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Bond Characteristics of Deformed Steel Rebar in Palm Kernel Shell (PKS)-Rubberised Concrete Composite

Eric Boateng[1], Charles K. Kankam[2], Anthony K. Danso[1], Joshua Ayarkwa[1], Alex Acheampong[1]

1. Department of Construction Technology and Management, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana
2. Department of Civil engineering, KNUST, Kumasi, Ghana
E-mail: Ekboateng1@gmail.com (Corresponding author)

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Abstract: The bond mechanism between concrete and steel is an important input parameter in the design of reinforced concrete elements. The reuse of waste materials as aggregates in concrete has led to the discovery of different types of concrete with unique bond characteristics. This paper reports on the bond characteristics of concrete produced from waste automobile tire chips and palm kernel shell aggregates and deformed mild steel rebars. A total of 125 concrete cubes (150 x 150 x 150mm) with metal inserts were cast from 21 concrete mixes with varied content of PKS and waste automobile tire aggregates. Pullout test was carried out to evaluate the strength of the bond mechanism between the steel and the various concrete mixes. The results revealed that bond strength decreased with increasing PKS and tire content. Moreover, increasing the bar size and embedment length reduced the bond stress. The ratio of the bond stress and compressive strength was found to be averagely 63.88%. Regarding the bond failure mechanism, it was identified that failure of the specimen occurred through either rebar pullout or tensile splitting of the concrete. Based on the results obtained, it was concluded that PKS and tire can be used as partial replacement of granite aggregates in concrete since the resultant concrete can develop adequate bond with steel bars in structural applications.
Keywords: Bond strength; Rubberised concrete; Palm kernel shell; Waste tire; Deformed steel rebar.

1. Introduction

Globally, reinforced concrete (RC) is extensively used for the construction of various building and civil engineering structures due to its durability, versatility and economy [1]. The performance of reinforced concrete as structural material depends strongly on the strength of the bond mechanism between the steel and concrete. The bond ensures that, stresses are safely transferred between the steel and concrete [2]. In cases where an element is loaded beyond its bond strength capacity, high deformation in the form of slip occurs. This makes, the serviceability and ultimate strength of RC structures a function of the bond between concrete and steel [3].

Different types of concrete exist with unique bond characteristics with steel [3-7]. This includes rubberised (RuC) and palm kernel shell concrete (PKSC). Rubberised concrete is a class of lightweight concrete obtained by replacing the traditional concrete aggregates with rubber particles derived from the processing of waste automobile tires. Similarly, PKSC is also produced from palm kernel shell, a by-product of the oil palm tree. In most countries, tire and PKS are considered as wastes and dumped in the open thus constituting a nuisance to the environment and human health with little economic benefits [8,9].

Previous studies have established that, both PKSC and RuC possess excellent qualities as structural lightweight materials. For instance, rubberised concrete has been found to possess high energy and sound absorption capacities, high impact resistance, high damping ratio etc. making it an excellent material for the construction of structures subjected to sudden loadings such as those under earthquake zones [10-13]. Similarly, PKSC has similar structural behaviour and characteristics as normal weight concrete [14-17].

As an effort to extend the scope of investigations on PKS and rubberised concrete, the current study was carried out to evaluate the characteristics of the bond stress between steel rebars and PKS-rubberised concrete composite (i.e. concrete having both PKS and tire as aggregates). Previous investigations focused on either rubberised concrete [18-21] or PKSC [22-24]. Romanazzi et al. [18] investigated the interaction between rubberised concrete and steel rebars. In that study, tire particles were used as partial (6%-24%) replacement of fine natural aggregates in concrete. The study reported a 20% decrease in bond strength with reference to the control mix due to a simultaneous decrement in the compressive strength of the corresponding concrete. In another study, Alengaram et al., [22] compared the bond properties of oil palm kernel shell concrete and normal weight concrete (NWC) produced using fly ash and silica fumes as supplementary cementitious material and pozzolans. The bond stress of the PKSC was found to be about 86% of the corresponding NWC. More recently, Odeyemi et al., [23] studied the bond properties of partially replaced self-compacting PKSC and recorded a bond stress of 5.56 N/mm^2.

