweight concrete, and established that using PKS for aggregate replacement increased its water absorption but decreased the concrete workability, tensile strength, and compressive strength with an increase in PKS content. However, the results were still within the range acceptable for lightweight aggregates, and concluded that PKS could replace aggregate for lightweight concrete.

A research carried out by Donald and Jonas 2015, used PKS to replace sand partially for sand in sandcrate block production at various percentage, 0%, 10%, 20%, 30%, 40% and 50% with water cement ratio of 0.5. It was established that the compressive strength of PKS blocks exceeded the minimum requirement of 2.8 N/mm2 at age 28 days when the PKS replacement did not exceeds 40%. The use of low density polyethylene waste as partial replacement for sand in the production of high strengths concrete pavement bock was also examined by Eric et al (2014) and observed that the density, compressive strength, flexural strength and splitting strength decreased as the polyethylene content increased. It was concluded that if 10% - 50% of the plastic content is used, the resulting Interlocking pavement block would satisfy the requirement for pedestrian walkways, light traffic and heavy traffic situations.

According to Rahul et al (2019), the use of plastic waste as a partial replacement of coarse aggregate in Interlocking pavement block of 0%, 2%, 2.5%, 3%, 3.5%, 4%, 8% and 10% gave high compressive strength at 2.5%, 3%, and 4%, but decreased at 10% replacement compared with control sample.

2. Materials and Methods

2.1 Materials

The materials used in this study were, fine aggregates (sharp sand), filler materials (PKS processed to Nano-sized), binder (Waste Plastic – PET) (Plates 1 - 3), Paver block formwork, metal bucket, lubricating oil, wheel barrow, shovel, weighing balance, measuring tape, hand trowel, head pan, and hand trowel. These materials were sourced from different locations and processed as described in Table 1 below.

Plate 1: Sharp Sand

Plate 2: Raw Palm kernel shells

Plate 3: Waste Plastic –PET

Table 1: Raw Materials: for the study

Raw Materials		Source	Processing
Fine Aggregate	Sharp sand (Plate 1)	Federal University of Agriculture, Abeokuta (FUNAAB), Ogun State, Nigeria	Washed and freed from deleterious materials
Filler	Palm Kernel Shell (Plate 2)	Directorate of University Farms (DUFARMS) Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.	Washed, dried, freed from deleterious materials. It was allowed to pass through sieve size 0.075 mm diameter, and thereafter milled into Nano-Size at Eleweran, Abeokuta
Binder	Waste Plastic (Plate 3)	Federal University of Agriculture, Abeokuta, Ogun State, Nigeria	Shredded and melted in a fabricated metallic drum
Metal Mould (200 mm x 100 mm x 60 mm)		Department of Civil Engineering Workshop, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria	Constructed
Lubricating oil		Purchased at Abeokuta, Ogun State	

2.2 Methods

Physical and engineering properties of Palm kernel shell, fine aggregate, Waste Plastic – PET were determined. The components of the Paver block were subjected to laboratory tests based on the standard specifications recommended by the American Society for Testing and Materials (ASTM), namely: Particle Size Analysis (ASTM D422 63 (2007)), Specific gravity of the aggregates (ASTM D854-00), and X-Ray Fluorescence (XRF) (ASTM C311 (2019)), Compressive Strength Test (ASTM D695), Flexural Strength Test (BS EN 12390-5 2009), Water Absorption Test (BS EN 1338 2003), Scanning Electron Microscopy (SEM) Analysis.

2.3 Polymer Paver Blocks Mix Design

Control sample, produced with Waste Plastic (PET) and Sharp sand was first prepared. The mix ratio was 1:2 (i.e. Waste Plastic (PET): sand for sample), and thereafter, modified with Nano-sized PKS at various percentages of 5%, 10%, 15%, 20%, and 25%. In the production of sample, the measured sand was heated in a metal bucket up to a temperature of 260^{0}C to completely melt the PET, and this was consistent with the experimental observations of Chauhan et al, (2019). This was done with respect to the mixed ratio (1:2), and the mix is turned thoroughly (Plate 4). The metal mould 200 mm x 100 mm x 60 mm was cleaned and lubricated.

