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ORIGINAL ARTICLE

Innovative sustainable concrete using waste tyre steel fibres and milled palm kernel shell

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Abstract: Over the years, numerous studies have been carried out on the sustainable use of waste tyre steel fibre and palm kernel shell in concrete production. However, the study on the integration of waste tyre steel fibre (WTSF) and milled palm kernel shell (MPKS) in concrete production, especially fibre reinforced concrete (FRC) is yet to be evaluated hence, this research studied the effects of waste tyre steel fibre and milled palm kernel shell as fine aggregate partial replacement in FRC. Five different sets of concrete samples were cast which are, ordinary concrete (A_0), concrete with 10% MPKS replacement with fine aggregate (A_1), and others with 10% MPKS and 0.5% WTSF at a varying length of 25 mm, 35 mm and 45 mm (A_2, A_3 and A_4) respectively, the diameter of the WTSF ranges from 1.34 mm-1.69 mm. concrete mix of 1:1.5:3 and 0.6 water cement ratio were adopted. From the study, slump value decreased with an increase in the length of the WTSF. Furthermore, the compressive and splitting tensile strengths increased with increase in the length of fibres. The least and highest 28-day compressive strength values of 21.3 and 30 N/mm^2 and tensile strength values of 1.9 and 3.2 N/mm^2 were recorded for A_0 and A_4 respectively. Lastly, A_4 showed the highest strength for both compressive and tensile strengths. This research shows an integration of MPKS and WTSF to improve mechanical properties of concrete structures thereby contributing to sustainable construction practices and waste management techniques.

Keywords: fibre reinforced concrete, milled palm kernel shell (MPKS), waste tyre steel fibre, compressive strength, tensile strength, physicochemical

1 Introduction

Concrete is majorly most widely used construction material due to its numerous applications in civil infrastructure projects [1]. It is a versatile construction material which constitutes mainly of fine aggregate, coarse aggregate, cement and water mixed in certain proportion [2]. The aggregates which are widely used in concrete are of fine and coarse. Sharp sand or river sand makes up of fine aggregate while gravel and crushed stones are components of coarse aggregate. River sand has been one of the major points of attention in civil construction material because of its cost and environmental influence of harnessing this material such as riverbed depletion etc.

Concrete technology has evolved significantly over the years, triggered by the demands and needs for more affordable, long-lasting durable and sustainable construction materials. There are a lot of special concretes which have evolved due to special demand and advancement in material science and

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concrete technology.

Steel, glass, natural, and synthetic fibres are just some of the many fibre kinds that are frequently utilised as discreet reinforcement in concrete mixtures to improve the properties of concrete. The resultant outcome of the process is then called fibre reinforced concrete (FRC). According to [3] and [4], steel fibres are discussed to have been the most utilised fibre to improve the mechanical performance of concrete. They are included in the mixture in short, discrete lengths with various length to diameter ratios called aspect ratio, ranging from 20 to 100 [5].

Since the manufacture of industrial conventional steel fibres have drawbacks such as the emission of greenhouse gas and the high cost, research on extracting fibre from waste items such as waste tyres other than natural raw resources has increased [6],[7]. Vehicle tyres that have expired are the primary source of recycled steel fibres [8].

Waste tyre steel fibre (WTSF) are steel fibres derived from tyres that have completed their useful or service life. The fibres are substituted for conventional fibres in fibre reinforced concrete (FRC) which the final end product from waste tyre steel fibre reinforced concrete (WTSFRC). A crucial component of comprehending WTSFs' possible uses in engineering and building materials is their geometrical characterisation [9]. The geometrical nature of WTSFs, like aspect ratio, length and diameter significantly impacts the mechanical properties of the resultant composite materials. The length of WTSFs is an important geometrical property that affects its dispersion into concrete materials [10],[11].

Meanwhile, [10] found that compressive strength of concrete was up to 13% higher when WTSF content was 1% and up to 5% higher when WTSF content was 0.5% compared to the control mix. Also, the results of the compressive strength test carried out on WTSFs were published by [12]. The findings indicate that the use of 7.62 cm long WTSFs increased the concrete's strength as the WTSF content increased. However, strength was somewhat diminished when the WTSF content exceeded 3%. With a WTSF of 10.16 cm long, a similar pattern was observed for the study. When employing higher dosages and longer lengths of WTSF, the compressive strength of WTSF-reinforced concrete decreases which could be related to poor workability which resulted in a matrix with unwanted pores and cavities.

WTSFs have an effect on concrete's splitting tensile test, which measures a material's ability to withstand cracking or fracturing under stress. Results demonstrated that adding 2% WTSF (62 mm length) to concrete by volume led to a maximal increase in the STS of up to 149%, suggesting that WTSFs can greatly boost the concrete’s tensile strength [9]. Also, [13] observed a 14% increase in concrete STS with the inclusion of 0.6% WTSF. When compared to plain concrete. [14] discovered that adding 0.75% volumetric content of WTSF and conventional steel fibre to concrete produced enhanced splitting tensile tests of 28 and 26.33%, respectively. The concrete brittleness was changed into being ductile upon the integration of WTSFs. Variable WTSF diameter and length give an additional interlocking mechanism; a 50% improved splitting tensile test was seen after 0.75% volumetric content WTSFs were added.

