Studies in Engineering and Exact Sciences
ISSN: 2764-0981

A study on grounded palm kernel shells (GPKS) as a partial replacement for sand in mortar

Um estudo sobre cascas de palmiste moídas (GPKS) como substituto parcial da areia em argamassa

Estudio sobre la cáscara molida de almendra de palma (GPKS) como sustituto parcial de la arena en el morteiro

DOI: 10.54021/seesv6n1-016

Originals received: 11/20/2024
Acceptance for publication: 01/10/2025

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ABSTRACT
The use of waste materials in mortar production offers an effective solution to address environmental challenges and waste management issues. Agricultural wastes such as rice husk, wheat straw, hazel nutshell, and sugarcane bagasse have been utilized as aggregates in mortar. However, limited studies have explored the application of grounded palm kernel shells (GPKS) as a partial replacement of sand in cement mortars. This study investigates the effects of incorporating GPKS as a partial replacement of sand on the physical and mechanical properties of mortar. The GPKS replacement levels of 0, 5, 10, 15, 20, and 25% were used with a mix ratio of 1:4 (cement to sand), and a water-cement ratio of 0.7. In all, 120 cubes of size 100 × 100 × 100 mm were prepared and cured for up to 28 days, and at 7 days intervals for density, water absorption, compressive strength, and tensile strength. Although the results for GPKS replacement of fine aggregate specimens were lower than the control specimens, the results for the various GPKS replacements met the standard requirement for cement mortar grade M6. The 10% GPKS replacement obtained better average results among all the various replacement proportions with a density of 1978.33 kg/m^3, water absorption of 3.35%, compressive strength of 12.59 N/mm^2, and

tensile strength of 0.569 N/mm^2. The study, therefore, concludes that GPKS can be used as a replacement for sand in cement mortar at a recommended level of 10% for construction applications.

Keywords: Compressive Strength. Density. Grounded Palm Kernel Shell. Mortar. Sand. Tensile Strength.

RESUMO

O uso de materiais residuais na produção de argamassa oferece uma solução eficaz para enfrentar os desafios ambientais e as questões de gerenciamento de resíduos. Os resíduos agrícolas, como casca de arroz, palha de trigo, casca de avelã e bagaço de cana-de-açúcar, têm sido utilizados como agregados na argamassa. Entretanto, poucos estudos exploraram a aplicação de cascas de palmiste moídas (GPKS) como substituição parcial da areia em argamassas de cimento. Este estudo investiga os efeitos da incorporação de GPKS como substituição parcial da areia nas propriedades físicas e mecânicas da argamassa. Os níveis de substituição de GPKS de 0, 5, 10, 15, 20 e 25% foram usados com uma proporção de mistura de 1:4 (cimento para areia) e uma proporção de água-cimento de 0,7. Ao todo, 120 cubos de tamanho 100 × 100 × 100 mm foram preparados e curados por até 28 dias, e em intervalos de 7 dias, para verificar a densidade, a absorção de água, a resistência à compressão e a resistência à tração. Embora os resultados da substituição de GPKS dos espécimes de agregado fino tenham sido inferiores aos dos espécimes de controle, os resultados das várias substituições de GPKS atenderam ao requisito padrão para argamassa de cimento de grau M6. A substituição de 10% de GPKS obteve melhores resultados médios entre todas as várias proporções de substituição com uma densidade de 1978,33 kg/m3, absorção de água de 3,35%, resistência à compressão de 12,59 N/mm2 e resistência à tração de 0,569 N/mm2. O estudo, portanto, conclui que o GPKS pode ser usado como substituto da areia na argamassa de cimento em um nível recomendado de 10% para aplicações de construção.

Palavras-chave: Resistência à Compressão. Densidade. Casca de Palmiste Moída. Argamassa. Areia. Resistência à Tração.