The sample was transferred into the mould, and compacted. Then the blocks were allowed to cool for 24 hours before they were demoulded. The Polymer Interlocking Paver Block was modified with Nano-sized PKS at various percentages of 5, 10, 15, 20, and 25 %,(Plate 5), and all the samples were subjected to various laboratory tests. Compressive strength and Flexural strength were determined for the samples at age 7, 21, and 28 days, respectively. Likewise, all other parameters were determined. The modified Polymer Interlocking Paver Block with percentage that gave the best result was subjected to SEM, and analyzed further.

Plate 4: Production Process of Polymer Interlocking Paver Blocks

Plate 5: Polymer Interlocking Paver Blocks modified with various percentages of Nano-sized Palm kernel shells

3. Results and Discussion

3.1 Particle Size Distribution Analysis

The shape of the curve indicates that it is a gap-graded soil with the value of Cc, 0.62 which is significantly less than 1 (Figure 1). Since the soil has low value of Cu, 2.62, and it is sand, this corresponds to a poorly graded sand.

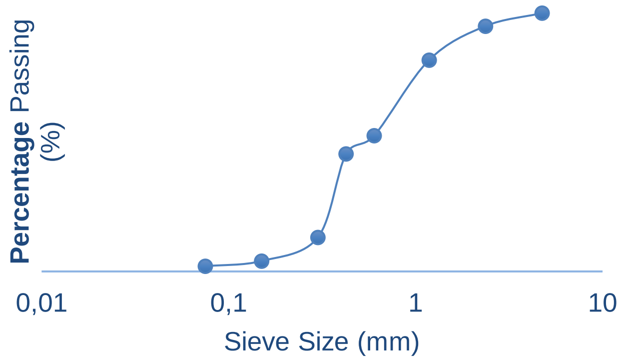

Figure 1: Particle Size Distribution of Sharp Sand

3.2 Specific Gravity of Materials

The results of specific gravity of sharp sand, Nano-sized PKS and Waste Plastic (PET) are shown in Table 2. The specific gravity obtained for Nano-sized PKS and Waste Plastic (PET) were lower than that of sharp sand, and this implies that both Nano- sized PKS and Waste Plastic (PET) are lightweight aggregates compared with the conventional aggregate. The value obtained for Nano- sized PKS agreed with Ndoke (2006). This shows that the combination of these two lightweight aggregates in the production of Polymer Interlocking Paver block would result in lighter weight Polymer Interlocking Paver block compared with the Paver block made of conventional aggregates.

Table 2: Specific Gravity of Materials

Materials	Specific Gravity
Sharp Sand	2.64
Nano- sized PKS	1.82
Plastic (PET)	0.80

3.3 Analysis of X-Ray Fluorescence (X-RF)

The analysis of X-RF revealed the chemical composition of Nano- sized PKS used (Table 3). The results showed that Nano- sized PKS particle possessed high percentage of Iron (III) Oxide and silicon oxide which made it suitable to be used as reinforcement, and accounted for some level of brittleness in the composite material. This result is in tandem with Samotu et al (2015). In addition, the presence of CaO, ZrO_2, K_2O, and Al_2O_3 were observed, and their combination with iron (III) and silicon oxides also probably spoke for the strength possessed by the composite material.