Furthermore, the oil palm industry is important in many countries being a source of income such as Malaysia, Indonesia and Nigeria. According to [15], Malaysia and Nigeria, for example, are estimated to produce over 4 and 1.5 million tonnes of oil palm shell (OPS) solid waste annually, respectively. Only a small portion of this waste is used as fuel, which is typically used as solid fuel for steam boilers at palm oil mills. Some people, particularly villagers and those who cannot afford to purchase cooking gas or electric cooking materials, adopt this as fuel to cook in an open hearth alongside shaft derived from the final produce

[16] Conducted an investigation on the proportioning of the mixture for oil palm kernel shell (OPKS) in lightweight concrete using concrete batches of 1:1.6:0.96 and 1:1.53:0.99 for the C:S: OPKS ratio with cement content of 450 kg/m^3 produced results showing a minimum slump of 20 mm, a density between 1800 and 1900 kg/m^3, and a minimum compressive strength of 15 N/mm^2.

[17] examined the structural application of lightweight concrete with palm kernel shells (PKS) integrated using a 1:1:2 mix ratio and a w/c of 0.5. from the study the PKS beam demonstrated a 3.981 kN load resistance after 28 days, with a flexural strength of 2.883 N/mm2 and a deflection of 0.947 mm.

Lastly,[2] substituted fine aggregate in their concrete mix with finely milled palm kernel shell

(MPKS), which is a byproduct of milling palm kernel shell until it is well ground into fines or grain-like particles. Concrete mix of 1:1.5:3 with 0.6 w/c was used in the study. Cubes measuring 150 mm by 150 mm by 150 mm were cast with different percentage replacements ranging from 0% to 100% at 10% intervals. The study's findings demonstrated that, in comparison to the control sample, the sample with 10% fine aggregate replacement exhibits the ideal value, which has a substantial impact on workability and increases compressive strength. This study shows that MPKS can be used sparingly to increase workability and compressive strength of concrete.

Although various studies have been conducted to establish the effective and sustainable use of agro-industrial wastes such as waste tyre steel fibre and palm kernel shell in concrete production. However, the study on the combined effects of WTSF and MPKS in concrete production is yet to be thoroughly evaluated. Hence, this study focused on the assessment of the potential use of WTSF and milled palm kernel shell in fibre reinforced concrete. The study evaluates the mechanical strength, microstructure, elemental components and physicochemical analysis of MPKS-WTSF concrete mix.

2 Materials and Methods

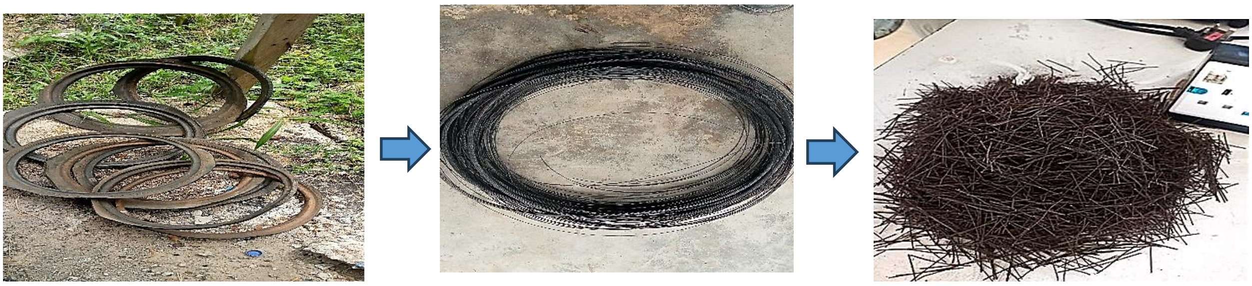
2.1 Materials

2.1.1 Materials Sourcing

The fine and coarse aggregates used were gotten from river sand in Ede and Slava Quarry Company respectively, meanwhile, the cement used was Dangote cement and was sourced from vendors around Ede. Also, the waste tyres were sourced from different mechanic and vulcanizer's workshop in Ede. Lastly, palm kernel shells were gotten from Oloki Village in Ede South Local Government.

2.1.2 Materials Processing

The sourced tyres were burnt in an enclosed environment to extract the embedded steel fibres, although the burning was adopted due to unavailability of pyrolysis machine however, the tyre were burnt in a closed-end steel drum to avoid emission of toxic matters into the environment. The extracted steel fibres were then separated and cut into three different sizes, i.e 25 mm, 35 mm and 45 mm, the diameter of the fibres was then determined, and the corresponding aspect ratio was calculated as shown in **Fig. 1**.below.



(a) Shredded tyre (b) Extracted steel after burning (c) Waste tyre steel fibre

Fig. 1. Waste tyre steel fibre processing

The sourced palm kernel shells were washed with ordinary clean water and then sun dried. The sun-dried palm kernel shells were then milled to get a final product of milled palm kernel shell (MPKS) as shown in **Fig. 2** below.

2.2 Methods and Testing

2.2.1 Materials Characterization

Sieve analysis and specific gravity tests were conducted on both the MPKS and sand according to [18] as shown in **Fig. 3a** and **Fig. 3b** respectively.

Also, the diameter of the different lengths of the fibres was determined and their corresponding aspect ratios were evaluated.