RESUMEN

El uso de materiales de desecho en la producción de mortero ofrece una solución eficaz para hacer frente a los problemas medioambientales y de gestión de residuos. Residuos agrícolas como la cáscara de arroz, la paja de trigo, la cáscara de avellana y el bagazo de caña de azúcar se han utilizado como áridos en morteros. Sin embargo, pocos estudios han explorado la aplicación de cáscaras de palmiste molidas (GPKS) como sustituto parcial de la arena en morteros de cemento. Este estudio investiga los efectos de la incorporación de GPKS como sustitución parcial de la arena en las propiedades físicas y mecánicas del mortero. Se utilizaron niveles de sustitución de GPKS de 0, 5, 10, 15, 20, y 25% con una proporción de mezcla de 1:4 (cemento a arena), y una proporción agua-cemento de 0,7. En total, se prepararon 120 cubos de tamaño 100 × 100 × 100 mm y se curaron hasta 28 días, y a intervalos de 7 días para determinar la densidad, la absorción de agua, la resistencia a la compresión y la resistencia a la tracción. Aunque los resultados de la sustitución de GPKS de los especímenes de árido fino fueron inferiores a los especímenes de control, los resultados de las distintas sustituciones de GPKS cumplieron el requisito estándar para el mortero de cemento de grado M6. La sustitución del 10% de GPKS obtuvo mejores resultados medios entre todas las proporciones de sustitución con una densidad de 1978,33 kg/m3, una absorción de agua del 3,35%, una resistencia a la compresión de 12,59 N/mm2 y una resistencia a la tracción de 0,569 N/mm2. El estudio, por tanto, concluye que el GPKS puede utilizarse como sustituto de la arena en el mortero de cemento a un nivel recomendado del 10% para aplicaciones de construcción.

Palabras clave: Resistencia a la Compresión. Densidad. Cáscara de Palmiste Molida. Mortero. Arena. Resistencia a la Tracción.

1 INTRODUCTION

The construction industry faces increasing challenges related to the depletion of natural sand resources and environmental concerns arising from unsustainable material usage (Ngoc & Schnitzer, 2009; Korankye & Danso, 2024). This affects the production of mortar (Rehman et al., 2020) and greatly impacts the construction process and cost since mortar is one of the most commonly used materials in the construction industry (Al-Numan, 2024). Affordable mortar production has been a major concern in recent times (Ogundipe et al., 2020), owing to the growing need for natural aggregates consumption caused by the expansion of housing infrastructure around the world (Akhtar & Sarmah, 2018). In Africa, there is a lack of affordable houses which is mostly due to the high cost of conventional building materials (Zievie et al., 2024; Onyegiri & Ugochukwu, 2016), these conventional building materials have a negative impact on the environment and have led to the perceived inappropriateness of locally available materials (Danso, 2013; Akadiri, 2011).

The construction industry relies extensively on Indigenous building materials such as fine aggregate for the production of mortar, concrete, and sandcrete blocks (Khan et al., 2020). Apparently, agricultural waste such as palm kernel shells (PKS) is abundant and underutilized in many regions, particularly in tropical countries (Addo, 2021). Research has been done on the utilization of agricultural waste as a substitute for aggregate for construction applications. A study by Danso and Appiah-Agyei (2021) investigated the effects of particle size variation of palm kernel shells (PKS) serving as an alternative to coarse aggregate in concrete, using a mix ratio of 1:2:3 and a 0.6 water-cement ratio and fund that 12mm PKS concrete yielded a maximum compressive strength of 10.2 MPa followed by 10mm (9.8 MPa) and 6mm (8.8 MPa). Addo (2021) examined the mechanical properties of Portland cement-based masonry blocks incorporating sand and palm kernel shell (GPKS) with mix ratios of 1:4, 1:5, and 1:6, with sand replaced by GPKS at 0%, 20%, 40%, and 50%, and a water-cement ratio of 0.55. The study found compressive strengths for 1:4 mixes with 20% and 40% GPKS were 4.91N/mm² and 3.13N/mm², respectively, below the control value of 5.54 N/mm², falling within the BS 6073-1:1981 standard minimum of 2.8N/mm². Dadzie and Yankah (2015) carried out an experimental study on utilizing palm kernel shells (PKS) as a partial substitute for sand in the production of masonry units. The findings indicated that masonry units with over 40% PKS substitution became significantly more permeable, with water absorption values below 13%. Mortar containing 10% to 40% PKS was deemed suitable for both internal and external masonry walls. The study also observed that the density of PKS masonry mortar decreased by approximately 10%, but mortar's compressive strength exceeded the minimum requirements specified in BS 6073-1:1981.

