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Models for Predicting Strength Reduction Factors for Concrete that Utilizes Palm Kernel Shells and Waste Automobile Tires as Aggregates

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Palm kernel shells (PKS) and waste automobile tires do not only enhance the properties of concrete (e.g. damping ratio, ductility, impact resistance etc.), but also their rational utilization can significantly reduce carbon footprints and environmental pollution globally. In this study, a multivariate regression analysis was carried out to develop models for predicting the reduction factors and thereafter the strengths (compressive strength, flexural tensile strength, split tensile strength and bond strength) of concrete that utilizes PKS and waste automobile tire chips as partial to full replacement of the conventional crushed granite stones as coarse aggregates. The strength reduction factors, S_{RF}, were modelled as a function of the total aggregate replacement level (TAR), and the volume of PKS (P) and tire (T) particles in a given concrete mix whilst the performance of

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the models was assessed using the Mean Squared Error (MSE) and the Coefficient of Determination (R^2) techniques. After studying several mathematical functions, it was found that a single linear regression model can be used to predict the strength reduction factors for all the mechanical properties of the concrete tested but with different function parameters. The values of the S_{RF} ranged from 0 to 1 depending on the aforementioned factors. However, a S_{RF} of 0.53 (53%) can be achieved at the 50% optimum replacement where P50T50 for any of the mechanical properties. Furthermore, for each of the concrete properties, the S_{RF} was positively correlated with the volume of PKS but negatively correlated with the TAR level and volume of tire particles in the concrete matrix. Thus, an increase in the TAR level or tire content decreases the S_{RF} and vice versa. In conclusion, the proposed models can be used to establish the target strengths of PKS.

Keywords: Strength reduction factors; rubberised concrete; palm kernel shells; waste tire; compressive strength; modulus of rupture; split tensile strength; bond strength; models.

1. INTRODUCTION

The use of palm kernel shells (PKS) and waste automobile tires as aggregates in concrete has gained worldwide acceptance predominantly as a result of their environmental and performance related benefits when utilized in concrete composite [1,2]. For instance, rubber filled or rubberised concrete (RC) is known to have high impact resistance, ductility, toughness, sound and energy absorption capacities compared to normal concrete [3,4]. Jie et al. [3] in their study noted that, the damping ratio of RC is more than normal concrete. Similarly, Habib et al. [4] showed that replacing 25% of the total aggregates (both fine and coarse) with tire improves the damping ratio of concrete by over 90%. This ductile performance, high damping coefficient, high energy absorption and ability to sustain loads after peak strength and other characteristics of RC makes the material beneficial for structural applications under dynamic, impact, cyclic, and collision loads such as for structures located in earthquake zones [5]. Currently, a significant proportion of rubberised concrete is used in civil engineering applications in road and rail foundations, embankments, crash barriers, bumpers and artificial reefs [6,7]. The trend is expected to increase as continuing research is carried out to gain deeper understanding of the material.

Regarding, PKS, the material has also been utilized in the construction industry as sub-grade, sub-base or base course material in road construction, as granular filter material for water treatment and as a substitute for poor lateritic soil [8-10]. Recently, it is being used to produce structural lightweight concrete for various engineering applications in beams, slabs, foundations etc. [11-13].

Just like any type of concrete, the mix design and proportioning of PKS or rubberised concrete to achieve the desired strength for structural applications is very important. In the traditional trial mix method, the process usually involves many experiments that consume materials and labour resources thereby rendering the process expensive and time consuming [14]. Therefore, how to get the expected 28-day strength of concrete with different mixing ratios in time for construction is a subject that is worthy of in-depth study. Khatip and Bayomy [15] in the late 90s, utilized the strength reduction factor approach as the basis for predicting the strength of concrete that incorporates tire rubber. Subsequent studies [16,17] employed this strategy to study the strength of rubberised concrete. The approach involves calculating the strength reduction factor for a new concrete mix based on its constituent materials and the strength of the control plain concrete [15]. Based on the reduction factors and the strength of the plain concrete, the corresponding strength (say the compressive strength) of the new concrete can be calculated. The method is simple, efficient and easy to use in predicting the strength of concretes that utilize waste materials such as tire rubber and PKS as aggregates.