Concrete that incorporates both PKS and tire as aggregates represents a unique structural material with different performance characteristics. Currently, no empirical study exit that describes the nature of the bond mechanism between this type of concrete composite and steel rebar. Investigation in this direction is therefore considered necessary. The current study was designed to fulfil this knowledge gap by investigating the bond characteristics of PKS-rubberised concrete composite with deformed mild steel rebar. The nature of the bond failure mechanism, effect of bar size, effect of embedment length among other host of variables were investigated in the bond strength characterization. Correlation between bond strength and compressive strength is also presented.

2. Materials and methods

2.1 Materials

1) Concrete

The materials used for the concrete production included used automobile tire chips, palm kernel shells, crushed granite stones, pit sand and ordinary Portland cement. All the materials were locally obtained in Ghana. The ordinary Portland cement (Class I, 42.5R) was manufactured by Ghana cement company (Ghacem). The tires were cut into evenly distributed particle size aggregates with a maximum size of 14 mm. They were washed thoroughly with potable water and subsequently treated with 10% Sodium Hydroxide solution for 30 mins. Similarly, the PKS aggregates were washed and subsequently soaked in water for about 20 mins before being used. Both the PKS and crushed granite stones had maximum size of 14 mm.

A control mix with 28-day compressive strength of 20 N/mm^2 was designed using crushed granite stones as coarse aggregate. Twenty additional mixes were prepared by replacing portions of the granite stones in the control mix with PKS and tire aggregates. The fine aggregate, cement content and water-cement ratio were however, kept constant for all the mixes as shown in Table 1. Five cubes per mix were cast to evaluate the compressive strength of each concrete mix.

2) Steel

Standard deformed mild steel rebars with the surface characteristics described in Table 2 were used in the study. Three (3) pieces of each bar diameter type were sampled from different sections of a full bar to evaluate their mechanical properties in accordance with BS 4449 [25] specifications. From the values recorded, the average yield stress of the steel was 325 N/mm^2.

2.2 Study variables

Three variables were considered in the bond strength characterization. These were the coarse aggregate type, rebar size and rebar embedment length.

1) Aggregate type: The current study sought to replace the conventional crushed granite aggregates in concrete with PKS and tire chips. Consequently, 0%, 25%, 50% 75% and 100% replacement levels were considered. For each Total Aggregate Replacement (TAR) level, the PKS and tire chips were combined in five different mixes: P0T100, P25T75, P50T50, P75T25 and P100T0. This resulted in 21 different concrete mixes.

2) Bar size: Four different bar sizes were used: 10, 12, 16 and 20 mm.

3) Embedment length: The length of the steel rebars embedded in the concrete was either 150 mm or 75 mm.

2.3 Preparation of specimen

Steel moulds, (150 x 150 x 150 mm) with the inside coated with engine oil (formwork releasing agent) were placed on a flat concrete floor. Pieces of steel reinforcement bars, about 450mm long were cleaned and centrally embedded in each of the moulds. Fresh concrete was then poured into the moulds in three equal layers with each layer compacted using mechanical vibration table. The top of the concrete was leveled with that of the mould using trowel. For each mix, five cubes were cast. The cubes were demoulded after 24 hours and cured in a trough full of potable water until the test day. In all, there were 25 tests with five (5) specimens per test making a total of 125 specimens. The cubes were labelled for identification purposes. Figure 1 shows the specimens ready for testing.

2.4 Test procedures

A number of techniques exist for evaluating the bond stress between concrete and steel. This includes the rebar pullout test, bond beam test, cantilever bond test and the University of Texas beam test [26,27]. However, the current study adopted the rebar tension pullout test technique due to the relative simplicity of the test program.

Figures 2 & 3 show the setup of the pullout test which was carried out at the Structures Laboratory of the Department of Civil Engineering, KNUST, Kumasi, Ghana. The cubes were each inserted into an apparatus designed to hold the concrete cube in position while the steel rebar is being pullout. During the test, a bar at the bottom of this device is fixed to the lower jaws of the electronic tensile test machine (ETTM) while the upper jaws hold the embedded steel rebar. A steel plate at the top of the test apparatus allows for the uniform distribution of the load onto the concrete specimen. The load was applied by a 2000 kN capacity electronic tensile test machine at a rate of 0.833 kN/sec until failure in the form of either tensile splitting (crushing) of the concrete or pullout of the steel rebar occurred. The failure load was recorded. For each group, the average force of the five (5) replicate specimens was used to determine the bond stress using the equation proposed by BS 8110-1 as follows [28]:

$$f_b = P/\pi Dl \tag{1}$$

where, f_b is the bond stress which is assumed to be uniform over the embedment length; P = the pullout force, L = the embedment length; D = the diameter of the bar.