Another study by Obioma (2023) on the effect of partially replacing sand with laterite on the strength properties of concrete found that the hardened density and compressive strength improved with up to 5% laterite replacement but began to decrease beyond this point. Based on these findings, the study discourages using laterite as a partial sand substitute in concrete beyond 5% replacement, as the compressive strength significantly declines at higher percentages. Jannat et al. (2021) in their research on the incorporation of nutshell waste into bricks, mortar, and concrete, such as adding Argan Nut Shell Powder (ANSP) and Walnut Shell (WS) to unfired bricks found lower density, water absorption, and thermal conductivity. They found a weak adhesion between the nut shell particles and the clay matrix that led to a decrease in the strength of the bricks.

From the above studies, it can be observed that no study has used grounded palm kernel shells (GPKS) as a partial replacement of sand in cement mortars. The use of GPKS in construction materials will reduce the environmental impact of burning waste palm kernel shells which results in the introduction of carbon dioxide (CO_2) in the atmosphere. It will also contribute knowledge on the use of waste palm kernel shells as a substitution for aggregate in construction applications. This study, therefore, explores the physical and mechanical properties of cement mortar produced with GPKS as a partial replacement for sand. GPKS was used as a replacement of sand at levels of 0, 5, 10, 15, 20, and 25% in cement mortar specimens of size 100 × 100 × 100 mm. The specimens were tested for water absorption, density, compressive strength, and tensile strength to determine their physical and mechanical properties.

2 MATERIALS AND METHODS

2.1 MATERIALS

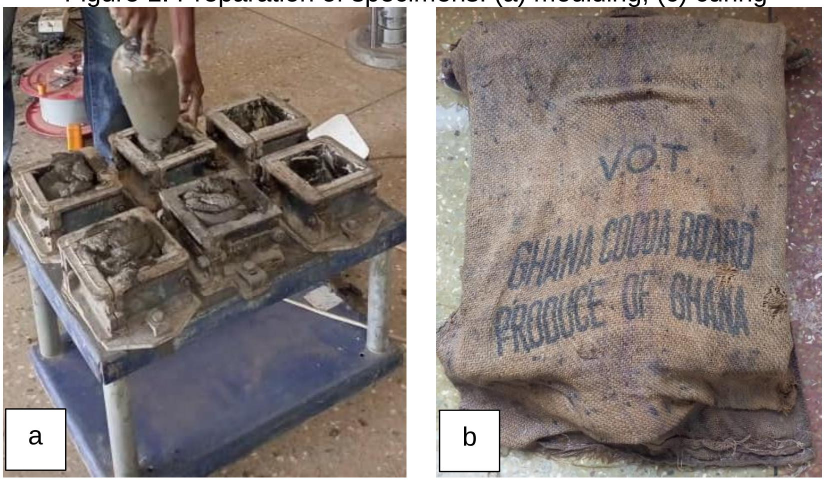
Cement, sand, grounded palm kernel shells (GPKS), and water were the materials used for producing the mortar. Ordinary Portland Cement (OPC) CEM II/B-L32.5N produced by Ghana cement (GHACEM) limited conforming to ASTM C150-07:2012 was used. Graded river sand, with a fineness modulus of 2.85 and a specific gravity of 2.55, passing through a 2mm sieve, was utilized as the fine aggregate. Palm kernel shells were sourced from a local palm kernel oil production factory in Adweso-Koforidua, located in the Eastern Region of Ghana. The shells were thoroughly washed with hot water to remove dust, mud, and oil residues that could affect the mechanical properties of the mortar. After washing, the shells were sun-dried to eliminate any remaining oil. Once dried, the shells were ground into finer particles using a milling machine at the Kwadaso Soil Research Center in the Kwadaso Municipality of Kumasi, Ghana. Both the GPKS aggregates and sand (fine aggregate) samples were then sieved through a 2mm sieve to obtain the desired aggregate size.

