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Strength Relationship of Metakaolin Blended Laterite Rock Concrete

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Abstract: *The strength relationship of metakaolin blended laterite rock concrete (MK-LRC) is studied. The aim is to predict the splitting tensile strength of MK-LRC as a function of compressive strength for design purposes. Various regression analysis was carried out using experimental data. The reliability of the proposed equations were tested using the method of integral absolute error (IAE). Results revealed that a logarithmic function was deemed adequate as it had the least IAE value of 9.95% as well as an acceptable coefficient of determination* R^2 *value of 0.8335. The study also showed that the optimum strength performance of MK-LRC was obtained at 5% MK replacement for fine aggregate. Furthermore, in comparison to other existing concrete models, the splitting tensile strength of MK-LRC is relatively low, owing to the poor physical and mechanical properties of laterite aggregate.*

Keywords: *Laterite rock concrete, metakaolin, compressive strength, splitting tensile strength, regression analysis*

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I. INTRODUCTION

Infrastructural deficit and a growing advocacy for sustainability in the construction industry has increased the use of locally available materials. One of such material is laterite rock aggregate, a ubiquitous material in tropical countries like Nigeria, Malaysia, Brazil etc. The use of these local materials is more beneficial from a sustainability perspective as it is cheaper, environmentally friendly having less embodied energy particularly in the transportation phase (Amadi & Igwe, 2020; Kasthurba et al., 2014).

Several researches have been carried out on the use of laterite as coarse aggregate for concrete often referred to as Laterite Rock Concrete LRC (Afolayan et al., 2019; Akpokodje & Hudec, 1992; Ephraim et al., 2016; Muthusamy & Kamaruzaman, 2012). Studies have shown that the mechanical and durability properties of LRC come short in comparison to conventional concrete (Ephraim et al., 2018; Kamaruzaman & Muthusamy, 2012; Muthusamy et al., 2015; Muthusamy et al., 2015). This is owing to the weak properties of the laterite aggregate such as high porosity and high water absorption (Ephraim et al., 2018; Kamaruzaman & Muthusamy, 2012; Muthusamy et al., 2015). To overcome this shortcoming, Amadi & Igwe (2020) used metakaolin MK as a partial replacement for fine aggregate to improve the strength performance of LRC. The study revealed that a combination of metakaolin and superplasticizer improved LRC performance comparable to conventional granite concrete and the optimum performance as measured by the compressive and splitting tensile strength was recorded at 5% MK replacement.

This study is aimed at modelling the relationship between compressive and splitting tensile strength of metakaolin blended laterite rock concrete (MK-LRC). This is important as there is a dearth of knowledge on the strength relationships of concrete, more so LRC. Though compressive strength is the primary criterion to design concrete, however the knowledge of tensile strength is required to estimate the load at cracking (Jaber et al., 2018). This was corroborated by Chhorn et al. (2018) when they asserted that sufficient tensile strength is essential to withstand fatigue cracking, especially in pavement applications. Therefore, analyzing the relationship between compressive and tensile strength is important to understand and predict the behaviour of MK-LRC for design purposes.

II. EXPERIMENTAL PROGRAM

2.1 Materials

Laterite supplied from Nnewi, Anambra State was used wholly as coarse aggregate. The fine aggregate was local river sand having a fineness modulus of 2.6. The sieve analysis for the aggregates was conducted in accordance with ASTM 136, see Fig. 1. The binder was Ordinary Portland Cement produced by Dangote group and conforming to NIS 444-1:2003. Metakaolin (MK) was used as partial replacement for fine aggregate. The physical properties of materials used for this research is shown in Table 1. A Polycarboxylate ether superplasticizer complying with EN 934-2 was used for this research. Portable water was used for the concrete mixing and curing.

