*Original Research Article*

# The Effect of Waste Automobile Tire and Palm Kernel Shells as Aggregates in Concrete on Tensile Strength and Failure Modes

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## ABSTRACT

The use of waste materials as aggregates in concrete is hailed by many as a huge step towards addressing the overreliance on granite stones as aggregate in concrete. It also offers a strategic eco-friendly means of disposing these wastes to minimize their impact on the environment. This study assessed the tensile strength and modes of failure of concrete that utilizes waste automobile tire chips (T) and palm kernel shells (PKS) as partial to full replacement of the conventional crushed granite stones as coarse aggregates in concrete. Portland cement concrete mix, 1:1.5:2.5 (cement: sand: granite coarse aggregate) was prepared as control from which twenty additional mixes were generated by replacing portions of the granite stones with PKS and tire aggregates while the sand and w/c ratio were kept constant. A total of 105 cylindrical specimens (150 x 300mm) and 155 beams (100 × 100 × 500 mm) were cast to evaluate the split tensile ($f_{spt}$) and flexural tensile ($f_{ct}$) strengths of the concrete mixes at 7, 14, 21, 28, 56 and 90 days of curing while observing their modes of failure. The results showed that, there is systematic decrease in the tensile strength of concrete with increase in the volume of tire and PKS particles. However, up to 50% replacement level, adequate tensile strength can be achieved for structural purposes. At this replacement level, the mix with P50T50 recorded $f_{ct}$ of 3.10 N/mm$^2$, representing 59% of the control mix. From the failure patterns observed, the mixes with high volume of tire exhibited ductile failure mode; thus giving ample warning before the ultimate failure while the PKS concrete's failure were more brittle and explosive. In conclusion, a blend of PKS and tire as aggregates in concrete is recommended especially for structures subjected to sudden loadings such as those located in earthquake zones.

*Keywords: Rubberised concrete; Palm kernel shells; Waste tire; Split tensile strength; Modulus of Rupture*

## 1. INTRODUCTION

The behaviour and overall performance of concrete as a structural material is significantly influenced by its constituent materials most especially the aggregates. The aggregates which constitutes about 60-70% of the volume of concrete impacts on strength, durability, transport properties and modes of failure of concrete [1,2]. Over the past years, naturally occurring mineral resources such as granite stones have been widely used as coarse aggregates in concrete. According to the United States (U.S) Geological Survey [3], the U.S alone consumed about 7.65 billion metric tonnes of crushed stones for road construction and other civil engineering works between 2017 and 2021. Globally, an estimated 50 billion metric tonnes of aggregates is reported to be produced yearly [4]. The fast depletion of these natural resources to meet the growing demand for concrete coupled with the rising cost of processing these aggregates has necessitated the need to find alternative sustainable material for concrete. Ettu et al. [5] in their study noted that, granitic stones used as coarse aggregates in concrete are usually hauled at high cost from the quarries to construction sites which increases the cost of construction projects. The above challenge propelled interest in the use of waste materials as alternative aggregates for concrete production. As rightly stated by Kumar et al [6], in the past, the need for using waste materials in concrete was considered a desirability, but today it has become a compelling necessity owing to the threats they pose to the environment and the need to find alternative aggregates for concrete.

Palm kernel shells (PKS) and end-of-service-life automobile tires are major source of waste in most countries and a threat to environmental sustainability. The PKS are by-products from the processing of oil palm fruits while tires are discarded as waste after their end-of-service-life. These materials are highly non-biodegradable and their disposal at landfills contaminate air and water bodies thus posing severe health and environmental risks [7-9]. Additionally, the carbon black powder produced through the pyrolysis of waste tire is also known to have negative effect on the environment. Consequently, the idea of using these waste materials as aggregates in concrete is regarded as a novel approach that offers a strategic and eco-friendly means of disposal [10]. Unsurprisingly, research on the use of PKS and tire as aggregates in concrete has been on the rise.

Reports from earlier investigations suggest that used automobile tire chips and PKS are good materials for concrete. In the works of previous researchers [11-15], tire-filled or rubberised concrete was found to have high energy absorption capacity, high impact resistance, damping ratio, good bond with steel and adequate strength for structural application etc. Habib et al. [15] for instance showed that replacing 25% of the total aggregates (both fine and coarse) with tire improves the damping ratio of concrete over 90%; a characteristic that makes rubberised concrete beneficial for structures subjected to sudden loads such as those located in earthquake zones [16].