2.2 PREPARATION OF SPECIMENS

The materials were batched by weight using a mix ratio of 1:4 (cement to sand) and a water-cement ratio of 0.7. GPKS were used to replace sand at levels of 0, 5, 10, 15, 20, and 25%. A mechanical pan mixer was used to mix the materials for producing mortar cubes. Six different mixtures were prepared using a rotating pan mixer. Prior to mixing, all materials were measured based on the specified mix proportions. The sand was first added to the pan, followed by cement while the mixing pan was rotating. GPKS was then added according to the specified replacement ratio. The dry mix was rotated in the pan while water was gradually added until the desired water/cement ratio of 0.7 was achieved.

After mixing, the mortar was placed into metal moulds of size 100 × 100 × 100 mm as shown in Figure 1a, and compacted using a mechanical vibrating table. The moulded samples were left to set in the moulds for 24 hours before being demoulded and transferred for curing. Curing was carried out using the jute sack method. The sacks were saturated with water and evenly spread over the surface of the mortar cubes. The jute sacks were kept continuously moist by wetting them twice daily to ensure proper curing. This method acted like a mulch, retaining moisture on the surface of the mortar cubes as seen in Figure 1b. The mortar cubes (specimens) were cured for up to 28 days, while testing was done in 7-days intervals.

Figure 1. Preparation of specimens: (a) moulding, (c) curing



Source: Prepared by the authors (2024).

2.3 TESTING OF SPECIMENS

2.3.1 Density

The density of the specimens was determined following the guidelines outlined in BS EN 1015-6:1999. Three replicates were tested for density at 7, 14, 21, and 28 days for each mix design. The density of the specimen was determined by measuring the volume and the mass. These measurements were then used to calculate the density of the mortar samples using the formula:

$$\text{Density} = \frac{\text{Mass of sample}}{\text{Volueme of same Sample}} \quad (1)$$

2.3.2 Water absorption

The percentage of water absorption is an indicator of the pore volume or porosity in hardened mortar, representing the portion occupied by water when saturated. The water absorption of specimens after 28 days of moist curing was measured following BS EN 1015-18:2002. The water absorption is calculated by determining the difference between the absorbed mass of the specimen and the oven-dry mass of the specimen, expressed as a percentage of the oven-dry mass. After the curing period, the selected specimens were dried in an oven at 105°C overnight. Prior to immersion in water, the mass of each specimen was recorded. The specimens were then submerged in water for 30 minutes. The formula below was used to calculate the water absorption:

$$\text{Water Absorption} = \frac{M_2 - M_1}{M_1} \times 100 \quad (2)$$

where M_1 = mass after oven dry, and M_2 = mass after immersion water.