In the work of Khatip and Bayomy [15], equation 1 was proposed to quantify the strength reduction factor for compressive strength of any rubberised concrete as a function of rubber content.

$$S_{RF} = a + b\,(1 - R)^m \quad \text{……………. (1)}$$

$$\text{On condition that, } a = 1 - b \quad \text{……......... (2)}$$

Where, S_{RF} is the strength reduction factor which varies from 0 to 1; R is the ratio of the volume of rubber content and total aggregate volume; *a, b* and *m* are parameters of the model. The function parameters (a, b and m) were found to be 0.18, 0.82 and 10 for concrete strength 20 MPa and 0.1, 0.9, and 7 for rubberised concrete with 28-day compressive strength of 38 N/mm². From their test results, it was observed that the model parameters change for different strength levels with the values decreasing as the strength of concrete increases. Guneyisi et al. [16], in a subsequent study obtained values of 0.125, 0.875 and 4.55 for a, b and m respectively for higher strength concrete with and without silica fumes having 90day compressive strength of 54-86 N/mm^2.

From the above studies, it is obvious that the strength reduction factor approach has been utilized to a much success. The current study sought to extend the scope of investigations in this area by evaluating the reduction factors and consequently develop models for its prediction for concrete that utilizes both PKS and tire as aggregates. The previous studies, despite their effort focused on only rubberised concrete (i.e. concrete that utilizes waste automobile tire chips as aggregates). As a result, currently no empirical model exists for predicting the reduction factors for concrete that utilizes PKS as aggregate or PKS rubberised concrete composite. With the increasing demand for and utilization of these types of concrete in the construction industry, it is considered necessary to develop models to assist in the prediction of their strength reduction factors to facilitate the mix design process. In view of the above, this study experimentally evaluated the strength reduction factors for the mechanical properties (i.e. compressive strength, tensile strength and bond strength) of concrete that utilizes PKS and waste automobile chips as partial to full replacement of crushed granite stones as coarse aggregates. Multivariate regression analysis was also carried out to study the correlation between the various variables of the study. The current study is significant for mix design purposes as it offers valuable tool for analyzing the target strengths of concrete.

2. EXPERIMENTAL PROCEDURES AND MODEL DEVELOPMENT

2.1 Data Source

The aim of the study was to develop models for predicting reduction factors and strength of concrete that utilizes PKS and waste automobile tire chips as partial to full replacement of the conventional crushed granite stones as coarse aggregates. Consequently, a total of 420 concrete specimens comprising 105 cubes, 105 cylinders, 105 prisms and 105 cubes reinforced with steel bars were cast and tested at 28days to obtain data for the compressive strength, split tensile strength, flexural tensile strength and bond strength models respectively (See Table 1). In each test category, 21 different concrete mixes with varied contents of PKS and tire were used as presented in Table 2.

The end-service-life automobile tires were shredded manually using knives and cutlass into an evenly distributed sized aggregates with size ranging from 5mm to 14 mm. The shredded tire chips were washed with water and subsequently soaked in 10% NaOH solution to enhance their bond with the cement paste. The PKS were also washed with water to remove all impurities. For each concrete mix, five replicate specimens were prepared. All the concrete materials (pit sand, Portland cement, crushed granite stones, PKS and tire) were obtained locally in Ghana.

For the compressive strength, test was done on 150 x 150 x 150 mm concrete cubes in compression in accordance with BS EN 12390-3 [18]. The modulus of rupture (MOR) of the concrete was also assessed using 100 mm × 100 mm × 500 mm beams as recommended by BS 12390-1 [19]. The specimens were subjected to a single-point loading in accordance with BS EN 12390-5 [20] using a Universal Flexural Testing Machine with load capacity of 220 kN. Similarly, the split tensile strength was determined on 150mm x 300mm cylinders in accordance with BS EN 12390-6 [21] specifications. The load was applied to the specimen until failure occurred through tensile splitting of the concrete.

Data for the bond strength model was also obtained using the tension rebar pullout test technique. In this test, the 150mm cubes with metal inserts were mounted into a 2000 kN capacity electronic tensile test machine to apply the loads until failure in the form of either tensile splitting of the concrete or pullout of the steel rebar occurred. The load was applied at a rate of 0.833 kN/sec. The bond stress was subsequently calculated using equation number 49 of BS 8110-1 [22]. All the tests were carried out at the Structures Laboratory of the Department of Civil Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. Descriptive analysis/statistics of the test results on compressive strength is reported by Boateng et al [23].