(a) Washing

(d) MPKS

(b) Sun drying

(c) Milling

Fig. 2 Milled palm kernel shell processing

(a) Sieve analysis setup

(b) Specific gravity setup

Fig. 3. Material Testing

2.2.2 Mixture design

Concrete grade of 1:1.5:3 and 0.6 water cement ratio (w/c) were adopted. The high w/c was reported by [2] as the most effective w/c for concrete with MPKS to form complete cement hydration. Five different samples were cast which are; ordinary concrete sample, concrete with MPKS, and concrete with MPKS and steel fibres at varying length of 25 mm, 35 mm and 45 mm. Meanwhile, the percentage MPKS replacement was kept constant at 10% as reported by [2] to be the percentage with the highest concrete performance. 0.5% by volume of concrete was maintained for steel fibre inclusion [9] as shown in **Table 1**.

Table 1. Design mix table

Sample	Waste Tyre Steel Fibre Length (mm)	Percentage by volume of concrete (%)	Weight of WTSF inclusion (0.5%) (kg)	Weight of MPKS replacement (at 10%) (kg)
A0	0	0	0	0
A1	0	0	0	2.782
A2	25	0.5	1.66	2.782
A3	35	0.5	1.66	2.782
A4	45	0.5	1.66	2.782

2.2.3 Concrete mixing

25.038 kg, 55.64 kg and 2.782 kg of fine aggregates, coarse aggregate and MPKS respectively were thoroughly mixed until a homogenous mix was achieved on a clean and impervious platform. Afterwards, known weight of cement was added and mixed thoroughly until a uniform and homogenous concrete mix was achieved. Water of determined quantity was added and mixed until there was a uniform concrete mix, after which, known volume of waste tyre steel fibre (WTSF) was added into the concrete a bit by bit and subsequently mixed together to avoid balling of fibres, the process was continued until it was ensured that the steel fibres were evenly dispersed throughout the concrete matrix as shown in **Fig. 4**a.

The freshly mixed concrete was placed in a slump test cone to determine its workability which was afterwards formed into a 150 x 150 x 150 mm cube and a 100 mm diameter and 200mm height cylinder and well compacted using manual rod tapping as shown in **Fig. 4b** and **Fig. 4c**. Later, the cast concrete samples were cured in water for three varying curing ages i.e 7, 14, and 28 days. The cured concrete at each particular curing age was brought out of water weighed and subjected to compressive and splitting tensile using OKH-2000 compressive strength testing machine with accuracy of 1 and maximum testing force of 2000 kN made by Hebei Ti Anrui Generate Electricity Equipment Co. LTD. as shown in **Fig. 5a** and **Fig. 5b** below.

(a) Mixing of concrete (b) Workability testing (c) Sample casting

Fig. 4. Concrete mixing and casting

The compressive strength (CS) and tensile strength (TS) test were calculated using Eq. (1) and Eq. (2) respectively. The result was expressed in units of force per unit area, typically megapascals (MPa).

$$CS = \frac{P}{A} \tag{1}$$

Where P is the applied load; A is the area of the specimen.

$$T = \frac{2P}{\pi LD} \tag{2}$$

(a) Compressive strength testing

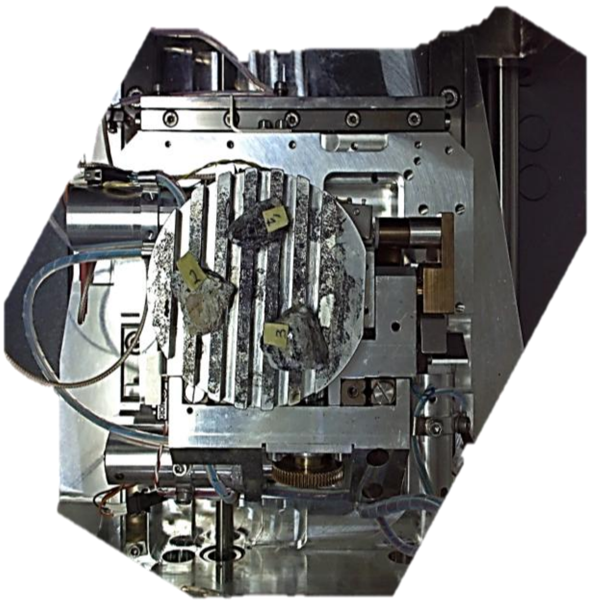
(b) Tensile strength testing

Fig. 5. Testing of hardened concrete

2.2.4 Microstructural and elemental testing

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) were conducted on the most improved samples to establish the microstructural and elemental compositions of the samples, the equipment used for this test was Zeiss SmartEDX as shown in **Fig. 6a**. Samples were mounted on aluminum stubs using conductive carbon tape and coated with a thin gold layer to prevent charging. Each sample was labeled and oven-dried at 60 °C to remove moisture. The prepared stubs were loaded into the Zeiss SEM chamber as shown in **Fig. 6b**. The SmartEDX detector was used to perform elemental analysis. As the electron beam interacted with the sample, characteristic X-rays were emitted and detected, allowing identification and quantification of elements on the sample surface as shown in **Fig. 6b**.