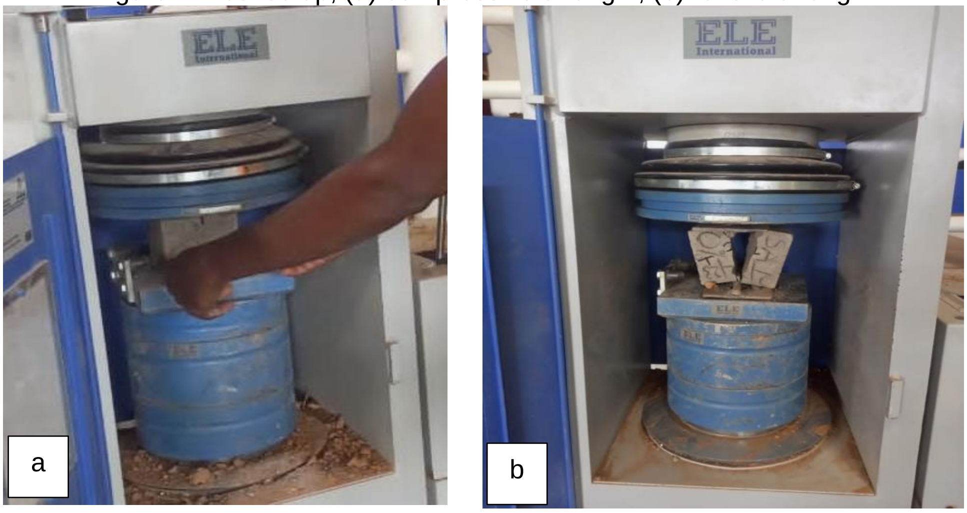
2.3.3 Compressive strength test

The compressive strength test for the specimens was carried out in accordance with the guidelines specified in BS EN 772-1:2011+A1:2015. The prepared specimens were placed in a digital universal compressive strength testing machine for evaluation. Each specimen was positioned between the bottom and top plates of the ELE 2000kN compressive strength machine as shown in Figure 2a. A load was applied gradually until the specimen was crushed. The crushing load and the resulting strength of each sample were recorded. The compressive strength was then calculated using the formula:

Compressive Strength = $\frac{F}{A}$

where F= Force, and A= Area

Figure 2: Test setup, (a) compressive strength, (b) tensile strength



Source: Prepared by the authors (2024).

2.3.4 Tensile strength test

The tensile test was determined by the required standard BS EN 12390-6:2009. The specimens were placed in the ELE 2000kN compression test machine with the aid of a jig to split the sample as seen in Figure 2b. A load was applied gradually until the specimen was crushed. The crushing load and the resulting strength of each sample were recorded. The split tensile strength was then calculated using the formula:

Split Tensile = $\frac{2F}{\pi l d}$

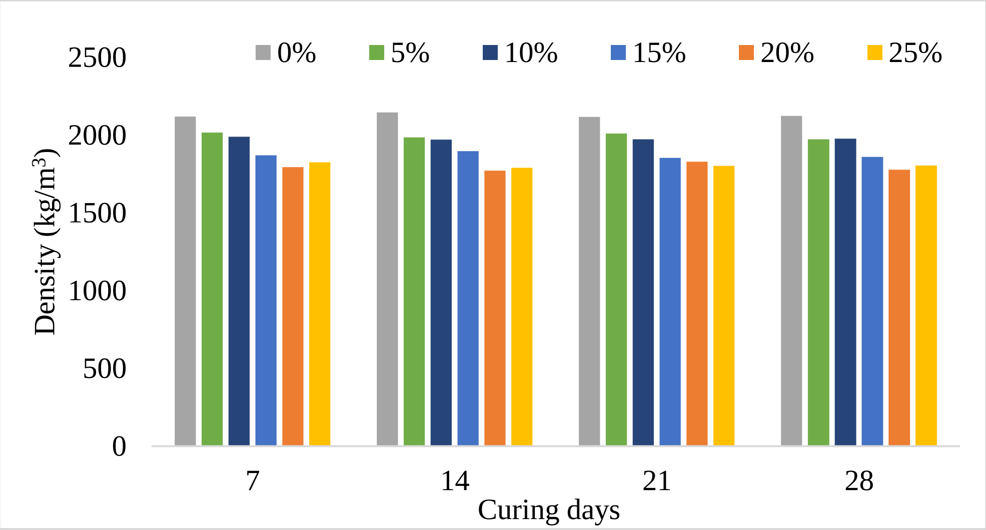
where F= Force, l= length of specimen, and d= diameter of specimen