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Similarly, it is well documented that PKS can be used to produce structural concrete of adequate strength for construction purposes [18-20]. Shafigh et al., [18] achieved a compressive strength up to 48 N/mm$^2$ using limestone powder and crushed PKS aggregates. Similarly, Alengaram et al., [20] also obtained a compressive strength of 37 N/mm$^2$ through the use of silica fumes and class F fly ash.

As an effort to extend the scope of investigations on rubberised and PKS concrete, the current study was designed to assess the tensile strength and modes of failure of concrete that utilizes both materials as coarse aggregates. The tensile strength is an important mechanical property of concrete that is considered in the design of reinforced concrete members. With its value being only 7–15% of the compressive strength, the tensile strength still has significance in terms of durability and serviceability [21,22]. For instance, the propagation and control of cracks in reinforced concrete members are strongly related to the tensile strength of concrete. Hence ignoring the tensile strength of concrete may lead to serviceability and durability problems. Earlier studies focused on the tensile strength of either PKS concrete [18, 23-25] or rubberised concrete [26-28]. However, concrete that incorporates both PKS and tire as aggregates is a unique product with different performance characteristics that needs to be examined.

On the basis of the above, the current study experimentally assessed the flexural tensile strength, split tensile strength and modes of failure of concrete that utilizes both PKS and automobile tire as partial to full replacement of the conventional crushed granite stones in concrete. The effect of the duration of curing among other host of variables on the performance of this novel concrete composite were assessed.

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## 2. MATERIALS AND METHODS

### 2.1 Materials

The concrete for the tests were prepared using ordinary Portland cement (Class CEM I 42.5 R), pit sand (nominal size 4.75 mm), crushed granite stones (maximum size 14mm), waste automobile tire chips and palm kernel shells as shown in Fig 1. These materials were obtained locally in Ghana. The PKS and tire were used as coarse aggregates in the concrete mix. The bulk tires having a weight range of 45kg-150kg, were cut into an evenly distributed size aggregates with a maximum size of 14mm. Similarly, the PKS aggregates had an average shell thickness of 4mm and 14mm maximum size. The particle size distributions of the aggregates were determined through sieve analysis. The aggregates were air dried in the laboratory at a temperature of 23 ± $2^{o}$C and relative humidity: 50 ± 5%.

Fig. 1 (a) Cement, sand, tire and crushed granite aggregates (b) PKS aggregates

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### 2.2 Preparation of aggregates

**(i)** **The PKS-** Palm kernel shells are known to have higher water absorption rate which affects the workability of concrete and cement hydration [29]. Hence to prevent this, the PKS aggregates were washed thoroughly and subsequently soaked in water for about 20 minutes before being used for the experiment.

**(ii)** **The tire**-The end-of-service-life (waste) automobile tires were shredded manually using knives and cutlass into the required sizes. The shredded tire particles were then washed with potable water to clean off all impurities. Following the recommendations of Mohammadi et al. [30] and Si et al. [31], it was necessary to treat the tire particles to enhance their bond with the cement paste. Consequently, the tires were soaked in 10% Sodium Hydroxide (NaOH) solution for 30 minutes.The solution was prepared by diluting 500g of NaOH pellets in 5000ml of deionized water. This treatment made the crumb rubber (CR) surface rough, removed the zinc stearate and other impurities to make the CR surface hydrophilic [31].

### 2.3 Study variables

The objective of the current study was to assess the effect of partial to full replacement of the conventional granite coarse aggregate with both tire rubber and PKS aggregates on the tensile strength and modes of failure of concrete. As a result, the experimental program utilized three different coarse aggregates: crushed granite stones, palm kernel shells and waste automobile tire chips. The total volume of granite coarse aggregate replaced in a given mix also referred to as the "total aggregate replacement (TAR)" level was varied as follows: 0%, 25%, 50%, 75% and 100%. For each TAR level, five combinations of the PKS (P) and tire (T) were considered: P0T100; P25T75; P50T50; P75T25 and P100T0. Consequently, concrete with identification "R25-P75T25" implies 25% of the volume of the granite aggregates in the control mix, has been replaced with PKS and tire aggregates such that 75% and 25% of the replaced volume is made of PKS and tire particles respectively. From these, a total of 21 concrete mixes including the control mix were prepared. The water-cement ratio (w/c) and the volume of the fine aggregate were however maintained constant in all the mixes as shown in Table 1.