Table 1. Summary of test specimens

Test description	Description of specimen	No. of specimen	Remarks
Compressive strength	150mm cubes	105	There were 5
Split tensile strength	150 x 300mm cylinders	105	replicate
Modulus of rupture	100 x 100 x 500mm beam prisms	105	specimens
Bond strength	150mm cubes with metal inserts	105	per test

Table 2. Concrete mix proportions

Sn	Specimen mix ID	Cement (kg/m^3)	Sand (kg/m^3)	Crushed granite (kg/m^3)	PKS Aggregates (kg/m^3)	Tire Aggregates (kg/m^3)	w/c
1	R0-P0T0	462	693	1155	0	0	0.45
2	R25-P0T100	462	693	866.25	0	184.80	0.45
3	R25-P25T75	462	693	866.25	48.97	139.06	0.45
4	R25-P50T50	462	693	866.25	93.32	92.4	0.45
5	R25-P75T25	462	693	866.25	146.92	46.20	0.45
6	R25-P100T0	462	693	866.25	195.89	0	0.45
7	R50-P0T100	462	693	577.04	0	370.52	0.45
8	R50-P25T75	462	693	577.04	97.94	277.66	0.45
9	R50-P50T50	462	693	577.04	195.89	185.26	0.45
10	R50-P75T25	462	693	577.04	293.83	92.40	0.45
11	R50-P100T0	462	693	577.04	391.78	0	0.45
12	R75-P0T100	462	693	288.75	0	555.79	0.45
13	R75-P25T75	462	693	288.75	146.92	416.72	0.45
14	R75-P50T50	462	693	288.75	293.83	277.66	0.45
15	R75-P75T25	462	693	288.75	440.75	139.06	0.45
16	R75-P100T0	462	693	288.75	587.66	0	0.45
17	R100-P0T100	462	693	0	0	740.59	0.45
18	R100-P25T75	462	693	0	194.50	555.79	0.45
19	R100-P50T50	462	693	0	391.78	370.52	0.45
20	R100-P75T25	462	693	0	587.66	185.26	0.45
21	R100-P100T0	462	693	0	783.55	0	0.45

Note: 1) "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 (P) and tire (T) particles respectively. 2) R = Total volume of granite aggregates replaced with PKS and Tire

2.2 Statistical Data Analysis

It is well documented that the strength of concrete decreases when portions of the granite aggregate are replaced with PKS or tire particles [1,8]. This reduction in the mechanical properties of concrete referred herein as the reduction factor was simulated in this study using regression analysis. The relations between the reduction factor (the dependent variable) and the volume of PKS, volume of tire and the TAR level (the independent variables) were evaluated. For each concrete property (compressive strength, split tensile strength, modulus of rupture and bond strength), the reduction factors (S_{RF}) were calculated as the ratio of the given property of concrete for the mixture containing PKS and tire aggregates to that of the control plain concrete; expressed mathematically as:

$$S_{RF} = \frac{S_{pt}}{S_o} \quad \text{……………………………… (3)}$$

where S_{pt} is the strength of concrete containing certain volumes of PKS and tire aggregates; S_o is the corresponding strength of the control plain concrete (i.e. concrete produced from crushed granite aggregates). The data obtained were used to develop models for predicting the reduction factors for each of the concrete properties.

2.3 Model Reliability Assessment

In testing the effectiveness and prediction accuracy of the proposed models, the study adopted the correlation coefficient (R^2) and the Mean Relative Error (MRE) techniques as presented in Eqns. 4 and 5:

$$R = \frac{\sum_{i=1}^{n}(x_i-\bar{x})\,(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\,\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad \text{................ (4)}$$

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x_i}{y_i}-1\right| \text{ x } 100\ \% \text{.................. (5)}$$

where y_i is the model output or predicted value; x_i is the measured or experimental value of concrete strength, $\bar{x}$ is the average measured or experimental value, $\bar{y}$ is the average predicted value, and n is the number of collected data samples. According to Zhang et al [24], models with good predictive capabilities have lower MRE (values ≤ 10%) and higher R values (values closer to 1).