3 RESULTS AND DISCUSSION

3.1 DENSITY

Figure 3 shows the result of the density of the specimens. It can be seen that as the percentage of GPKS aggregate replacement increases, a decrease in density is observed. This means that as the quantity of the GPKS increases in the specimen the weight of the specimen reduces. A similar result was found in the study by Addo (2021) where the densities reduced from 1773 to 1665 kg/m³. This can attributed to the lower specific gravity of the GPKS as compared to the natural sand. The density of specimens in this study on the 28-day curing was between 2123.33 and 1805.33 kg/m³ which were better than the densities obtained in previous studies by Danso and Appiah-Agyei (2021) which ranged from 1497.27 to 1684.67 kg/m³ and Addo (2021) which ranged from 1773 to 1665 kg/m³. A study by Brown and Danso (2024) obtained higher densities ranging from 2001 to 2144 kg/m³. It must be noted that the 0% GPKS content (control) specimens obtained higher densities than all the GPKS replacement specimens. The reduced densities of the specimens with a higher content of GPKS was likely to affect the strength properties of the specimens with high GPKS content. The density values obtained are within the recommended density values of 1700 to1900 kg/m³ by ASTM C270:2019.

Figure 3: Density of specimens

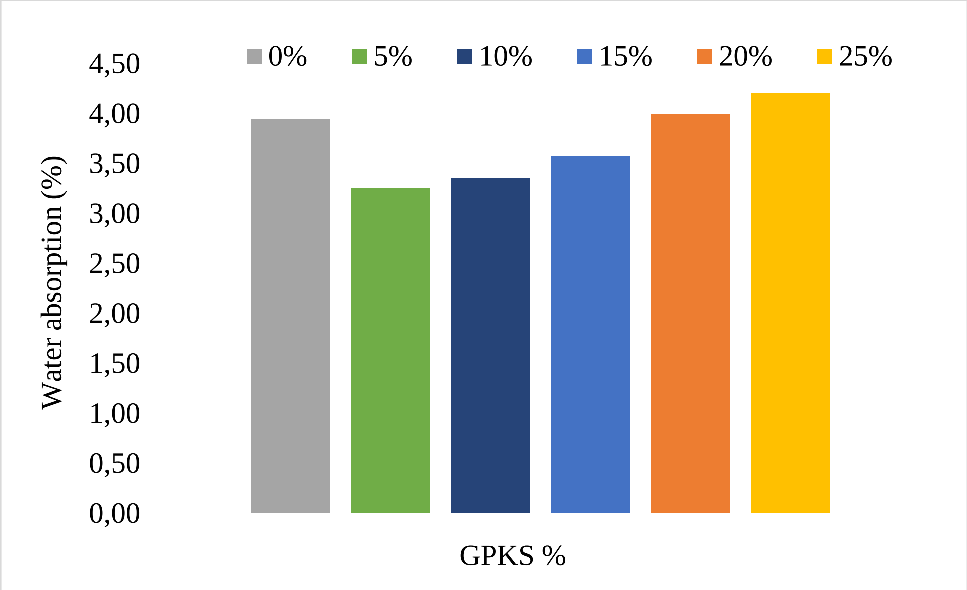


Source: Prepared by the authors (2024).

3.2 WATER ABSORPTION

The result of the water absorption test conducted on specimens is displayed in Figure 4. The result indicates that the water absorption percentage increased when the proportion of GPKS replacement increased. The water absorption of mortar is crucial for determining the material's porosity. After 28 days of curing, the control specimen obtained a water absorption of 3.94%. With the addition of GPKS aggregate, the water absorption decreased, starting at 3.25% for a 5% replacement, indicating improved water resistance. This trend continued as the percentage of GPKS replacement increased, the 10% GPKS replacement achieved 3.35% water absorption, suggesting further improvement. However, the 15% GPKS replacement exhibited increased water absorption at 3.57% which continued to 4.21% for the 25% GPKS replacement. The enhancement in water resistance is likely due to GPKS's low porosity and hydrophobic surface. This suggests that GPKS can significantly improve mortar's water resistance, making it a promising material for areas with high moisture exposure. Similar results were found in the studies by Dadzie and Yankah (2015), and Addo (2021). The absorption values obtained in this study are better than the 10% recommended by ASTM C1403:2022, and the 12% value recommended by BS 2028:2000.