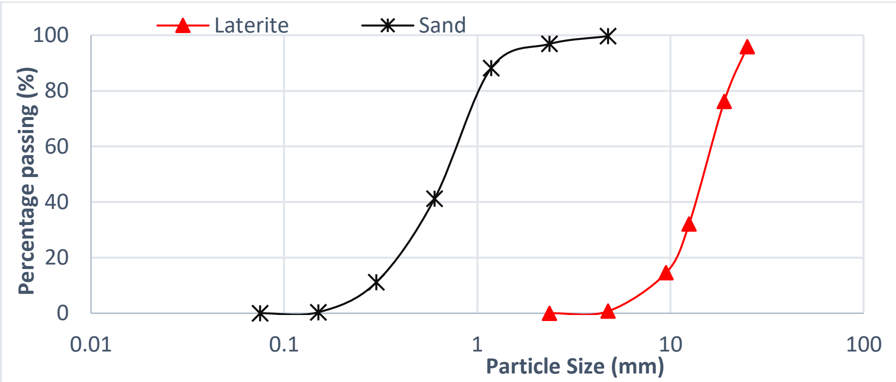

Fig. 1: Particle size distribution of aggregates

Table 1: Physical properties of materials

Property	Metakaolin	Cement	Laterite	Granite
Water absorption (%)	-	-	4.8	0.69
Specific gravity	2.54	3.11	2.68	2.62
Specific surface area (m^2/g)	11.30	0.35	-	-
LA abrasion (%)	-	-	29.3	15.73

2.2 Method

Concrete nominal mix of 1: 1.5: 2 with w/c of 0.45 was adopted to obtain concrete of fairly good quality. MK was partially used to replace sand as fine aggregate at 0 %, 5 %, 10 % and 15 % by mass of sand. See Table 2. MK replacement levels were stopped at 15% because of difficulties (stiffness) witnessed in mixing beyond 15% using the mechanical mixer. Superplasticizer was added where necessary at a dosage of 1 litre/ 100 kg cement. This is within the manufacturer's dosage specification. A total of 8 different mixes were designed. For each mixture, 9 number 150 x 150 x 150 mm concrete cubes and 9 number 150 mm diameter by 300 mm height concrete cylinders were cast, compacted and cured for compressive strength and split tensile strength testing respectively. In all, a total of 72 cubes and 72 cylinders were used.

The following reference is used to denote the various mixes. L to represent laterite, M for metakaolin and S for superplasticizer. For instance, mix LSM_{10} represents laterite concrete with superplasticizer and 10% metakaolin.

2.3 Testing

Workability was tested using the slump and compacting factor test in accordance with BS EN 12350-2:2009 and BS EN 12350-4:2009 respectively. Concrete demoulding was done after 24 hours, thereafter the concrete was cured by immersion in water. Compressive strength and split tensile strength tests were done at 3, 14 and 28 days in compliance with BS EN 12390-3-2009 and ASTM C 496 respectively. Three specimens were used for each testing age and the average result taken.

Table 2: Proportioning of concrete and workability of mixes

MK (%)	Notation	w/c	Constituents (kg/m^3)					SP (l)	Slump (mm)	Compacting Factor
			Water	Cement	Sand	Laterite	MK			
0%	LM0	0.45	203	450	675	900	0	0	105	0.754
	LSM0	0.45	203	450	675	900	0	3.6	174	0.968
5%	LM5	0.45	203	450	641	900	34	0	0	0.737
	LSM5	0.45	203	450	641	900	34	4.05	95	0.959
10%	LM10	0.45	203	450	607.5	900	67.5	0	0	0.684
	LSM10	0.45	203	450	607.5	900	67.5	4.5	65	0.933
15%	LM15	0.45	203	450	574	900	101	0	0	0.635
	LSM15	0.45	203	450	574	900	101	4.5	24	0.91

2.4 Statistical regression

To ascertain the correlation between split tensile strength and compressive strength of MK-LRC, the use of regression analysis was proposed. The tensile strength at a given age represents the dependent variable (outcome) while the compressive strength represents the independent variable tested at same age. The result of the laboratory test on split tensile strength and compressive strength constitute the experimental data as shown in Table 3. Different types of regression equations were considered such as but not limited to linear equations, power functions, polynomial, exponential and logarithmic functions.