(a) SEM-EDX Machine Setup



(b) Samples in Zeiss SEM Chamber

Fig. 6. Elemental and microstructural testing

3 Results and Discussions

3.1 Sieve Analysis

The gradation curves for the sand and MPKS are shown in **Fig 7**. From the figure, the shape and gradation curve of MPKS is similar with the work of [2].

The particle size distribution result yielded a Coefficients of Uniformity (Cu) of 3.6 for MPKS and 2.8 for the fine aggregate, and Coefficients of Curvature (Cc) of 1.5 for MPKS and 1 for fine aggregate. Cc and Cu are coefficients to classify soils and aggregates based on their particle size distribution. A soil is said to be well-graded if its Cu is greater than 4 for gravels and greater than 6 for sands, and its *Cc* is in the range of 1-3 [25]. According to BS EN 933-1, [19] Cu < 6 indicates uniform soil while Cu > 6 indicates well graded soil. Based on the result gotten, it showed that both materials fall under uniform soil, also, Cc indicates the shape of the gradation curve, Cc between 1 and 3 indicates i.e 1 < Cc < 3 a well graded soil. From the result obtained, Cc of the samples showed that both materials are well-graded soil and are suitable for construction purposes. Furthermore, the obtained results confirmed that both materials could be used for concrete production and complied with BS EN 933-1: 2012.[19]

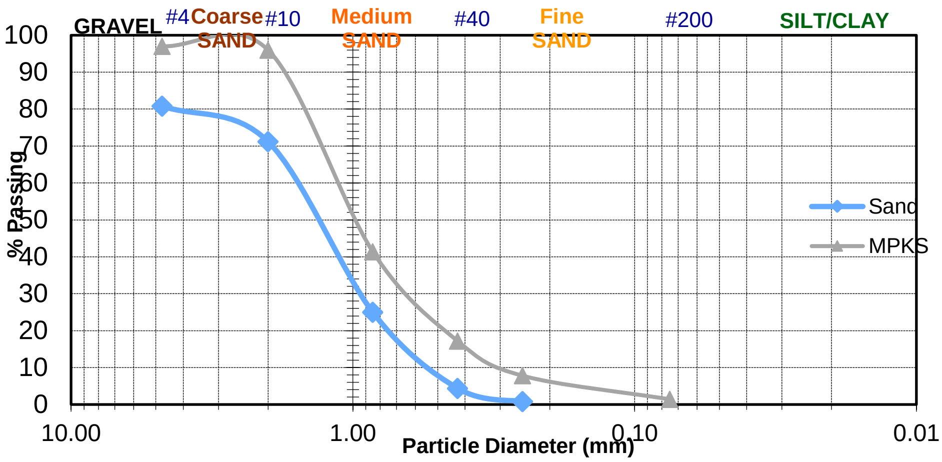


Fig. 7. Gradation curve

3.2 Specific Gravity

The results for specific gravity are depicted in **Table 2.** which reveal that the values satisfy the standard specification of BS 1377 [20] which varies between 2.6-2.8 and suitable for concrete production. Furthermore, the result of the specific gravity is similar to the findings of [2] as the values are very close.

Table 2. Specific gravity result

Sample	Slump Value
Sand	2.8
MPKS	1.3

3.3 Waste tyre steel fibre properties

The steel fibre's diameter used range from 1.34 mm to 1.69 mm. Furthermore, the aspect ratio for 45 mm, 35 mm and 25 mm fibre length varied from 26.9-37.3, 20.7-29.0 to 14.8-20.7 respectively. The aspect ratio of fibre significantly impacts the properties of concrete, higher aspect ratio improves tensile strength of concrete and affects fibre-matrix bonding influencing concrete's overall performance this is evident in the performance of concrete with highest aspect ratio gotten in this study.

3.4 Workability of concrete samples

Table 3. represents the workability of the samples, the table reveals slump value of 80 mm, 70 mm, 62 mm, 51 mm and 25 mm for A_0, A_1, A_2, A_3 and A_4 respectively. The results for slump values revealed that the slump value decreased with increase in the size of steel fibre inclusion. This trend of reduction in slump value as fibre size and volume increases is corroborated in the study of [9] and [21]

Furthermore, sample A_4 of 45 mm fibre size shows the least slump value of 25 mm which still satisfies the standard specification and can be used for major concrete works. Although, superplasticizer was not employed in the batching of concrete in this study, nevertheless, the reduction in slump is not significant as investigated by [9]. This reveals that MPKS could be employed in fiber reinforced concrete when increasing the water cement ratio without the use of superplasticizer while achieving the desired strength. The decrease in slump value can be traced to the effects of both materials added i.e MPKS and WTSF, both materials absorb water during mixing of concrete which resorted to decreasing hydration water, hence, decrease in slump.

Additionally, the highest slump achieved is 80mm for sample A_0 which is the control sample, the result of the slump is a little bit deviated from the one gotten by [2] this could be as a result of different moisture content condition as well as different fine aggregate employed; however, the slump still satisfies BS EN 12350-2:2019 [22] specification and could be used in concrete production.