Figure 4: Water absorption of specimens

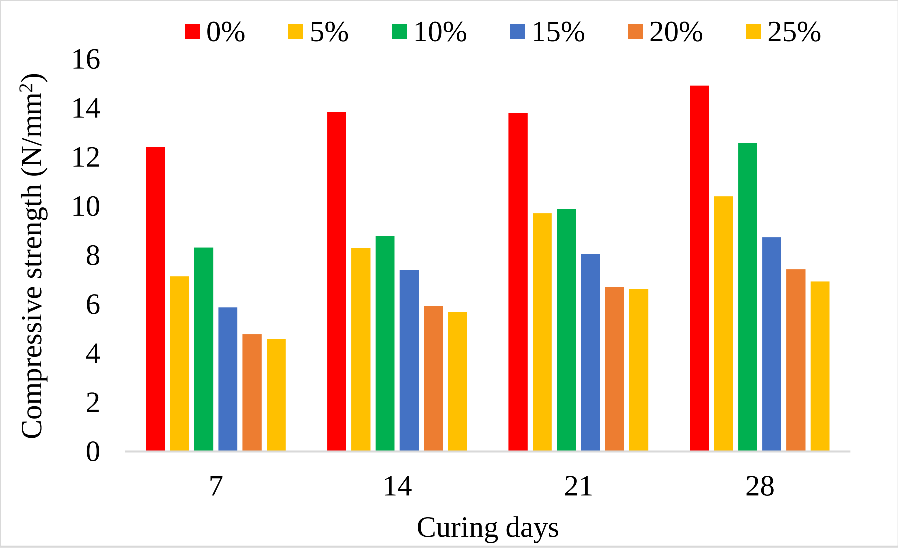


Source: Prepared by the authors (2024).

3.3 COMPRESSIVE STRENGTH

The compressive strength result of the specimens is displayed in Figure 5. It can be observed that the control specimens achieved the highest compressive strength as compared with all the GPKS replacement proportions. Among the GPKS replacement proportions, it can be seen that the compressive strength increased up to 10% replacement and strength declined with a further increase in GPKS content. This result is consistent with previous studies conducted by Adewole (2016), Dadzie and Yankah (2015), and Brown and Danso (2024). At 28 days, the control specimens' compressive strength was 14.92 N/mm², while the 10% GPKS replacement had 12.59 N/mm², a decrease of about 18%. These findings suggest that partial replacement of sand with GPKS aggregate leads to a decrease in compressive strength. However, all the compressive strengths recorded were greater than 6 N/mm², which implies that the mortar produced with GPKS aggregate as replacement of sand satisfied the requirement for cement mortar grade M6 and therefore can be used for construction applications. The compressive strength values achieved in this study beyond the recommended 3.5 N/mm^2 for sandcrete blocks by the British standard BS EN 772-1:201127, and 2.8 N/mm^2 for sandcrete by the GS 766:2011. This implies that the compressive strength achieved by the cement mortar produced with GPKS aggregate as replacement of sand are satisfactory.