### 2.4 Mix design, sample preparation and curing

A control mix, with a 28-day targeted compressive strength of 20MPa was designed in accordance with the Department of Environment (DOE) [32] concrete mix design method. The volume of granite in the concrete mix was replaced with PKS and tire aggregates in varied quantities as shown in Table 1. For each mix proportion, the quantity of concrete required for each test was batched using the mass of the constituent materials and the mixing done using a mechanized concrete mixer. The mixing took approximately 3 minutes for each concrete batch.

The inside surfaces of the metal moulds were coated with formwork releasing agent (used engine oil) 15minutes prior to casting of the concrete. The fresh concrete was cast into the respective moulds and compacted in two layers using a mechanized vibrating table and finished smooth using a hand trowel. In order to protect the fresh concrete from moisture loss while setting and hardening, the specimens were covered with polythene sheets for 24 ± 2 hours at a laboratory room temperature of 23 ± 2 $^{o}$C immediately after casting. After curing for 24 ± 2 hours in the

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moulds, the concrete specimens were stripped and labelled for identification purposes. They were subsequently placed inside curing tanks filled with potable water (at a temperature of 23 ± 2 $^{o}$C) for a specified number of curing days.

Table 1: Details of concrete mix proportions

| **Mix ID/Code** | **Cement (kg/m$^3$)** | **Fine Aggregate (kg/m$^3$)** | **w/c** | **Coarse Aggregates mix proportions C:GA:P:T** |
|---|---|---|---|---|
| **R0-P0T0** | 462 | 693 | 0.45 | 1: 2.5: 0: 0 |
| **R25-P0T100** | 462 | 693 | 0.45 | 1: 1.875: 0: 0.4 |
| **R25-P25T75** | 462 | 693 | 0.45 | 1: 1.875: 0.106: 0.301 |
| **R25-P50T50** | 462 | 693 | 0.45 | 1: 1.875: 0.202: 0.20 |
| **R25-P75T25** | 462 | 693 | 0.45 | 1: 1.875: 0.318: 0.1 |
| **R25-P100T0** | 462 | 693 | 0.45 | 1: 1.875: 0.424: 0 |
| **R50-P0T100** | 462 | 693 | 0.45 | 1: 1.249: 0: 0.802 |
| **R50-P25T75** | 462 | 693 | 0.45 | 1: 1.249: 0.212: 0.601 |
| **R50-P50T50** | 462 | 693 | 0.45 | 1: 1.249: 0.424: 0.401 |
| **R50-P75T25** | 462 | 693 | 0.45 | 1: 1.249: 0.636: 0.2 |
| **R50-P100T0** | 462 | 693 | 0.45 | 1: 1.249: 0.848: 0 |
| **R75-P0T100** | 462 | 693 | 0.45 | 1: 0.625: 0: 1.203 |
| **R75-P25T75** | 462 | 693 | 0.45 | 1: 0.625: 0.318: 0.902 |
| **R75-P50T50** | 462 | 693 | 0.45 | 1: 0.625: 0.636: 0.601 |
| **R75-P75T25** | 462 | 693 | 0.45 | 1: 0.625: 0.954: 0.301 |
| **R75-P100T0** | 462 | 693 | 0.45 | 1: 0.625: 1.272: 0 |
| **R100-P0T100** | 462 | 693 | 0.45 | 1: 0: 0: 1.603 |
| **R100-P25T75** | 462 | 693 | 0.45 | 1: 0.421: 1.203 |
| **R100-P50T50** | 462 | 693 | 0.45 | 1: 0: 0.848: 0.802 |
| **R100-P75T25** | 462 | 693 | 0.45 | 1: 0: 1.272: 0.401 |
| **R100-P100T0** | 462 | 693 | 0.45 | 1: 0: 1.696: 0 |