3. RESULTS AND DISCUSSION

3.1 Reduction Factors

Variation of the strength reduction factors (S_{RF}) with increase in the TAR level for the various mechanical properties of the concrete tested are presented in Figs. 1 – 4. As shown in these figures, there is a systematic reduction in the S_{RF} for all the properties of the concrete tested with increase in the total aggregate replacement level. For the mix with P25T75, analysis of the compressive strength data showed that, the S_{RF} decreased from 1.0 to 0.695 when 25% of the volume of the granite aggregates was replaced with PKS and tire particles. For this same mix, the S_{RF} decreased further to 0.438, 0.2703 and 0.216 when the TAR was increased to 50%, 75% and 100% respectively. This confirms the earlier findings by Guneyisi et al. [15] that an inverse relationship exists between the S_{RF} and aggregate replacement level. This finding suggests that increasing the volume of tire and PKS aggregates in concrete reduces its strength properties. As noted by [5,11,17,23], the reduced strength of PKS or rubberized concrete can be attributed to the comparatively weaker bond between the aggregate (rubber or PKS) and cement paste compared to that of crushed granite stones. Consequently, any attempt to improve the strength reduction factors should look at the aggregate-cement bond.

Regarding the tire and PKS combination, it was observed that, at each TAR level, the S_{RF} increases with increase in the PKS content. For instance, from the compressive strength tests, at 25 % TAR, the mix, P0T100, had S_{RF} of 0.539 but this figure increased to 0.695, 0.869, 0.960 and 0.973 when the PKS content was increase to 25%, 50%, 75% and 100% respectively. This trend is consistent for all the other properties of the concrete tested. Thus, the inclusion of PKS improves the strength reduction factor for the PKS rubberised concrete.

Comparing data for the four mechanical properties of the concrete tested, it was identified that, at TAR ≤ 25%, the SRF is higher for the compressive strength, followed by the modulus of rupture, split tensile strength and the bond strength (see Fig. 5). Moreover, for all the mixes and the properties tested, a minimum reduction factor of 0.5 can be achieved when the TAR ≤ 50% and the PKS content is ≥ 50%. For instance, at 50% TAR where the PKS was 50%, the reduction factors were 0.527, 0.581, 0.585 and 0.636 for the compressive strength, bond strength, *modulus of rupture and the split tensile strength res*pectively. Thus, it is safe to assume the strength reduction factor to be 0.5 for any of the strength properties where TAR = 50% and PKS ≥ 50%.