Table 1. Constituents and proportioning of the various concrete mixes

Mix ID	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Crushed granite (kg/m^3)	PKS Aggregates (kg/m^3)	Tire Aggregates (kg/m^3)	Compressive Strength (N/mm^2)
R0-P0T0	462	208	693	1155	0	0	21.27
R-25P0T100	462	208	693	866.25	0	184.80	11.47
R25-P25T75	462	208	693	866.25	48.97	139.06	14.78
R25-P50T50	462	208	693	866.25	93.32	92.4	18.48
R25-P75T25	462	208	693	866.25	146.92	46.20	20.41
R25-P100T0	462	208	693	866.25	195.89	0	20.69
R50-P0T100	462	208	693	577.04	0	370.52	5.51
R50-P25T75	462	208	693	577.04	97.94	277.66	9.32
R50-P50T50	462	208	693	577.04	195.89	185.26	11.20
R50-P75T25	462	208	693	577.04	293.83	92.40	13.27
R50-P100T0	462	208	693	577.04	391.78	0	15.44
R75-P0T100	462	208	693	288.75	0	555.79	3.76
R75-P25T75	462	208	693	288.75	146.92	416.72	5.75
R75-P50T50	462	208	693	288.75	293.83	277.66	6.21
R75-P75T25	462	208	693	288.75	440.75	139.06	9.41
R75-P100T0	462	208	693	288.75	587.66	0	11.15
R100-P0T100	462	208	693	0	0	740.59	2.71
R100-P25T75	462	208	693	0	194.50	555.79	4.59
R100-P50T50	462	208	693	0	391.78	370.52	5.22
R100-P75T25	462	208	693	0	587.66	185.26	7.83
R100-P100T0	462	208	693	0	783.55	0	10.19

R = Total Aggregate Replacement level; P = Palm Kernel Shell; T= Tire

Table 2. Physical characteristics of steel rebars

Bar Diameter		**Surface characteristics**			
Nominal (mm)	Actual (mm)	Rib height (mm)	Rib width (mm)	Rib spacing (mm)	Rib face angle (°)
10	9.75	0.6	0.6	5.8	56
12	11.50	0.7	0.8	6.9	55
16	15.33	1.0	1.3	8	50
20	19.78	1.4	1.5	11	49