Figure 5: Compressive strength of specimens

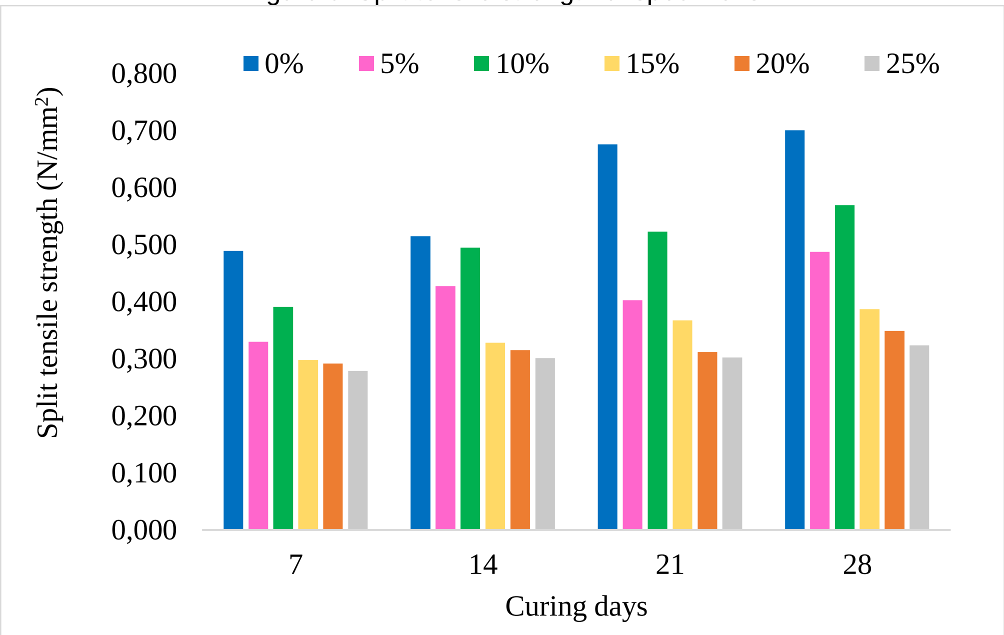


Source: Prepared by the authors (2024).

3.4 SPLIT TENSILE STRENGTH

The split tensile strength result of the specimens can be found in Figure 6. The result followed the trend of the compressive strength result with the control specimens achieving the highest tensile strength as compared with all the GPKS replacement proportions. It can be seen that among the GPKS replacement proportions, the tensile strength increased up to 10% replacement, and strength declined with a further increase in GPKS content. This result is similar to the results of previous studies conducted by Brown and Danso (2024), and Korankye and Danso, 2024. At 28 days of curing, the control specimens had a split tensile strength of 0.701 N/mm², while the 10% GPKS replacement specimens which recorded the peak tensile strength among the GPKS proportions had 0.569 N/mm², a decrease of about 23%, and the tensile strength declined with a further increase in GPKS content. This result suggests that increasing PKS proportion leads to a decrease in split tensile strength. The reduced tensile strength can be attributed to the lower density of GPKS as compared with sand. However, the result of the study satisfied the minimum requirement of 0.05 N/mm^2 tensile strength recommended by BS EN 12390-6:2000.

Figure 6: Split tensile strength of specimens



Source: Prepared by the authors (2024).

4 CONCLUSION

The study made it possible to partially replace natural sand with grounded palm kernel shells (GPKS) in producing cement mortar. This contributes to the reduction of natural resource depletion and promotes sustainable construction practices with socio-economic advantages such as producing affordable housing for people in the low-income bracket. This study investigated the effects of incorporating GPKS as a partial replacement of sand on the physical and mechanical properties of mortar. It was found that although the results for GPKS replacement of fine aggregate specimens were lower than the control specimens, the results for the various GPKS replacements met the standard requirement for cement mortar grade M6. The 10% GPKS replacement was found to have better results among all the various replacement proportions with a density of 1978.33 kg/m^3, water absorption of 3.35%, compressive strength of 12.59 N/mm^2, and tensile strength of 0.569 N/mm^2 which met the standard requirements for cement mortar. The study, therefore, concludes that GPKS can be used as a replacement for sand in cement mortar at a recommended proportion of 10% for construction applications. The use of GPKS as a replacement for sand in mortar promotes sustainability by recycling agricultural waste and reducing dependence on natural sand for mortar production. This alternative has the potential to produce eco-friendly construction materials.

5 LIMITATIONS OF THE RESEARCH AND RECOMMENDATIONS FOR FUTURE STUDIES

The study was limited to investigating only the physical and mechanical properties of cement mortar incorporating GPKS as a natural sand replacement. Again, only cement mortar with GPKS as a natural sand replacement was studied. Further research is needed to explore the thermal and long-term durability properties of GPKS replacement of sand in cement mortar to expand the scope of the study. Microstructural analysis is also recommended for future studies to understand the internal characteristics of the cement mortar produced with GPKS as a partial replacement for sand. The use of GPKS in the production of earth-based mortar is also recommended for future studies.

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