Table 3: Chemical composition of Nano-sized Palm Kernel Shells

Chemical Compound	Percentage Composition (%)
K_2O	6.18
Rb_2O	0.10
Al_2O_3	2.36
CaO	13.47
SiO_2	21.04
SO_3	0.65
PbO	0.02
ZrO_2	8.32
TiO_2	3.22
V_2O_5	0.12
Cr_2O_3	0.12
MnO	0.56
Fe_2O_3	42.96
Co_2O_3	0.20
NiO	0.18
CuO	0.19
ZnO	0.02
Ga_2O_3	0.02
As_2O_3	0.01
SrO	0.24
HfO_2	0.02

3.4 Compressive Strength Tests

Compressive strength of the samples (Polymer Interlocking Paver Block and the modified samples) at the ages 7, 14, 21, and 28 day was determined. It was observed that 5% Nano-sized PKS gave the highest compressive strength, and increased by 14.26%, 24.94%, and 75.67% at age 7, 21, and 28, respectively for the modified sample with 5% Nano-sized PKS compared with the control sample (Figure 2). The increase in compressive strength could be attributed to an increase in mechanical interlocking which improved the interfacial bonding of the modified sample. At 5% Nano-sized PKS, an optimal balance between plastic, sand and Nano-sized PKS which acted as filler in the modified sample was reached. This suggests that an effective coats of the sand and Nano- sized PKS particles, which enhanced cohesion. This result agreed with the report of Chauhan et al., 2019.

Further increase in Nano-size PKS content resulted in a consistent decrease in compressive strength up to 25% at age 7, 21, and 28 day, and the sample with 25% Nano-sized PKS content gave the lowest values with 65.92, 53.05, and 46.88% reduction, respectively, compared with the control sample. The decrease in value with an increase in Nano-size PKS content in the modified sample could be attributed to the PET content which could no longer enhance the binding capability of the component materials, hence, the incomplete encapsulation of sand and the Nano-sized PKS particles creating numerous pore spaces. Thereby, the modified samples were loosely packed and reduced the structural cohesion, and this agrees with findings by Agrawal et al., 2023; Jock et al., 2022; Awodiji et al., 2021. However, the modified Polymer Interlocking Paver Block with 5% Nano-sized PKS gave the highest value (30.69 N/mm^2).

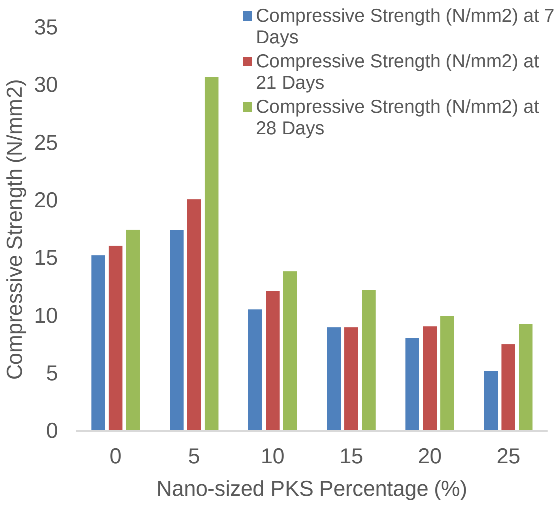

Figure 2: Compressive Strength of the Modified Polymer Interlocking Paver Block with various Percentage of Nano-sized PKS

These results agreed with the outcome of the study carried out by Akinleye et al. (2022) who examined the mechanical performance of interlocking paving stones with dissolved waste plastics. The results however showed that Nano-sized PKS along with waste plastic (PET) can be used to produce lightweight Polymer Interlocking Pavement Block up to 25% Nano-sized PKS content.

3.5 Flexural Strength Test

Flexural strength also known as modulus of rupture measured material's ability to resist deformation under load, and is crucial for pavement durability.