*C:CA:P:T = Cement: Granite Coarse Aggregate: Palm kernel shells aggregate: Tire aggregate*
*R = Total Aggregate Replacement level.*

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### 2.5 Test procedures

### 2.5.1 Modulus of rupture

The flexural tensile strength of the concrete also known as the modulus of rupture (MOR) was assessed using 100 mm × 100 mm × 500 mm beams as recommended by BS 12390-1 [33]. Excess moisture were wiped from the surfaces of the specimens and subsequently left in the open air for about 1hour before testing at 7, 14, 21, 28, 56 and 90 days. The specimens were simply supported at the ends and subjected to single-point loading in accordance with BS EN 12390-5

[34] using Universal Flexural Testing Machine with a 220 kN load capacity (Fig. 2). The flexural tensile strength (modulus of rupture) of the beam was expressed as:

$$f_{ct} = 3PL/(2bd^2) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where $f_{ct}$ = flexural tensile strength of test specimen ($N/mm^2$), P = maximum load applied (N), L = span of the test beam (mm), $b$ is the breadth and $d$ is the depth of the cross section.

### 2.5.2 Split tensile strength

The split tensile strength was determined on 150mm x 300mm cylinder specimens according to BS EN 12390-6 [35]. Strips of plywood (300mm length & 10mm thickness) were placed at the top and bottom of the specimen (Fig. 3). Load was applied to the specimen until failure occurred through tensile splitting of the concrete. The split tensile strength was calculated as follows:

$$f_{spt} = \frac{2P}{\pi L d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where: $f_{spt}$ = splitting tensile strength, N/mm²; P = maximum applied load (N); L = Length of test specimen (mm) and d= dimeter of specimen (mm).

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**Fig. 2- Modulus of rupture test**

**Fig 3. Split tensile test**

## 3. RESULTS AND DISCUSSION

### 3.1 Modulus of rupture

The cracking and deflection behaviour of concrete structures under flexure and those with minimum flexural reinforcement depends on the flexural tensile strength or modulus of rupture of the concrete. In the current study, the MOR of the concrete ranged from 1.18 N/mm$^2$ to 5.3N/mm$^2$ depending on the volume of PKS and tire particles in the mix. Generally, as shown in Fig. 4, the MOR decreased with an increase in the total aggregate replacement (TAR) level. The control specimen (the mix with only granite coarse aggregates) recorded an average flexural tensile strength of 5.30N/mm$^2$ but this decreased systematically as the volume of the granite aggregates was replaced with tire and PKS aggregates. The higher modulus of rupture value for the NWC compared to the PKS rubberised concrete may be attributed to the reasons reported by Khaleel et al. [36] and Mehta and Monteiro, [37]: higher aggregate-cement paste bond for rough textured/ crushed aggregates than smoother aggregates. Thus, the higher roughness of the granite aggregate surface and consequently, a better aggregate interlock and better bonding of the aggregates with the cement paste compared to the PKS and tire aggregates resulted in higher MOR for the granite filled concrete. Comparing this to the compressive strength results as reported by Boateng et al [11], the MOR is as high as 17.55% of the compressive strength for TAR content of less or equal to 50%. This represents an improvement over the 7-15% reported by Ahmed et al., [21]. Thus, at lower replacement levels (i.e. TAR $\leq$ 50%) there is slight improvement in the flexural tensile strength of concrete due to the presence of tire and PKS particles.

From Fig 5, the flexural tensile strength was also found to be influenced by the age of curing. There was a sharp increase in the tensile strength between the 7th and 28th day. However, beyond this age, the strength gain was gradual up to the 90th day of curing. On the 28th day, the control mix (R0-P0T0) and PKS rubberised concrete (R25-P75T25) recorded MOR of 5.30 N/mm$^2$ and 4.43 N/mm$^2$ respectively. For each of the above mixes, only a marginal 5% increase in the 28- day flexural tensile strength was achieved on the 90th day. Based on these findings, it can be concluded that the flexural tensile strength of PKS rubberised concrete can be calculated based on the 28-day strength gain.