Table 3. Slump results for workability

Sample	Slump value (mm)
A0	80
A1	70
A2	62
A3	51
A4	25

3.5 Compressive strength

The relationship between the compressive strength of the samples is presented in **Fig. 8**. According to the figure, the maximum strength of 29.9 N/mm2 was achieved at 7-day curing for 45 mm fibre length. The values of the compressive strength of the samples increase with increase in fibre lengths which is validated in the work of [9]. However, sample A_2 shows little deviation from the trend by showing lesser value compared to the preceding control sample and succeeding samples. 21.3 N/mm^2 and 21.6 N/mm^2 compressive strength value were recorded for A_0 and A_1 (i.e. control sample and sample with only MPKS respectively). The deviation could be linked to a localised fibre issue which occurred as a result of uneven distribution of clustered fibres in the samples, consequently creating weak zones within the composite. The orientation of fibre within concrete sometimes varies which contributes significantly to the integrity of the concrete especially the reduction in the overall concrete's strength [26].

Lastly, the 28-day sample showed an improved value of 30 N/mm^2 for sample A_4. From the figure, the 28-day result of each sample was either increased or it maintained the same value for 7-day result. In the case of A_4, a close result was gotten at 7-day while A_0 maintained the same value gotten at 7-day which is 21.3 N/mm^2. However, A_1, A_2 and A_3 showed an increase in compressive strength compared to their 7-day value. Furthermore, A_4 is 39% and 36% higher than A_0 and A_1 respectively. In addition, A_2 is 30% and 28% while A_3 is 19% and 17% higher than A_0 and A_1 respectively. Although A_3 showed a decrease in value compared to A_4 and A_2 nevertheless, the sample is higher than A_1 by 19%.

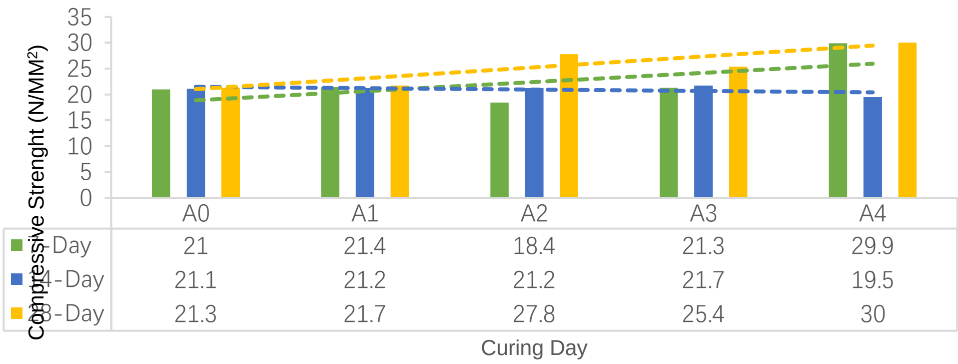


Fig. 8. Compressive strength results

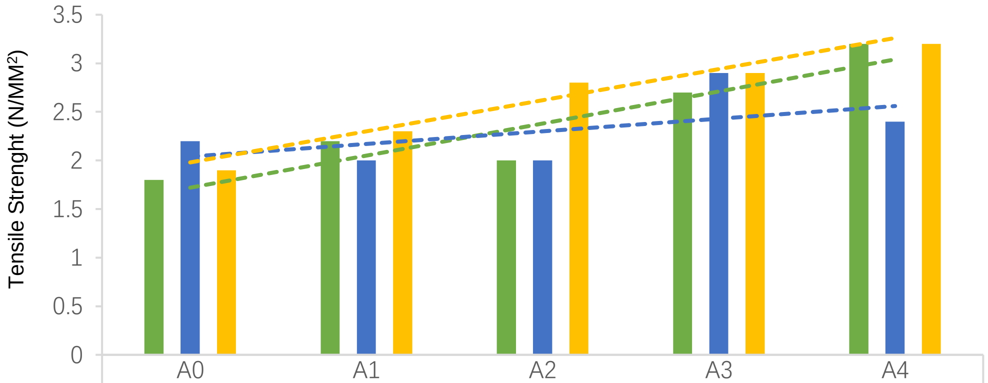
The increase in compressive strength due to the addition of steel fiber and MPKS, particularly in A_4, which shows a 38% improvement, aligns with the findings of [9] and [21] while the increase in strength of A_1 compared to A_0 is validated in the work of [2] although the 2% increment is a bit lesser than that of [2]. The values showed that A_4, with the higher aspect ratio between 26.9-37.3, exhibits the highest compressive strength value. However, the A_3 sample did not follow the same trend as its value is less than A_2. Nonetheless, the results are validated from the study of [9] and [13]. Lastly, the strength loss in some samples at 14-day could be linked to discrepancies in the mixing and placing of samples.

3.5 Tensile strength

The relationship of the splitting tensile strength of the samples is presented in **Fig. 9.** From the Figure, it is shown that the values of the splitting tensile strength increase with increase in the fibre length similar to the compressive strength. Sample A_2 shows a lesser value compared to the preceding and succeeding samples. 14-day samples possess a similar behaviour with the compressive strength. However, the splitting tensile strength increases with an increase in the length of fibre. This behaviour could be related to the reports of [9], [10] and [13].

Furthermore, the 28-day result showed the highest value of 3.2 N/mm^2 at A_4 compared to other samples. From the result, A_4 maintained its 7-day result of 3.2 N/mm^2 while other samples showed an increase in tensile strength compared to their individual 7-day result. Additionally, the tensile strength increased with an increase in the length of fibre with 45mm having the highest tensile value. This is corroborated with the work of [23] who reported the same trend.