It was observed that the flexural strength of the Polymer Interlocking Paver Block modified with 5% Nano-sized PKS content was 13.74 N/mm^2, increased by 11.05% compared with control sample (Figure 3). Increase in flexural strength could be as a result of an increase in structural adhesion of the modified sample because, the Nano-sized PKS filled the voids and thereby improved the bond that formed between the polymer and Nano-sized PKS. Further increase in Nano-sized PKS content to modify samples gave a decrease in flexural strength. Reduction in value could be as a result of the Nano-sized PKS agglomeration, thereby created weak zones, and since the modified samples might not be coated effectively, this could have eventually led to a reduction in the effective adhesion in the modified Polymer Interlocking Paver Block. However, the modified sample with 5% Nano-sized PKS content would be more durable and provide efficient stress distribution compared with the control sample.

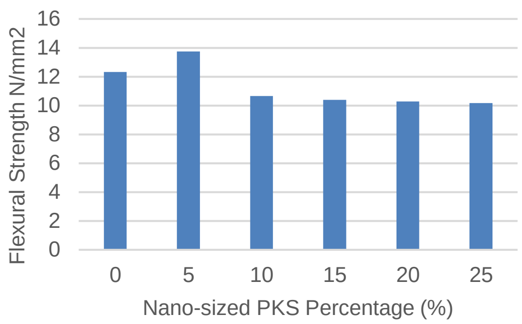

Figure 3: Flexural Strength of the Modified Polymer Interlocking Paver Block with various Percentage of Nano-sized PKS

3.6 Dry Density of the Modified Polymer Interlocking Paving Blocks

Dry density is a crucial parameter for assessing the quality and performance of paving blocks. Higher dry density generally indicates better strength, durability, and resistance to water absorption. Figure 4 shows a consistent decrease in the density of the modified Polymer Interlocking Paver Block with an increase in Nano-sized PKS at 28 days except at 5% Nano PKS which is greater than the control sample by 2.78% compared with the control sample.

There was an increase in density of the sample modified with 5% Nano-sized PKS initially because Nano-sized PKS acted as micro filler, filled the pores between polymer chains and aggregates, hence there was a good packing and the modified sample was more compacted because there was an optimal balance between plastic binding, sand and Nano-sized PKS particles [Suthar et al., 2024] which gave rise to reduction in the porosity of the sample.

However, further increase in Nano-sized PKS content resulted in reduction in density due to clustering of Nano-sized PKS, which created micro voids. Besides, the inability of the PET content to bind all particles effectively as Nano-size PKS content increases. However, results obtained for modified samples at various percentages of Nano-sized PKS aligned with the reports of Clarke (1993), when compared with paver block made with conventional materials that density value for light weight concrete is between 1200 and 2000 kg/m^3.

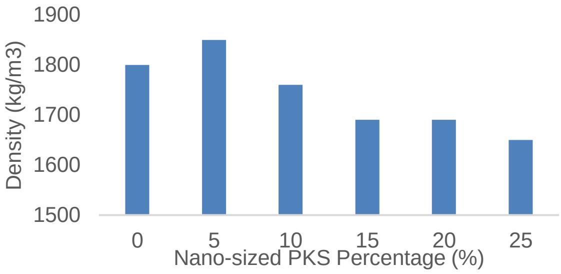

Figure 4: Density of the Modified Polymer Interlocking Paver Block with various Percentage of Nano PKS

3.7 Water Absorption Test

The water absorption test is an important factor in determining the durability of Interlocking pavement blocks. When water penetrates interlocking pavement blocks, it decreases their durability. Hence, the water absorption capacity of the samples were tested after 28 days for various percentage of Nano-sizes PKS, soaked in water for 24 h to determine the minimum and maximum allowable water absorption rates of the modified Polymer Interlocking Pavement block and how the samples would respond to change in weather conditions (Figure 5). The results showed that the water absorbed by all the modified samples at various percentage of Nano-sized PKS used were significantly lower than the control sample. The increase in water absorption observed in control sample could be as a result of voids that exist in the control sample which is a direct function of its porosity. The presence of voids and the weak interfacial bonding created between the polymer and aggregates, thereby made pathways for water to penetrate into the sample.