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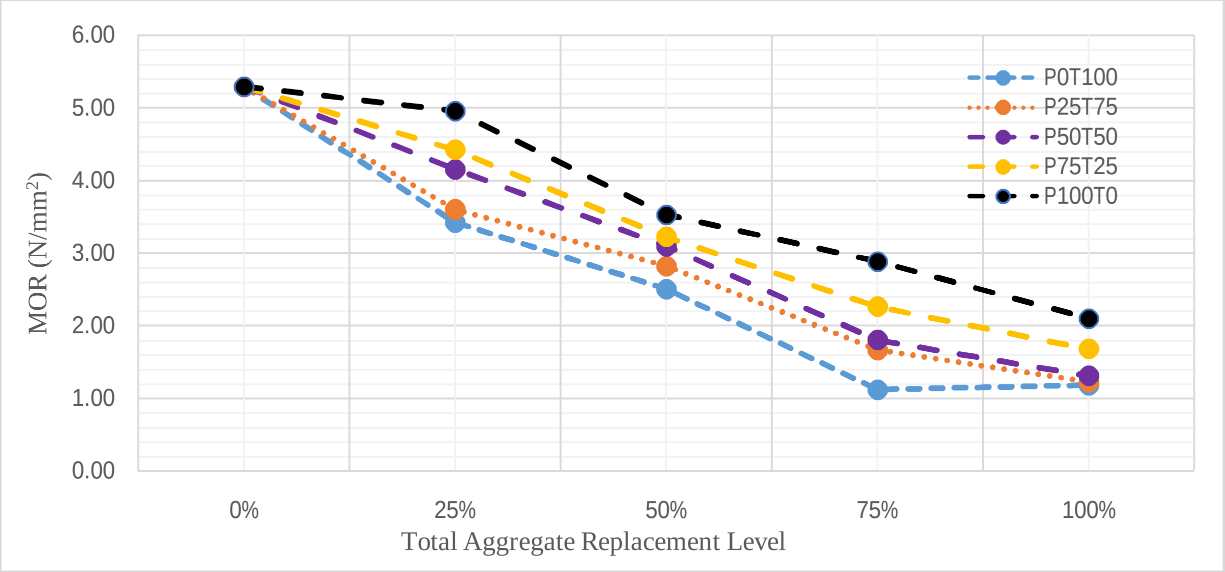