The reliability of proposed relationships derived from the regression analysis in this study was determined based on the integral absolute error (IAE) method. This index is used to evaluate the confidence level or fit of proposed relationships. The IAE is computed as shown in Eq. 1. An IAE value of 0% depicts a perfect regression equation where all predicted values equal observed (measured) value. This situation almost never occurs in statistics. Generally, the higher the IAE percentage, the less the confidence level. However, values less than 10% signify a good fit.

$$\mathrm{IAE} = \sum \frac{[(O_i - P_i)^2]^{1/2}}{\Sigma O_i} \times 100 \qquad \text{Eq. 1}$$

Where IAE = integral absolute error

O_i = observed value

P_i = predicted value

Table 3: Experimental data

MK (%)	Notation	Compressive strength (N/mm^2)			Split tensile strength (N/mm^2)		
		3 days	14 days	28 days	3 days	14 days	28 days
0%	LM0	24.15	30.52	33.95	1.08	1.84	2.26
	LSM0	28.44	34.67	39.11	1.3	1.95	2.4
5%	LM5	27.41	33.78	36.00	1.41	1.98	2.69
	LSM5	36.44	44.44	53.92	1.84	2.12	3.11
10%	LM10	21.04	28.15	32.59	0.92	1.7	2.12
	LSM10	25.48	33.19	38.52	1.48	1.91	2.55
15%	LM15	20.15	25.78	27.55	0.85	0.98	1.41
	LSM15	23.71	28.92	32.89	1.27	1.56	1.98

III. RESULTS

3.1: Regression model

Table 4 shows a summary of different models proposed for correlation of split tensile strength and compressive strength for MK-LRC. Equation (6) has the most level of reliability as seen by the IAE value of 9.95% as well as an acceptable coefficient of determination R^2 of 0.8335. Thus, Eq. (6) was adopted as the most adequate regression model.

Table 4: Summary of statistical models for regression analysis

Type of function	Equation number	Model	R^2	IAE (%)
Linear	(2)	$f_{st} = 0.0687 f_{cu} - 0.3992$	0.8046	11.28
Polynomial	(3)	$f_{st} = -0.0012 f_{cu}^2 + 0.1508 f_{cu} - 1.7694$	0.8349	10.41
Exponential	(4)	$f_{st} = 0.4827 e^{0.0394 f_{cu}}$	0.7534	14.91
Power	(5)	$f_{st} = 0.0156 f_{cu}^{1.3641}$	0.8248	11.96
Logarithmic	(6)	$f_{st} = 2.3125 \ln(f_{cu}) - 6.1534$	0.8335	9.95

$$f_{st} = 2.3125 \ln(f_{cu}) - 6.1534 \qquad \text{Eq. 6}$$

Where: f_{st} = splitting tensile strength (N/mm^2)
f_{cu} = compressive strength (N/mm^2)