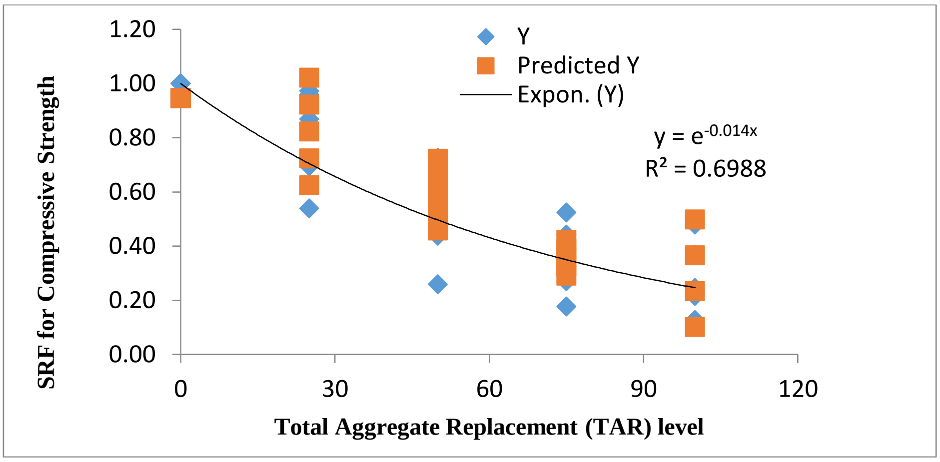

Fig. 1. Relationship between SRF for compressive strength and TAR

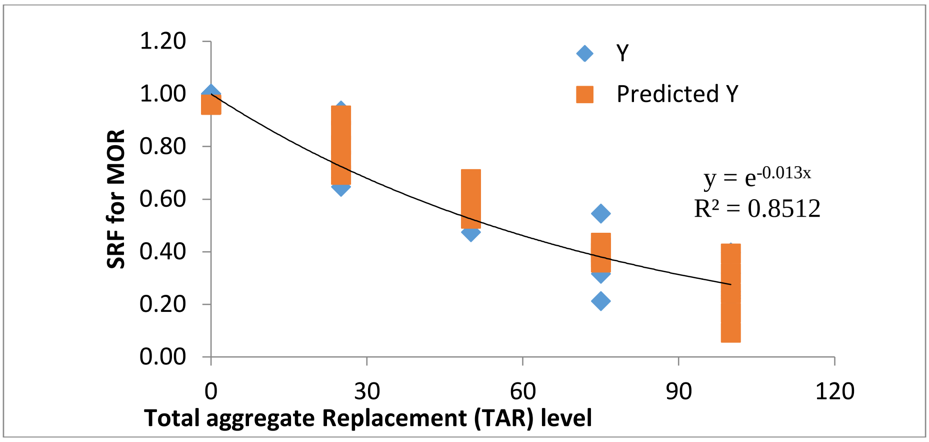

Fig. 2. Relationship between SRF for MOR and TAR

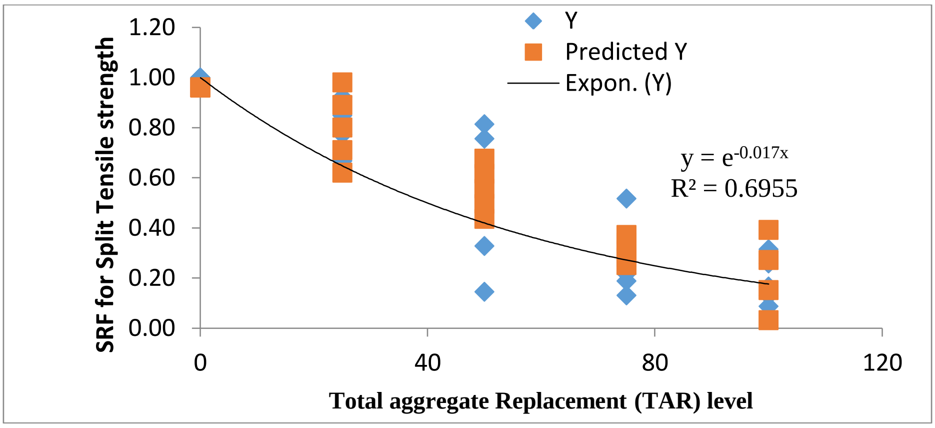

Fig. 3. Relationship between SRF for Split Tensile strength and TAR

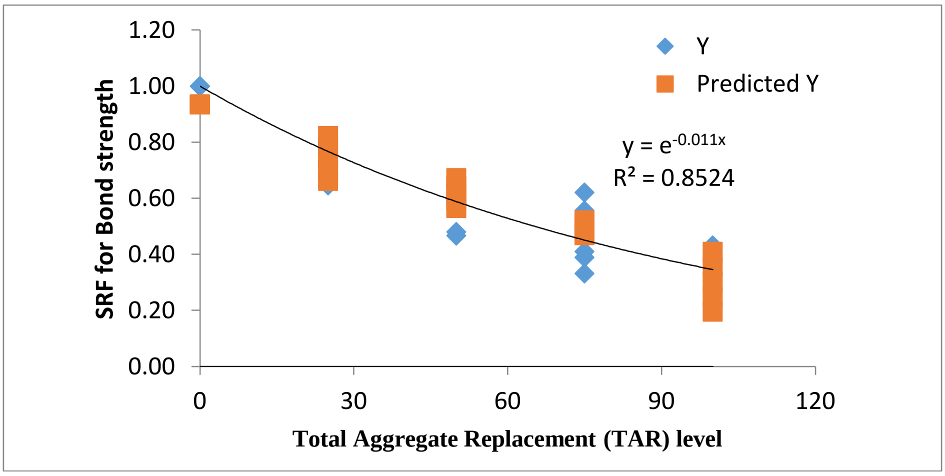

Fig. 4. Relationship between SRF for bond strength and TAR

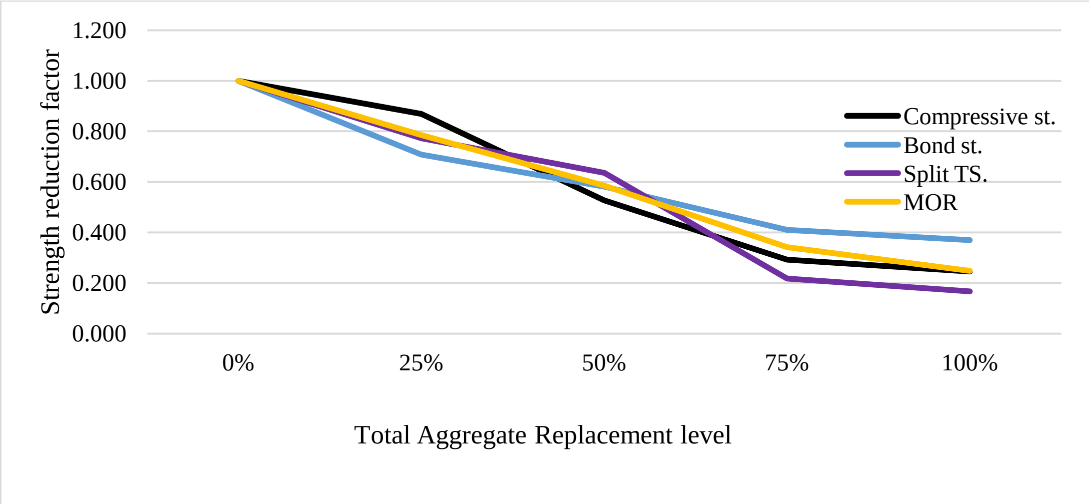

Fig. 5. Comparing the reduction factors for the various strength properties of the concrete tested for the concrete mix, P50T50 at different TAR levels

3.2 Proposed Model

After studying several mathematical functions, Eqn. (6) was proposed to estimate the reduction factors for the various strength properties.

$$S_{RF} = \beta_0 + \beta_1 P + \beta_2 T + \beta_3 TAR \quad \text{.......} (6)$$

where S_{RF} is the strength reduction factor with values ranging from 0 to 1; *T* and *P* are the tire and PKS aggregates contents respectively calculated as a volumetric ratio of each material and the total coarse aggregate volume; TAR is the total aggregate replacement level; β_0, β_1, β_2, and β_3 are parameters of the regression model. The values of *P* and *T* can be calculated from equations 7 and 8 as follows:

$$P = \begin{cases} P_1\% \,(100\text{-TAR})\,\% & ; where\ TAR < 100 \\ P_1\% & ; where\ TAR = 100 \end{cases} \quad \text{.......} (7)$$

$$T = \begin{cases} T_1\% \,(100\text{-TAR})\,\% & ; where\ TAR < 100 \\ T_1\% & ; where\ TAR = 100 \end{cases} \quad \text{.......} (8)$$

Note: T_1 and P_1 are the tire and PKS aggregate content calculated as a percent of the TAR

Table 3 shows the Pearson correlation coefficient (R^2), the *F* statistics and the other statistical parameters of the proposed model for each the concrete properties tested. From the results presented, the function parameters were found to vary for each of the concrete properties. This implies that the function parameters