**Fig 4: Variation of MOR with increase in PKS-tire content**

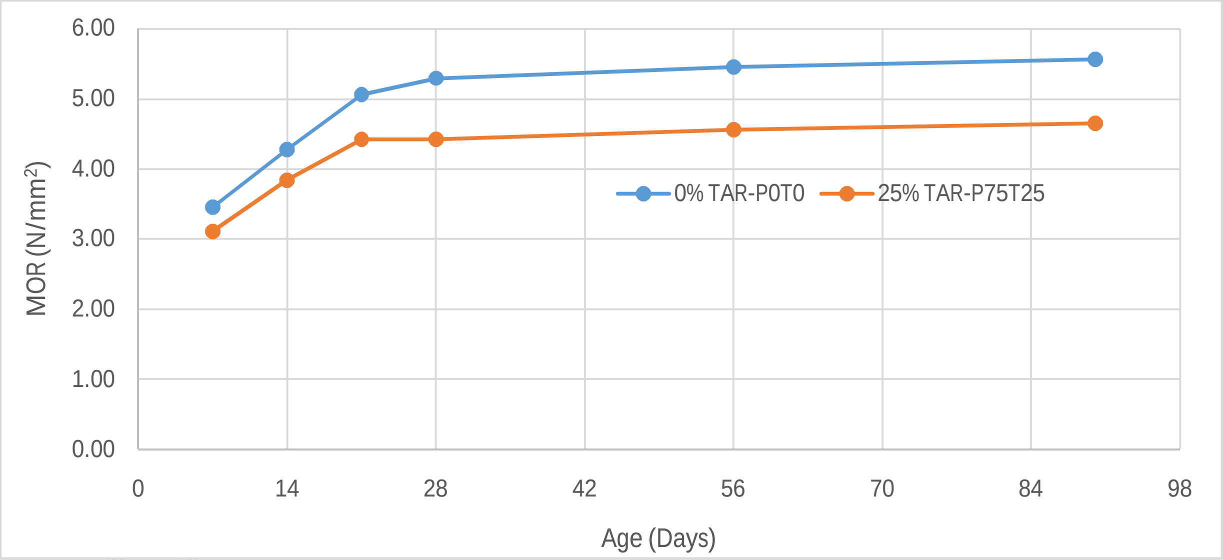

**Fig. 5- Modulus of Rupture with age of curing**

### 3.2 Split tensile strength

The results of the split tensile strength (SPS) test are shown in Fig. 6. From the results obtained, the pattern is similar to that of the flexural tensile strength as an increase in the TAR level results in a decrease in the SPS. The plain concrete had initial SPS of 2.42 N/mm$^2$ which dropped to 0.21N/mm$^2$ and 0.76N/mm$^2$ when the entire volume of the granite aggregate was replaced with tire and PKS aggregates respectively. This represents 91% and 69% reduction in strength for the rubberised and PKS concretes respectively. From the above and the results obtained, it was evident that the rate of strength reduction is lower for mixes with PKS aggregates. The ratio of split tensile strength and the compressive strength as reported by Boateng et al [11] ranged from 6.39% to 13.79% with a mean value of 9.7%. This is consistent with the general observation that the tensile strength of concrete is about 10% of its compressive strength [1].

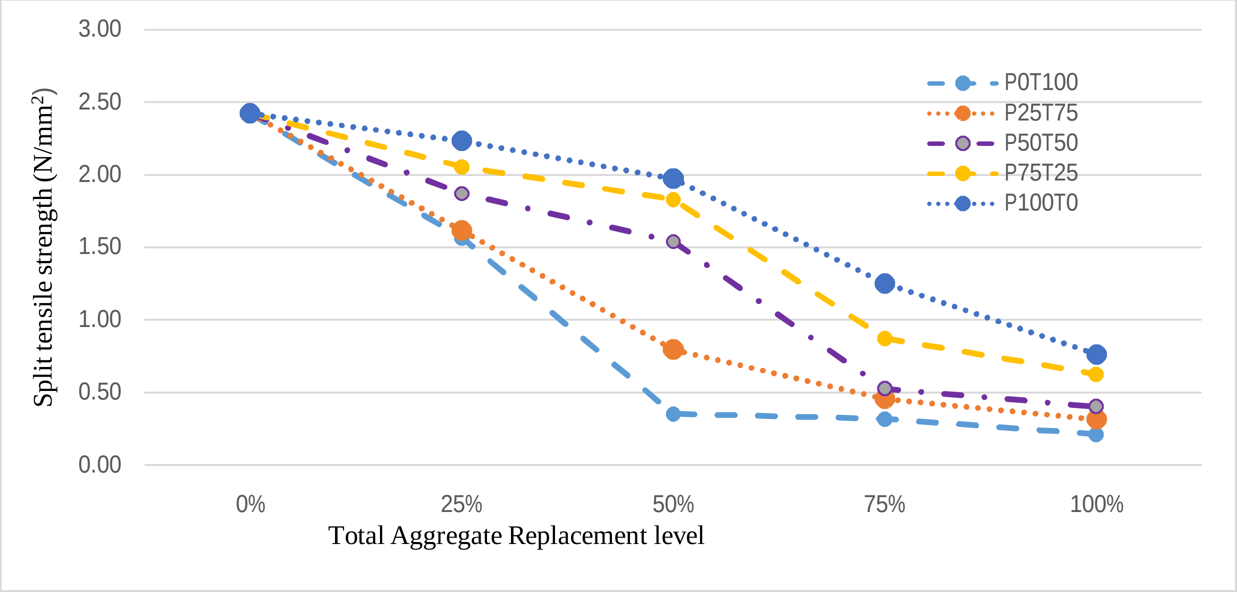

Fig 6: Effect of PKS-Tire content on split tensile strength

### 3.3 Failure modes of test specimens

Two failure patterns were identified for the test specimens: (1) brittle failure and (2) ductile failure. In the control specimen (concrete with only granite aggregates) and the PKS concretes, failure of the concrete was found to be explosive which resulted in full disintegration of the test specimens.

Failure was observed to be along the smooth convex surface of the PKS aggregates (Fig 7). The failure of the PKS concrete appears not to be as a result of failure of the PKS aggregates at least at early stages of hydration. As posited by Mannan and Ganapath [38], failure of PKS concrete at

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90 days is controlled more by the strength of the PKS-cement paste bond than by the strength of PKS aggregate itself. The mode of failure of the PKS concrete (PKSC) observed in this study, however, suggests that the strength of PKSC depends on the strength of the mortar, and the interfacial bond between the PKS and the cement matrix at least at early stages of hydration.