Lastly, A_4 was 69% and 39% higher than A_0 and A_1 respectively, A_3 is 52% and 25% and A_2, 48% and 22% higher than A_0 and A_1 respectively. This is validated in the result gotten by [9], [10] and [13].



	A0	A1	A2	A3	A4
7-Day	1.8	2.2	2	2.7	3.2
14-Day	2.2	2	2	2.9	2.4
28-Day	1.9	2.3	2.8	2.9	3.2

Fig. 9. Tensile strength results

3.6 Scanning electron microscopy (SEM) result

The Scanning Electron Microscopy (SEM) results for Samples A_1 (MPKS control sample) and A_4 (45mm sample) at a magnification of 250X are shown in **Fig. 10** and **Fig. 11.** respectively. From the picture the smooth or porous texture shows the presence of paste matrix which is an indication of quality hydration of the concrete samples, meanwhile, hydration plays a significant role in the strength and durability of concrete as a well hydrated concrete indicates a better performance. Also, the presence of fine or fibrous masses and the needle like crystals show the presence of calcium silicate hydrate (C-S-H) and Ettringite respectively. C-S-H is the main strength-giving product of a concrete sample, and its presence indicates improvement in strength properties of concrete, and this is evident in the strength performance of these concrete samples as they show higher strength characteristics especially A_4. The result showed that MPKS bonds strongly with the cement matrix and acts as additional flaws, promoting more saturated multiple cracking and enhancing ductility which is corroborated with the work of [27].

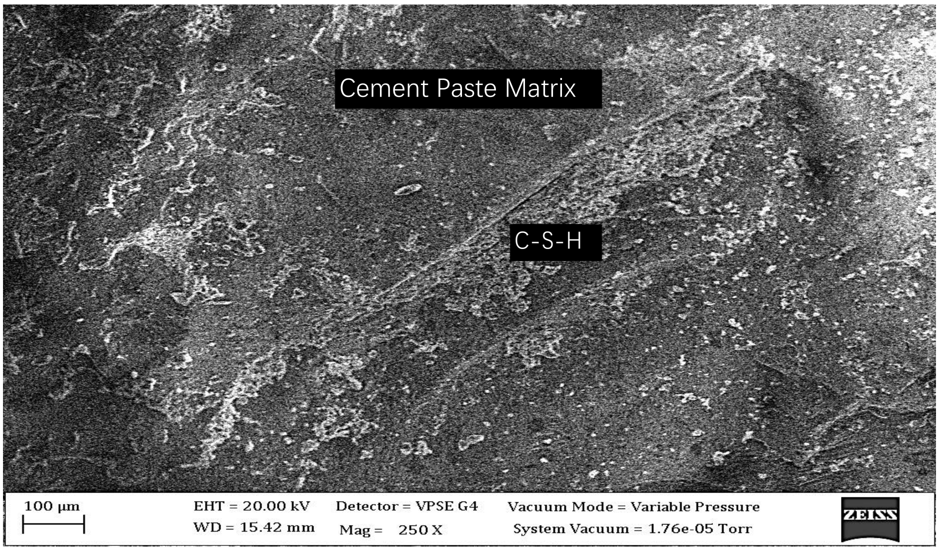


Fig. 10. SEM result for A_1

Similarly, Ettringite shows the early hydration product of a concrete sample which is also an indication for concrete strength. Furthermore, the high density of the concrete samples shows the concrete is well compacted and the pores are filled. This is likely due to the presence of MPKS which is believed to might have filled the pores due to its fine nature and its ability to fill voids. Ultimately, concrete with pores filled are stronger and more durable. Lastly the presence of fibre as shown in **Fig. 11.** portrays how the fibre content bonds strongly with the concrete which will consequently strop crack propagations. High-modulus fibers such as steel (SF) improve composite strength and toughness primarily by restricting the growth of large cracks and absorbing higher levels of tensile stress [28].

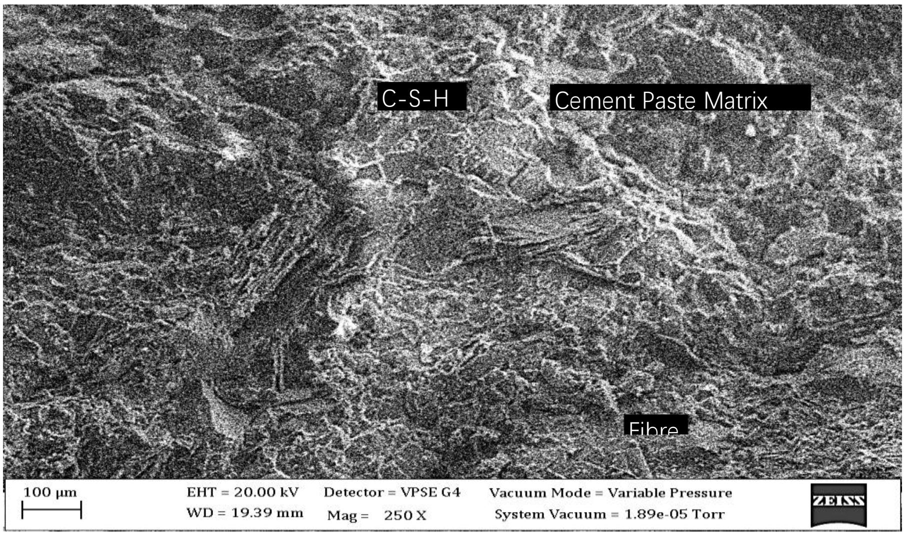


Fig. 11. SEM result for A_4

The bridging effect of fibers and their confinement to the matrix can inhibit crack formation and propagation [26]. This is evident in the compressive and tensile strength results of the samples with fibre contents especially A_4 and is validated in [24].