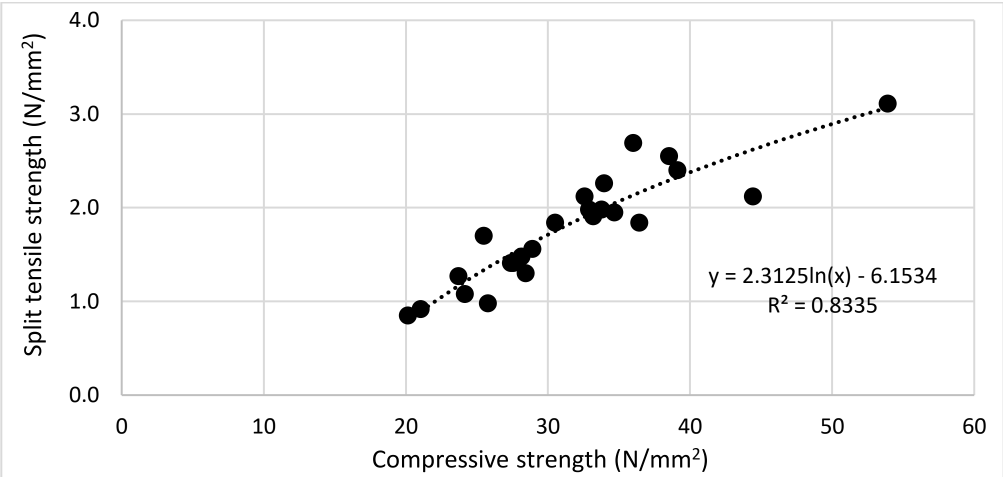

Fig. 2: Compressive and split tensile strength relationship of MK-LRC

Fig. 2 shows a scatter plot of split tensile strength against compressive strength with the line of best fit representing Eq. 6. The line of best fit shows that at higher compressive strength, the tensile strength increases at a slower rate relative to compressive strength. Similar results were obtained by Arioglu et al. (2006).

The effect of different curing age and varying metakaolin content was incorporated into this equation and studied. Result showed that within the range of data studied, it was found that the effect of curing age and MK content was insignificant with regards to this model. Thus, curing age and MK content is not influential in estimating split tensile strength from compressive strength of MK-LRC.

3.2 Comparison with existing equations

Table 5: Some of the existing models for compressive and splitting tensile strength relationship

Source	Model	Concrete type
ACI Committee 318 (1999)	$f_{st} = 0.56 f_{cu}^{0.5}$	Conventional concrete
Pul (2008)	$f_{st} = 0.106 f_{cu}^{0.948}$	Conventional concrete
Yao et al. (2017)	$f_{st} = 1.02 f_{cu}^{0.36}$	Deteriorated concrete
Chhorn et al. (2018)	$f_{st} = 0.47 f_{cu}^{0.511}$	Roller compacted concrete
Current study	$f_{st} = 2.3125 \ln(f_{cu}) - 6.1534$	MK-LRC

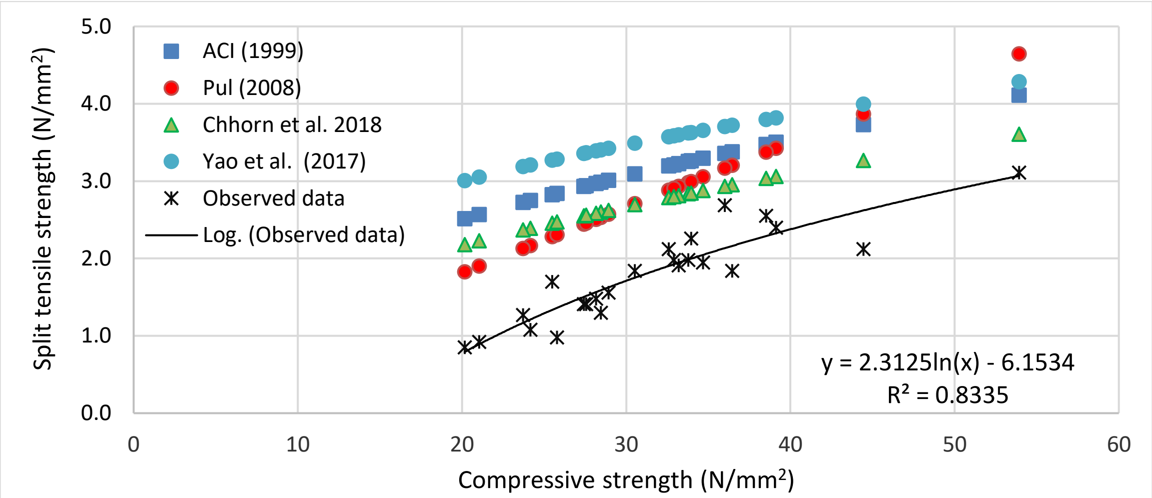

Fig. 3: Comparison between predicted splitting tensile strength for same compressive strength of MK-LRC using some existing concrete models and experimental results.