Fig. 1. Test specimen

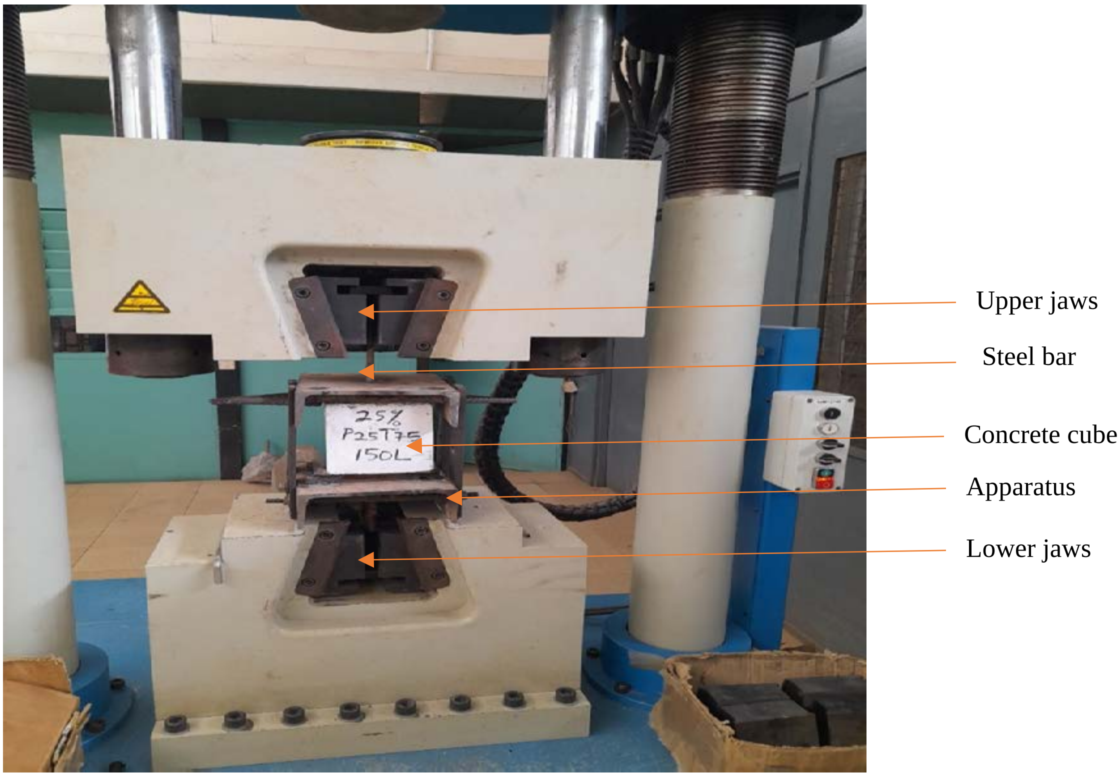

Fig. 2. Photograph of test setup

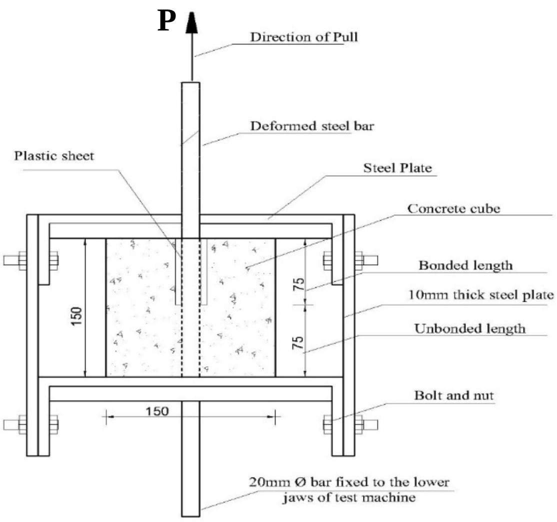

Fig. 3. Schematic diagram of the pull-out bond test apparatus

3. Results and discussion

3.1 Effect of total aggregate replacement level and PKS-tire content on bond strength

The strength of the bond mechanism at the concrete-steel interface was evaluated by considering the effect of PKS-tire content and the effect of TAR. From Fig. 4, the bond strength was found to be significantly affected by the TAR level. Irrespective of the PKS-tire combination, the bond strength decreases with an increase in the total aggregate replacement (TAR) level. At 0% TAR, the bond strength of the control specimen was 10.98 N/mm² and this value decreased to 3.34 N/mm², when the entire volume of the granite aggregate in the control mix was replaced with waste tire particles. This represents, 70% reduction in bond strength. Romanazzi et al., [18] also observed a similar trend where bond strength decreased with increase in rubber content. The general decrease in bond strength can be attributed to the decrease in the mechanical properties of the concrete. As shown in Table 1, the compressive strength of the concrete also recorded a downward trend. According to the reports by Si et al., [29]; Li et al., [30] and Eldin, and Senouci [31] the nearly smooth surface nature of tire aggregates, its hydrophobic nature and lower specific gravity contribute to weak bond between rubber fine aggregates and cement paste. This results in non-uniform stress distribution during loading and consequently accelerated cracking at some sections of concrete specimens. On the average, the bond strength was about 63.88% of the compressive strength.