However, a reduction in water absorption by 51.35% was observed in a sample modified with 5% Nano-sized PKS compared with the control sample. This could be ascribed to a reduction in pore connectivity that improved the particle packing and the microstructure of the modified sample, hence, stronger interfacial bonding was developed to prevent water ingress. Also, the hydrophobic nature from the polymer matrix could have been another contributory factor, because polymers are less water absorbent (Gounden et al., 2024; Youssef et al., 2015). Further various increase in percentages of Nano-sized PKS gave rise to an increase in water absorption rate. The increase in water absorption at this stage could be attributed to excessive Nano-sized PKS in the modified samples. The Nano-sized PKS agglomerated and created inadequate polymer encapsulation, and consequently, increased the porosity within the modified Nano-sized PKS structure. Besides, the hydrophilic nature of PKS (Bellili et al., 2022) could have led to the increase in water uptake.

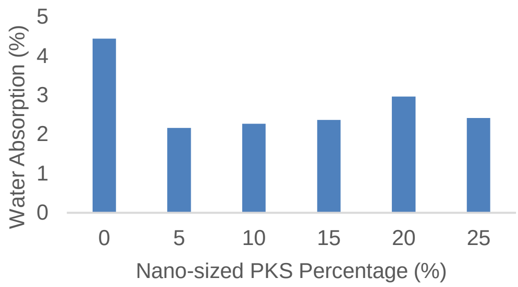

Figure 5: Water Absorption of Polymer Interlocking Paver Blocks Modified with various Percentage of Nano- Sized PKS

The values obtained at various percentage of Nano-sized PKS are within the permissible value of 7 % compared with Interlocking Paver Block made with conventional materials (BS EN 1338 2003).

The results obtained however, agreed with Ismail (2017), and thus, the use of Nano-sized PKS in Polymer Interlocking Paver Blocks will enhance its durability especially in waterlogged areas.

3.8 Abrasion Resistance

Abrasive resistance is a measure of the resistance of paving block to the wearing action due to traffic, and it is a direct function of its strength. The results obtained for all the modified samples at various percentage of Nano-sized PKS showed reduction in value compared with the control sample except at 20 and 25% Nano-sized PKS (Figure 6). The sample modified with 5% Nano-sized PKS gave the least value.

The lower abrasion index indicates better resistance to wear. The trend of this pattern could be as a result of increase in water holding capacity of the sample which led to a decrease in compressive strength, one of the major factors that control the abrasive behavior of the sample [Gencel et al., 2011] as Nano-sized PKS percentage increased. However, samples with 5 and 10% Nano-sized PKS satisfied the maximum abrasive limit for 28 days for Types I, II and III while other samples only satisfied the maximum abrasive limit for 28 days for Types II and III (pedestrian and light traffic pavement) when compared with Interlocking Paver Block made of conventional materials as specified by ASTM C902-15 (2015). This implied that Nano-Sized PKS reduces wearing of the pavement when used to modify Polymer Interlocking Paver block.

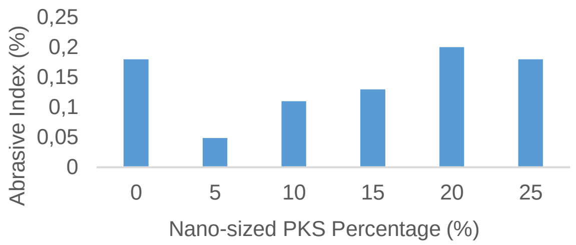

Figure 6: Abrasion Index of Polymer Interlocking Paver Blocks Modified with various Percentage of Nano PKS

3.9 SEM of the Polymer Interlocking Paver Blocks

Scanning electron microscopy was carried out on the 28 days cured samples in order to examine their internal structure. The samples selected for these tests were limited to the control sample and the modified Polymer Interlocking Paver Blocks with 5% PKS which exhibited maximum strength under applied load. Figures 7 and 8 showed the results obtained from the SEM Analysis on the control sample and the modified Polymer Interlocking Paver Blocks with 5% PKS, respectively. The SEM images in the Figures below revealed that the sample modified with 5% Nano-sized PKS has more fine particles, and appear smaller than the control sample. This however implied that a more uniform distribution of particles was achieved in the sample modified with 5% Nano-sized PKS compared with the control sample, and this consequently improved its strength, and this was in tandem with the reports of Olumuyiwa et al (2012) and Itam et al (2016).