Some of the existing models for compressive strength and splitting tensile strength relationship are shown in Table 5. The splitting tensile strength of MK-LRC was calculated using these existing equations and the predicted values were compared to the observed (experimental) data (see Fig 3). The results show that for a given compressive strength, the observed splitting tensile strength of MK-LRC was lower than the predicted values obtained by other existing concrete models. This may be a consequence of the poor properties of the laterite aggregate such as high porosity and high-water absorption. Qian & Li (2001) reports that MK promotes brittleness in concrete which may have reduced the tensile strength.

3.3 Relative Strength

The relative strength is expressed as the strength of a concrete mix divided by the strength of the control at a given age. Fig 4. shows the relative split tensile and compressive strength of all mixes at 28 days. Result shows that the compressive strength and split tensile strength of all the mixes follow a similar trend. The peak values were observed at 5% MK content with relative strength of 1.38 and 1.59 for tensile and compressive strength respectively. Thus, the optimum replacement percentage of sand with MK in MK-LRC is 5% as it gave the most compressive and split tensile strength. Similar result was obtained by Amadi & Igwe (2020).

It can also be observed that the relative compressive strength was generally higher than the relative split tensile strength. This is indicative that MK is more effective in improving compressive strength than tensile strength (Moghaddam et al., 2015; Qian & Li, 2001).

Figs. 5 & 6 show for 3 and 14 days, the compressive and split tensile strengths expressed as a percentage of the 28-day strength. The rate of compressive strength development is consistently higher than the rate of tensile strength development at all ages. At 3 days, an average of 70% of the 28-day compressive strength is developed whereas it is 55% for the split tensile strength. While at 14 days, the average ratio of 28-day strength development is 89% for compressive strength and 76% for split tensile strength. This result was corroborated by (Arioglu et al., 2006; Neville & Brooks, 2010) where it was stated that rate of increase of tensile strength with age is lower than that of compressive strength.