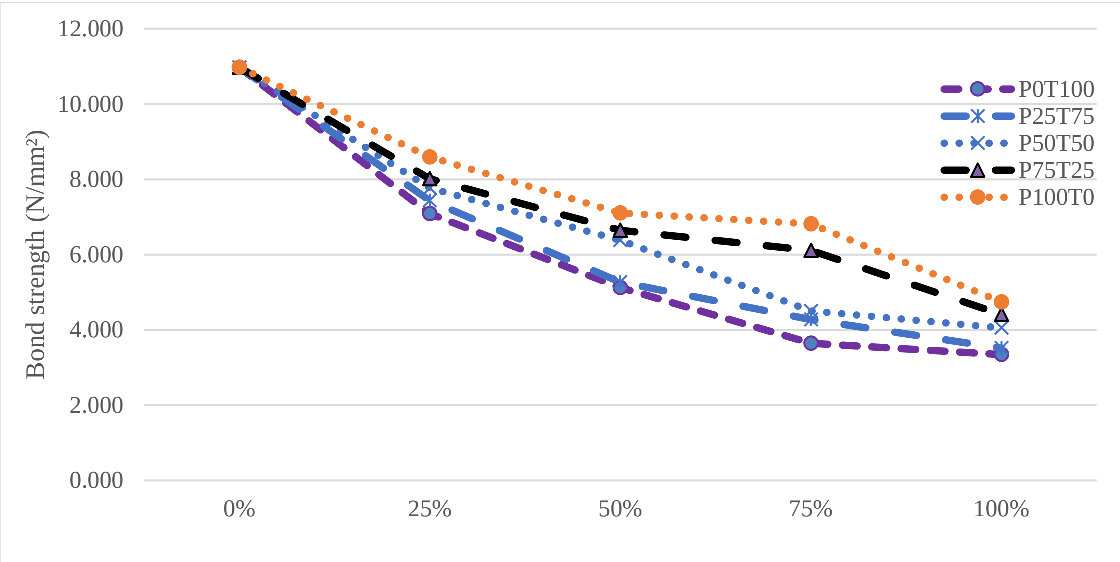

Fig. 4. Effect of Total Aggregate Replacement (TAR) level on Bond Strength

The effect of varying PKS-tire content on the bond stress is shown in Fig. 5. From the results presented, the inclusion of PKS aggregates has positive effect on the bond mechanism at the concrete-steel interface. The bond strength increases with an increase in PKS content but decrease with an increase in tire content. This phenomenon may be attributed to the comparatively good bond between cement paste and PKS aggregates compared to tire aggregate particles. Moreover, the relatively smaller particle size distribution of the PKS leads to better aggregate parking and improved mechanical properties. More so, the better shape and angularity of the PKS aggregates enhanced their bond in the concrete. This increase in mechanical properties accounts for the increase in the bond strength for the specimen with high PKS content. Specifically, at 25% TAR level, the bond strength was 7.09, 7.44, 7.77, 8.01 and 8.59 N/mm² for mixes with 0%, 25%, 50%, 75% and 100% PKS content respectively. Similarly, at 50% TAR level, the bond strength was 5.13, 5.27, 6.38, 6.65 and 7.11 N/mm² for the mixes with 0%, 25%, 50%, 75% and 100% PKS content respectively. The trend continued for the other TAR levels. Thus PKS aggregates can be utilized in rubberised concrete as means of improving its bond strength.

3.2 Effect of bar size and embedment length

The effect of bar size and embedment length on bond strength are presented in Figs. 6 and 7 respectively. The bond stress decreased with an increase in rebar size. In the current study, the bond strength was 8.01 N/mm², 5.98 N/mm², and 4.56 N/mm² for bar sizes 12 mm, 16 mm and 20 mm respectively. This is consistent with the findings in previous studies [32,33] which explained that reinforcing steel bars of smaller sizes have higher bond strength than specimens with larger bar sizes as a result of an increase in the cover to bar diameter (c/d) ratio. This increase in concrete cover improves confinement and prevents the formation and propagation of micro cracks.