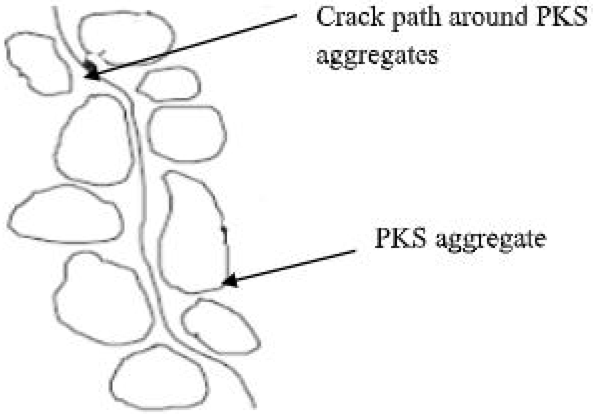

**Fig. 7 Schematic sketch of crack pattern of PKS specimen**

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For the rubberised concrete, however, failure was found to be gradual and the specimens were capable of sustaining the load even after failure without full disintegration. As shown in the split test (see Fig 8a & b), the NWC and concrete with high volume of PKS aggregates were split into two halves while the samples with high volume of rubber kept undetached.

Similarly, during the flexural tensile test (Fig 9), the rubberised concrete exhibited ductile failure mode compared to the brittle failure of the PKS concrete. This indicates that rubberised concrete has higher toughness and capacity to absorb energy and sustain large deflections until failure as noted by previous studies such as Huang et al., [39] and Zheng et al., [40]. This behaviour of the tire aggregates is beneficial to concrete structures that require good impact resistance properties. These two kinds of failure modes are however consistent with provisions of BS EN 12390-3 [41].

**Fig. 8 (a) Splitting of concrete into 2 halves for specimen with high volume of PKS aggregates (b) Sticking together of concrete for mixes with high volume of tire aggregates after split tensile test**

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**Fig. 9- Ductile failure of specimen with high volume of tire aggregate after flexural test**

## 4. CONCLUSION

The tensile strength is an important property of concrete that is required in the design of reinforced concrete members. This study presents an experimental investigation on the tensile strength and modes of failure of concrete that utilizes both PKS and tire as partial to full replacement of granite stones as coarse aggregates. The following conclusions may be drawn based on the results obtained and reported herein:

1. There is a systematic reduction in both the flexural tensile strength (FTS) and split tensile strength (SPS) of concrete with an increase in PKS and tire contents. A reduction of about 72% and 81% in the FTS and SPS are expected when the entire volume of the granite aggregate is replaced with PKS and tire. The rate of strength reduction however, decreases with increase in PKS content.
2. The SPS range from 1.18 N/mm$^2$ to 5.3N/mm$^2$ depending on the volume of PKS and tire particles in the mix. From practical point of view, the total aggregate replacement level should not exceed 50% of the total coarse aggregate volume (TCAV) due to the severe reductions in the tensile strengths beyond this point.
3. The ratio of the flexural tensile strength and compressive strength is about 17.55% for TAR $\leq$ 50% and 8% for TAR> 50%. Similarly, the split tensile strength was found to be averagely 9.7% of the compressive strength. It is therefore safe to assume that the tensile strength of PKS rubberised concrete is about 10% of its compressive strength.

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4. Failure of PKS concrete is more brittle compared to the ductile failure of rubberised concrete. On this basis, a blend of PKS and tire in the form P50T50 to P75T25 is recommended to obtain concrete of adequate strength and better failure mode. The toughness and ductility of rubberised concrete is beneficial in structural applications such as seismic zones and areas subjected to impact loading.
5. Binary combination of tire and PKS in concrete should be used since the tensile strength of the resultant concrete composite is adequate enough for structural applications.

From the current study, it was observed that beyond 50% TAR, there was severe reductions in the tensile strength of the concrete. It is therefore recommended that future studies should look at innovative ways of improving the tensile strength of this concrete beyond 50% replacement level.

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