strongly depend on the concrete property tested. Notwithstanding the above, all the proposed functions fit the data perfectly as shown by their higher R^2 values. For instance, the R^2 for the compressive strength model was 0.946, meaning about 94.6% of the values of the S_{RF} fit the regression model. In other words, 94.6% of the variations in the dependent variable (the reduction factor) are explained by the independent variables (i.e. PKS content, tire content & TAR level). In addition, all the relationships were statistically significant at 0.05 level as indicated by values of the analysis of variance, F statistic and its P value (i.e. all the P –values were all less than 0.05). The values of the Mean Relative Error (MRE) are less than 10%, which justifies the reliability of the proposed models as posited by Zhang et al [24].

Table 3. Parameters of the proposed models for the concrete strength properties and statistical test results

Model parameters	Concrete Properties			
	Compressive strength	Modulus of Rupture	Split tensile strength	Bond strength
β_0	0.94643	0.95877	0.96071	0.93518
β_1	0.37423	0.20080	0.32469	0.03765
β_2	-0.15513	-0.09996	-0.15556	-0.1761
β_3	-0.00822	-0.00767	-0.00893	-0.0056
Number of cases, n	25	25	25	25
R^2	0.93	0.96	0.90	0.91
MRE, %	9.41	7.48	9.20	8.09
P level	0.000	0.000	0.000	0.000
F statistics	99	152	64	68
Significance	Yes	Yes	Yes	Yes

A careful analysis of the parameters of the regression models reveals that, the S_{FR} is positively correlated with PKS content but negatively correlated with tire content and TAR level. This implies that the S_{RF} decreases as the volume of tire rubber in the mix and the TAR level increases but increases with an increase in PKS content. This finding is consistent with the reports of Guneyisi et al. [15] and Khaloo et al. [16] who also noted an inverse relationship between the strength reduction factors and total aggregate replacement level for rubber filled concrete.