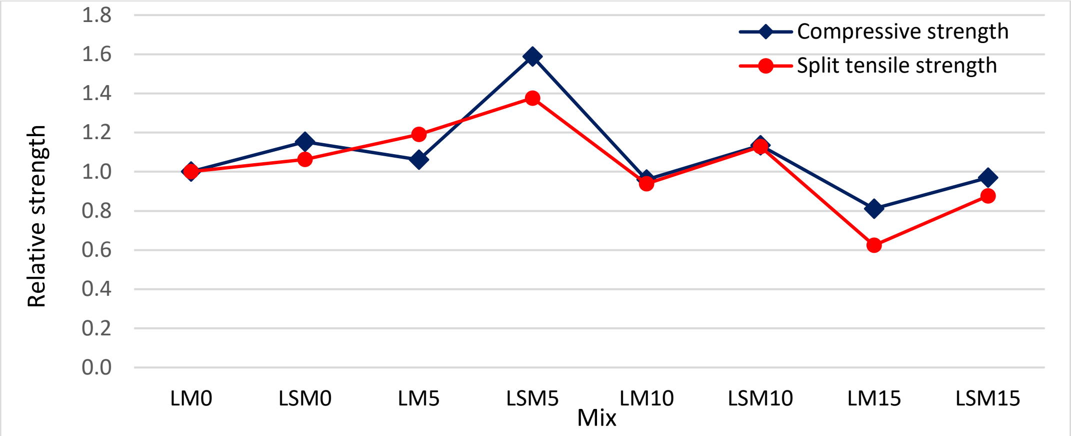

Fig 4: Relative compressive and split tensile strength at 28 days curing

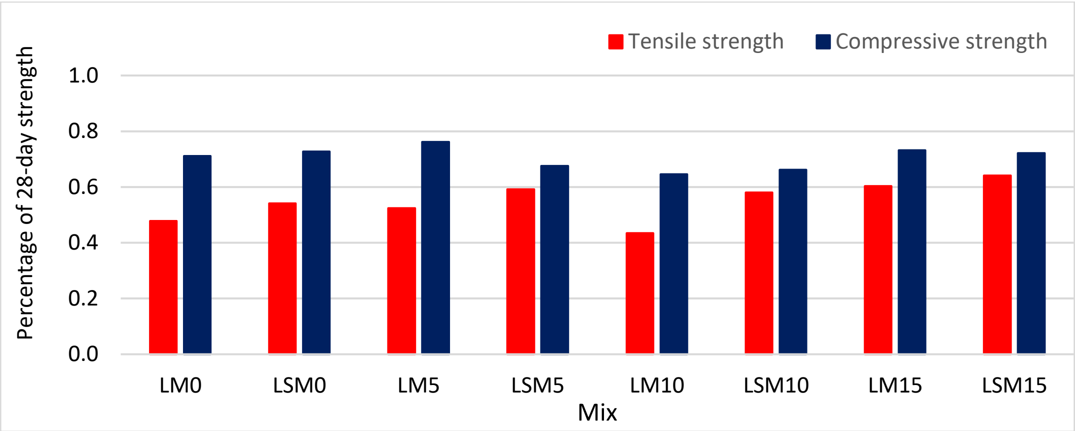

Fig 5: Rate of strength gain at 3 days

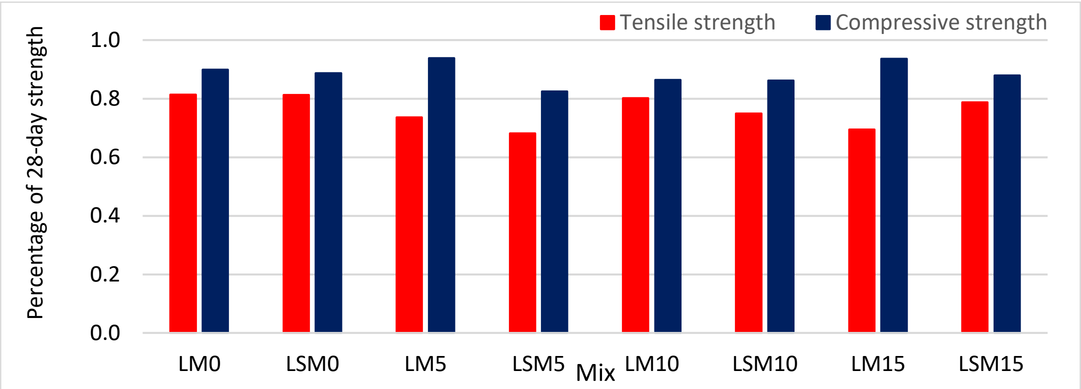

Fig 6: Rate of strength gain at 14 days

IV. CONCLUSION

- The following regression model has been derived for the splitting tensile strength as a function of the compressive strength. $f_{st} = 2.3125 \ln(f_{cu}) - 6.1534$
  This model with a coefficient of determination $R^2 = 0.8335$, integral absolute error (IAE) of 9.95% was deemed adequate for predicting the split tensile strength of metakaolin blended laterite rock concrete (MK-LRC).
- The optimum compressive and splitting tensile strength performance of MK-LRC was obtained at 5% MK replacement for fine aggregate.

- In comparison to other existing models for concrete, the tensile strength obtained from this model is low. This is due to the poor mechanical properties of laterite aggregate as well as the presence of Mk which promotes concrete brittleness.
- The rate of increase of tensile strength with age is lower than the rate of compressive strength increase.

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