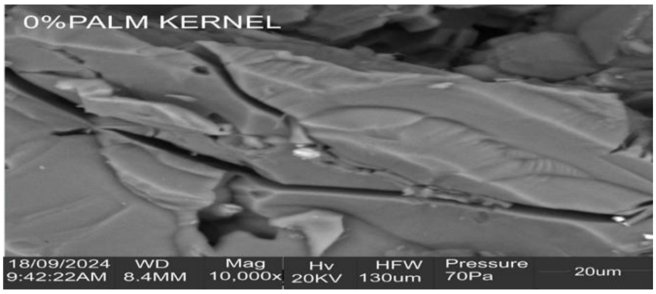

Figure 7: SEM for the Control Sample at 28 days (10000x Magnification)

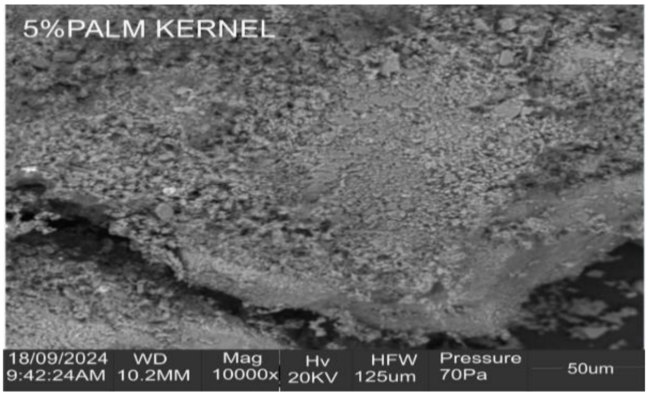

Figure 8: SEM for the Modified Polymer Interlocking Paver Block with 5% Nano-sized PKS at 28 days (10000x Magnification)

4. Conclusion

The use of Nano-sized Palm Kernel Shells, waste plastics (PET), and sand in the construction industry is an innovative idea, and has the potential to make a significant impact. Their usage in Polymer Interlocking Paver Block production would reduce pollutants accumulated which have spread across marine, freshwater, and terrestrial ecosystem. Besides, they are sustainable and cost-effective alternative to conventional paving materials. Also, introducing Nano-sized PKS to modify Polymer Interlocking Paver Block would enhance the abrasive resistance, and give excellent performance when properly mixed. However, based on the findings of the study, the following conclusions were drawn from the test results:

The X-Ray Fluorescence (X-RF) revealed Iron (III) Oxide (Fe_2O_3), Silicon Oxide (SiO_2) and Calcium Oxide (CaO) as dominant oxides in Nano-sized PKS particle, which made it suitable to be used as reinforcement, and accounted for some level of brittleness in the composite material. The inclusion of Nano- sized PKS in Polymer Interlocking Paver Blocks at various increase in percentage showed an improvement in compressive strength at 7, 21 and 28 days, and increased Flexural strength at 5% at 28 days. This implied an improvement in durability of the modified sample compared with the control sample.

The use of Nano-sized PKS would improve density, water holding capacity, and resistance to wear effectively at 5%.The use of these materials in the production of Polymer Interlocking Paver Block would reduce pollutants, and provide solutions to negative environmental effects of inappropriate solid waste disposal. The overall results revealed that sample modified with 5% Nano-sized PKS with waste plastic (PET) will ensure sustainability of natural materials in the production of Polymer Interlocking Paver Block when used appropriately.

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