On the basis of the above, it was expected that the specimen with 10 mm steel rebars should have higher bond strength than those with 12 mm bars. However, the reverse happened. The specimen with 10mm bars had bond strength of 7.6 N/mm^2 compared to the 8.01N/mm^2 recorded by those with 12mm rebars. In this case, the surface deformation characteristics (such as the rib height, thickness, spacing etc.) of the steel bars as indicated in Table 2 might have played a major role in the bond mechanism. It was observed that the surface characteristics of the 12 mm rebars were more pronounced than the 10 mm bars (Table 2). Hence despite the higher cover to bar diameter ratio, the bond strength of the specimens with 10 mm rebars was smaller than those with 12 mm bars. Furthermore, the difference between the actual diameters of the nominal 10 mm and 12 mm bars is small compared with those of the other bar sizes and this fact might have contributed to the significance of the ribs surface geometries. With regards to the embedment length, it was found that the pullout force increased with an increase in the embedment length but the average bond stress decreased. The bond strength for the 75 mm and 150 mm embedment lengths were 15.68 N/mm² and 8.01 N/mm² respectively.

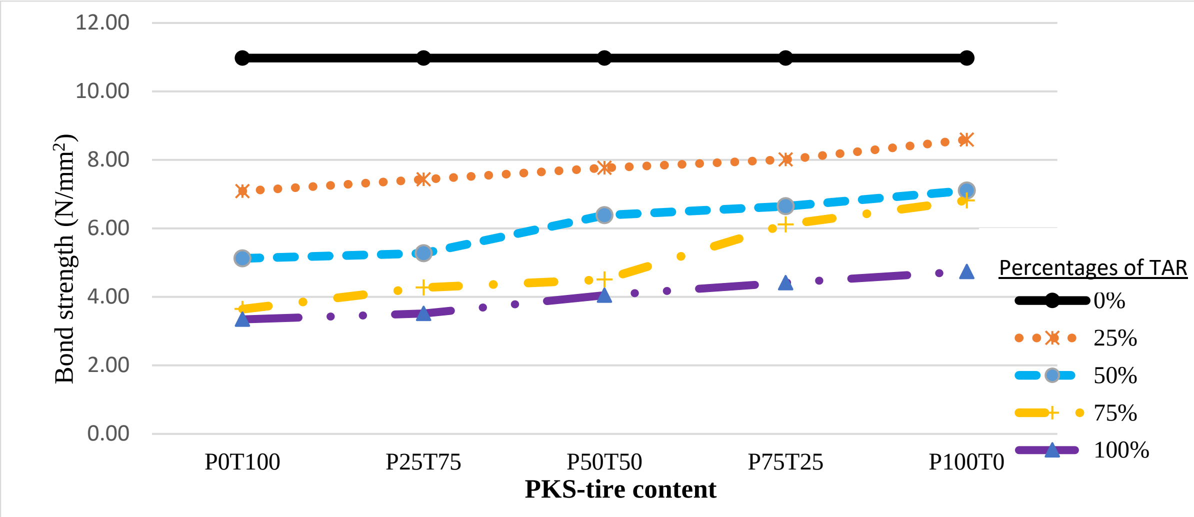

Fig. 5. Effect of PKS-tire combination in TAR on bond strength

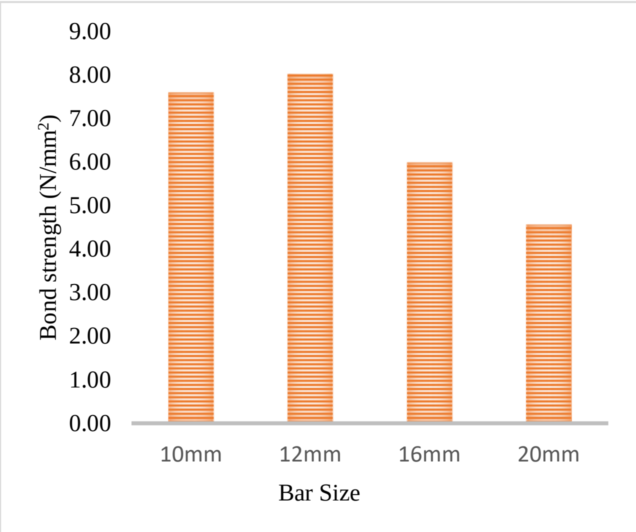

Fig. 6. Effect of bar size on bond strength

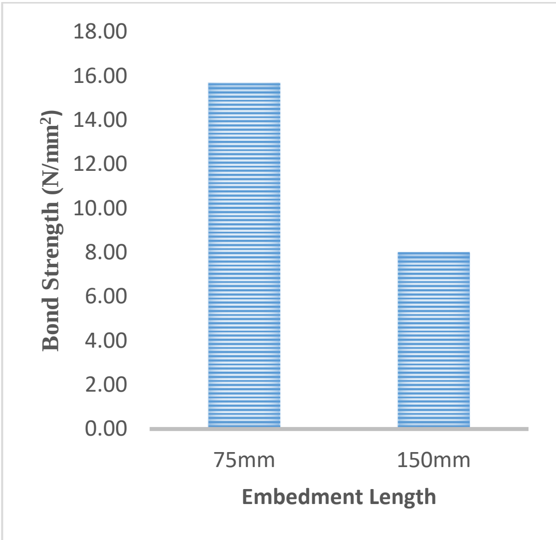

Fig. 7. Effect of Embedment length on bond strength

3.3 Bond failure mechanism

Two bond failure mechanisms were identified from the test results: (1) rebar pullout and (2) tensile splitting of the concrete (Figs 8 & 9). As explained by Ichinose et al [34] and Ahmed et al [7], pullout failure occurs when the concrete directly in front of the lugs of the rebar known as concrete key is first crushed. As the design shear stress exceeds the capacity of the concrete, pullout of the rebar occurs. This mode of failure is known to be associated with specimen with large concrete cover or a structural member with moderate shear reinforcement or both [32]. Consistent with the above findings, the specimens with 10 mm rebars in the current study failed through this mode (Fig 9). The splitting type of bond failure on the other hand occurs when the tensile strength of the concrete is exceeded following an initial small amount of slip. The initial slip causes cracking of the concrete, followed by further slips and an eventual complete failure of the bond [34]. The cracks are formed when the member is subjected to direct tension beyond the tensile strength of the concrete. Once the internal crack occurs, chemical adhesion and friction disappear and the bond resistance is offered by the mechanical