3.6 Elemental analysis

The Electron diffraction X-Ray spectrometer (EDX) results for the concrete samples A_1 and A_4 are presented in **Fig. 12** and **Fig. 13** respectively. The results show the presence of Si and Ca with Si having the highest atomic percentage of 83.13%. This shows the likeliness of the presence of C-S-H or silica-rich zone and the indication of pure and enriched silicate phase. This could be the result of the reaction of MPKS with the cement constituents, also, the Si/Ca ratio implies enhanced durability, and this is evident in its strength improvement characteristics compared to the control sample.

Furthermore, the EDX results for A_4 as shown in **Fig. 13** portray the presence of O, Si and Al. The result shows that the presence of these elements indicates a possible presence of silicate-rich material like C-S-H and aluminosilicate gel [29]. The result also shows the hydrated silicate phase, which likely represents C-H-S with some aluminum substitution or the presence of early hydration products like ettringite. Ettringite is a mineral that forms in certain types of cement and concrete, it's a calcium aluminum sulfate hydrate mineral which contributes to the strength and durability of concrete. This is evident in the highest strength characteristics shown by this sample compared to the other samples.

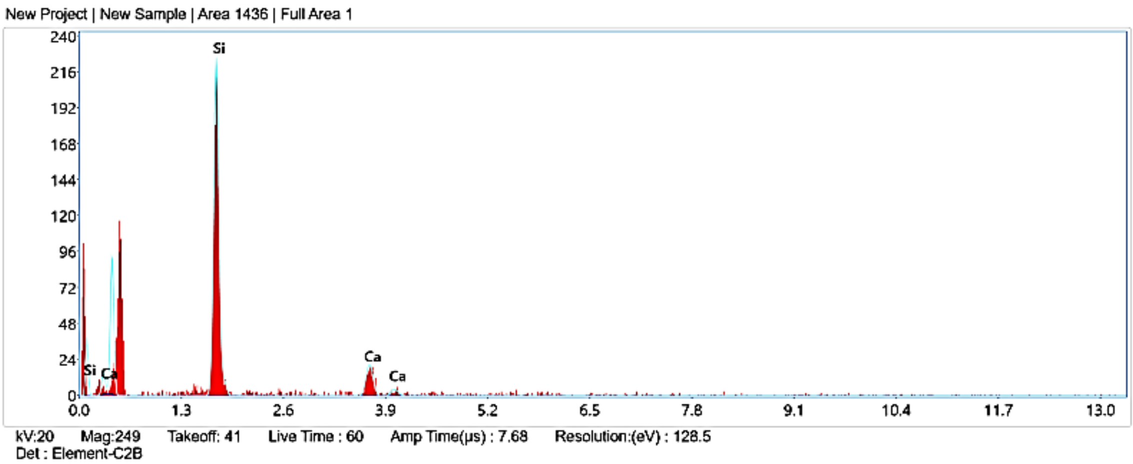


Fig. 12. A_1 EDX result

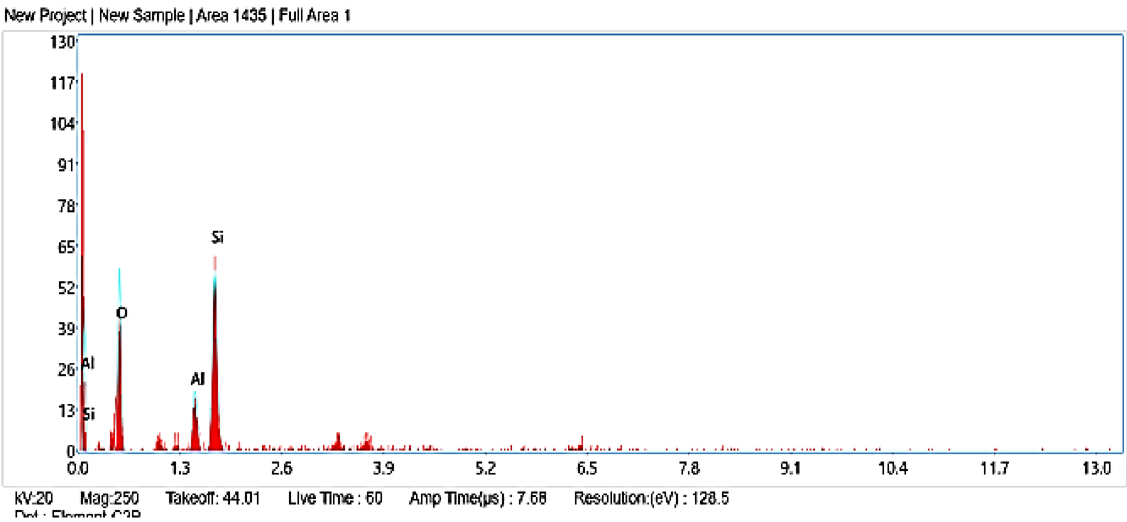


Fig. 13. A_4 EDX result

3.7 Physicochemical analysis

The influence of MPKS on the chemical composition and microstructure of the samples compared to the control sample as shown in **Fig. 12 and 13** reveals that sample A_4 exhibits the presence of Oxygen (O), silicon (Si) and aluminum (Al) indicating the likely formation of silicate-rich material like calcium silicate hydrate (C-S-H) and aluminosilicate gel. The presence of key elements like Al_2O_3, SiO_2, and CaO influences setting behavior and strength development, ultimately enhancing the overall strength and durability of the concrete samples [29]. This further suggests that MPKS contributes to the hydration and reaction processes, as evidenced in the mechanical strength of the samples.

Furthermore, the results demonstrate the influence of MPKS on the samples' microstructure relative to the control samples. Sample A_4 shows a more refined and denser matrix, as MPKS particles contributed to pore filling, which reduced porosity and enhanced overall density. This densification confirms that MPKS improved the Interfacial Transition Zone (ITZ) of the concrete. The ITZ typically contains numerous microscopic intrinsic grooves, pores, and cracks [30]. MPKS absorbs some free water since its initial moisture content which effectively lowered the local water-to-cement ratio in the ITZ region, thereby strengthening the interfacial bond between aggregates and the cementitious matrix

Also, **Fig. 11** further illustrates the synergistic fiber-matrix interaction, demonstrating how the combined presence of fibers and MPKS enhanced the Interfacial Transition Zone (ITZ). This resulted in a denser and more strongly bonded composite, which directly contributed to the improved overall strength performance of the concrete samples. The incorporation of fibers alters the pore structure and microstructure of the ITZ, subsequently influencing the material's damage progression. This enhancement can be attributed to the fibers modifying the matrix's air-void system, thereby mitigating damage accumulation and improving durability [28]

In summary, the improved physicochemical properties of the MPKS-fiber-cement matrix are directly evident in the enhanced mechanical strength, refined microstructure and favourable elemental compositions observed in sample A_4 compared to the other samples. These interconnected enhancements collectively explain the overall performance improvement of the modified concrete.