A comparison of the results of the current study and that reported in some literature demonstrates that the strength obtained in this study is slightly higher than those reported by the other studies. For example, at 7.5% TAR with P0T100, the S_{RF} attained by Li et al. [25] was 0.55 after 28days; Khatib and Bayomy [15] obtained a SRF of 0.6 and Khaloo et al [17] had 0.4 from a 7.5% total rubber concentration. In this study, Eqn. (6) gives a SRF of 0.874 for the compressive strength with 7.5% rubber concentration. The lower values obtained by some of these studies can be attributed to a lack of pretreatment of the tire–rubber particles (e.g. [17]), tire type and improper calibration of equations especially for mixes with high volume of tire particles. In summary, the above proposed models can be used to estimate the reduction factors of any concrete that utilizes PKS and tire as coarse aggregates. Based on the reduction factors obtained, the minimum target strength of a new concrete mix can be estimated to facilitate the concrete mix design process.

4. CONCLUSIONS

This study was designed to evaluate the strength reduction factors and consequently develop models for predicting the strength of concrete that utilizes PKS and waste tire chips as partial to full replacement of the conventional crushed granite stones as aggregate. Multivariate regression analysis was employed to study the relationship between the strength reduction factors (the dependent variable) and the independent variables (i.e. TAR, PKS content and tire content). Based on the results obtained and the analysis thereof, the following conclusions were made:

1. The strength reduction factors for PKS rubberised concrete range from 0 to 1 depending on the volume of PKS and Tire particles in the mix and the total aggregate replacement level. For all the mechanical properties of concrete, a S_{RF} of 0.53 can be achieved at the optimum replacement of 50% with P50T50.
2. The strength reduction factor (S_{RF}) is positively correlated with PKS content but negatively correlated with TAR level and Tire content. Implying a decreases in the S_{RF} with increase in the total aggregate replacement level and tire content. However, at each TAR, the reduction factor increases with increase in PKS content.
3. The reduction factors for any mechanical properties of PKS rubberised concrete with tire content T and PKS content P can be estimated using an equation of form:

$$S_{RF} = \beta_0 + \beta_1 P + \beta_2 T + \beta_3 TAR$$

where, S_{RF} is the strength reduction factor; *T* and *P* are the tire and PKS aggregates content respectively calculated as a volumetric ratio of each material and the total coarse aggregate volume; TAR is the total aggregate replacement level; The values of *P* and *T* can be calculated using the following equations:

$$P = \begin{cases} P_1\%\ (100\ \text{-TAR})\ \% & ;\ where\ TAR < 100 \\ P_1\% & ;\ where\ TAR = 100 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (i)$$

$$T = \begin{cases} T_1\%\ (100\text{-TAR})\ \% & ;\ where\ TAR < 100 \\ T_1\% & ;\ where\ TAR = 100 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots..\ (ii)$$

where T_1 and P_1 are the tire and PKS aggregate content calculated as a percent of the TAR.

4. The function parameters (β_0, β_1, β_2, and β_3) depend on the property of concrete. For compressive strength, the values of β_0, β_1, β_2, and β_3 should be taken as 0.94643, 0.37423, -0.15513 and -0.00822 respectively. Similarly, β_0, β_1, β_2, and β_3 should be taken as 0.95877, 0.20080, -0.09996 and -0.00767 respectively for modulus of rupture. The corresponding values for bond strength are 0.93518, 0.03765, -0.1761 and -0.0056 while that for split tensile strength are 0.96071, 0.32469, -0.15556 and -0.00893 for β_0, β_1, β_2, and β_3 respectively.

For mix design purpose, the above proposed models are helpful in establishing the target strengths of PKS rubberised concrete. However, in the current study, the PKS and tire chips were used as coarse aggregates in the concrete mix. It is therefore recommended that to further improve the model's prediction accuracy and reliability in future practical applications, future studies should utilize these waste as fine aggregates or both in concrete. Moreover, the effect of different chemical treatment of the tire on the strength reduction factors should also be investigated. These new studies will help enrich the learning samples for future model development.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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