interlock between the steel rebar and the concrete. At this stage, the bond strength is influenced by surface characteristics of the deformed bar and the concrete compressive strength [34]. In the current study, the specimen embedded with 12 mm, 16 mm and 20 mm exhibited this kind of failure mode (Fig 8).The splitting mode of bond failure of these bars may be attributed to their physical characteristics or surface geometry particularly the rib height and spacing coupled with small rib face angle.

Fig. 8. Tensile splitting or crushing of specimen with 16 mm diameter deformed mild steel rebar

Fig. 9. Rebar pullout bond failure of specimen with 10 mm steel rebar.

4. Conclusions

This paper presents the results of an investigation on bond characteristics of ribbed reinforcing mild steel bars in PKS-rubberised concrete composite. The influence of bar size, embedment length and PKS-tire content on the bond mechanism were studied. Based on the pullout bond test results obtained, the following conclusions are drawn:

1) Bond strength decreases with an increase in the combined PKS and tire content. However, at lower replacement levels (i.e. < 25%) the decrease in strength is gradual. For higher substitutions, there is drastic reduction in bond due to the simultaneous reduction in compressive strength of the concrete mix. The bond stress ranges from 3.34 N/mm^2 to 10.98 N/mm^2 depending on the combined PKS and tire content.

2) Bond strength decreases with an increase in bar size and embedment length. There is a reduction of 43% in bond strength by increasing the bar size from 12 mm to 20 mm. The higher bond strength for specimen with smaller bar size is as a result of increase in the cover to bar diameter ratio. Increase in concrete cover improves confinement and prevents the formation and propagation of micro cracks.

3) The ratio between bond strength and compressive strength has an average value of 63.88%. The ratio increased with increase in the total aggregate replacement (TAR) level.

4) There are two modes of bond failure: (i) tensile splitting of concrete and (ii) rebar pullout after crushing of concrete. The rebar pullout is associated with specimen embedded with smaller rebar sizes while those with large bars sizes failed by splitting of concrete when its tensile strength is exceeded.

In conclusion, PKS – rubberised concrete composite can be used for structural applications as the material has adequate bond strength with steel. The bond mechanism investigated in the current study was limited to concrete-steel bond. Future studies should look at the aggregates' bond with cement paste. Moreover, investigations designed towards finding innovative approaches of improving concrete-steel bond are also recommended.

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