4 Conclusions

From the research carried out on the effects of waste tyre steel fibres and milled palm kernel shell on the mechanical properties of fibre reinforced concrete. The key findings, practical implications, and study limitations are summarized as follows:

i. Both the fine sand and MPKS satisfied standard specifications for gradation (Cc, Cu) and specific gravity, confirming their suitability for concrete production. The incorporation of WTSF, with diameters ranging from 1.34 mm to 1.69 mm and aspect ratios between 14.8 and 37.3 depending on fiber length, significantly influenced workability. Slump decreased with an increase in fiber lengths, with the control mix (A_0) exhibited the highest slump. Notably, at a 10% MPKS replacement level and a 0.6 water-cement ratio, no superplasticizer was required to maintain adequate workability in the fiber-reinforced mixes, highlighting a practical and cost-effective mix design.

ii. The compressive and splitting tensile strengths increased progressively with an increase WTSF lengths. Mix A_4 (45 mm fibers) achieved the highest improvements. Specifically, A_4 showed a 39% increase in compressive strength and a 69% increase in splitting tensile strength compared to the control sample (A_0). while A_1 showed a 2% increase in compressive strength and a 20% increase in tensile strength compared to A_0.

iii. The microstructural analysis (SEM) revealed a denser matrix with reduced porosity in the samples containing MPKS, which is attributed to the pore-filling effect of MPKS particles. Furthermore, images clearly illustrated effective crack-bridging by the steel fibers, which contributes to post-cracking ductility and energy absorption. Elemental analysis (EDS) confirmed the presence of key hydration products, including calcium silicate hydrate (C-S-H) and aluminosilicate gels. This indicates that MPKS may likely participate in the reaction to enhance the interfacial transition zone (ITZ) and improve the overall bond within the composite system.

iv. The performance enhancement stems from a dual mechanism in which the MPKS acts as a micro-filler densifying the matrix and improving the fiber-matrix ITZ, and the WTSF provides an enhanced crack control and stress transfer, leading to higher tensile strength and toughness.

v. These findings provide a viable eco-friendly and sustainable strategy for concrete production, simultaneously valorizing two waste materials; palm kernel shell (an agro-waste) and waste tires (an industrial waste). The proposed mix, particularly the A_4 formulation, is recommended for applications requiring improved tensile capacity and crack resistance, such as in pavements, thin structural elements, or repair materials.

vi. The primary limitation of this study is its focus on laboratory-scale performance. The practical viability of massive MPKS usage requires investigation into long-term durability (e.g., resistance to chloride penetration, sulfate attack, and drying shrinkage), volume stability, mix optimization, and the economic logistics of large-scale waste sourcing and processing.

vii. Lastly, despite the highlighted limitations, this work successfully demonstrates the technical feasibility and mechanistic basis for using MPKS and WTSF to produce concrete with significantly enhanced mechanical properties. It establishes a foundation for developing sustainable, high-performance construction materials that contribute to a circular economy.

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CRediT authorship contribution statement

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Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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