International Journal of Civil and Structural Engineering Research ISSN 2348-7607 (Online)
Vol. 8, Issue 1, pp: (122-129), Month: April 2020 - September 2020, Available at: www.researchpublish.com

INVESTIGATING THE FRACTURE CHARACTERISTICS OF NIGERIAN RICE HUSK ASH (RHA) - BASED HIGH STRENGTH CONCRETE (HSC)

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Abstract: **Based on the initial research on the suitability of RHA in partial replacement of cement in HSC production, it was observed that between 10 – 20% replacement by weight of cement with RHA shows potential for use in the production of HSC based on their compressive strength. However, However, the use of compressive strength criteria only as a determinant in High Strength Concrete (HSC), especially in RHA-Cement blend concrete, has shown its inadequacies. Fracture Mechanics is a reliable experimental/analytical tool that has not been adequately used in the study of RHA-based HSC. Thus, the need to study its fracture mechanics parameters such as Crack Tip Opening Displacement ($CTOD_c$) test and Stress Intensity Factor (K_{IC}^{s}) to understand the behaviour of the RHA-based HSC to fracture toughness which is an indication of the strength of concrete when subjected to loading.**

Milled samples of the RHA were used in the preparation of RHA- Cement blends with the cement being replaced at 0%, 10% and 20% by cement weight. The 0% replacement served as a control for the experiment. 36 cubes of HSC with an expected compressive strength of 60MPa respectively were produced; 12 cubes for each percentage replacement aimed at affirming the compressive strengths were within the expected 60 MPa value. Then same mix design was used to prepare 78 beams (18, 30 and 30 for 0%, 10% and 20% RHA-Cement blend HSC) were prepared and subjected to experimental Fracture Mechanics three-point bending tests (TPBT) while the peak load for each beam before failure were recorded. The recorded peak loads were used to develop function via numerical computational and statistical models to determine the and values for the concrete.

Based on the numerical analysis done, there was a progressive increase in $CTOD_c$ and K_{IC}^{s} with an increase in RHA content in the concrete mixes with 20% having the highest $CTOD_c$ and K_{IC}^{s} ($1.4197\ MPa\sqrt{m}$ and $0.0317mm$) values compared to the control and the 10% RHA. Thus, it implies 20% RHA-cement blended HSC has more resilence compare to the 10% RHA.

Keywords: **Crack Tip Opening Displacement($CTOD_c$), Stress Intensity Factor (K_{IC}^{s}), Fracture Mechanics, Rice Husk Ash, High Strength Concrete, Construction, Concrete, Carbon Dioxide, Nigeria.**

I. INTRODUCTION

Nigeria had an estimated production of 9.86 million tonnes in 2017 from 353 thousand tonnes in 1968, growing annually at approximately 9.76% (data obtained from Index Mundi). It is expected that local rice production in later years has also increased significantly, given the Nigerian governments' drive and initiatives to increase local rice production. Estimations by [7] reveal that 200kg of husk is generated for every 1,000kg of rice grains produced. This would mean that approximately 1.2 million metric tonnes of rice husk are generated. A large proportion of this 1.2 metric tonnes is dumped in the environment as waste, while the rest is used for other uses such as heating or industrial use and the ash generated from such processes also dumped as waste in the environment. The indiscriminate dumping of the rice husk and its ash in the environment is a contributor to environmental pollution, which is expected to get worse as the Government realizes its objective of increasing rice production in the country.

The construction industry has been identified as one of the largest contributors to the production of Carbon Dioxide (CO_2), one of the greenhouse gases via anthropogenic activities worldwide [5]. 50% of the emission has been identified to be from the chemical process while 40% is from burning fuel [10], [4]. CO_2 emission during concrete production is recognized to be directly proportional to the amount of cement used in the concrete mix, accounting for 88% of the emissions associated with the average concrete mix [6] [8]. Thus, reducing the amount of CO_2 emission from concrete production will also reduce the amount of greenhouse gases in the atmosphere.

Rice Husk has been identified to be a prolific item, which can find use in various activities such as heating, cooking, drying electricity generation and other industrial uses [3]. Extensive research has been carried out into the use of RHA in the construction industry as a partial replacement for cement in the production of HSC due to the probable environmental and economic benefits. RHA contains between 87% - 97% of silica, and is highly porous and lightweight, with a high external surface area which makes it a viable material for use in concrete production.

This research thus focuses on the possible use of RHA due to its high pozzolanic properties as a partial replacement for cement in the production of HSC in Nigeria.

II. MATERIALS AND METHODS

The following materials were used in the course of the study:

a. Rice Husk Ash: The Rice Husk used in this experiment was obtained from Ire Ekiti, Southwest Nigeria. It was then burnt in open air within a temperature range of 500 – 800 ℃ after which the RHA obtained was sieved and milled.

b. Fine Aggregate: The fine aggregates utilized were gotten from the Lagos lagoon bed located at Oworonshoki, Lagos. The sand particles were passed through BS sleeve no. 4 (aperture 4.75mm) but retained on sieve 1 (aperture 0.06mm) to ensure that the dust particles were removed from the sand.

c. Coarse Aggregate: The coarse aggregate used in this research study were crushed granite of igneous origin. They size used was the recommended size of 2.36 to 12.70mm, to help improve the concrete.

d. Ordinary Portland Cement: The cement used was Ordinary Portable Cement OPC (Dangote Cement) which satisfies international standards of Ordinary Portland Cement and it ensured the cement passes the test for which its properties may be determined.

e. Portable Water: The water used was obtained from the laboratory taps. The water was portable and did not contain sulphate, ferric, alkaline, oils, vegetation or salt that could affect the properties of materials concrete in the fresh or hardened state (Annex A of BS 3148: 1980). Also, the water used was colourless, tasteless, odourless and free from decaying organic matter.

a. MATERIALS SELECTION AND CONCRETE DESIGN MIX

A preliminary investigation was conducted on the physical and chemical composition of the Rice Husk, granite, sand and cement used. Laboratory concrete proportioning trial mixes (to achieve a strength of 60 *MPa*) were then created using the methods prescribed in ACI committee 211 guide [1]. The RHA was varied between the trial mixes at proportions of 0%, 10%, 20%, 30%, 40% and 50%. Once the mixes were prepared, slump tests were carried out on the various concrete paste mixes, then the specimens were cured by immersion and ambient air for 7, 14, 21 and 28 days respectively. The table below shows the parameters used:

Table 1: Concrete Mix Design Material Specification (Grade M60)

Design Materials Specification	
Target strength (MPa)	60
Max size of aggregate used(mm)	12.7
Specific gravity of Cement	3.15
Specific gravity of fine aggregate (F.A)	2.63
Specific gravity of coarse aggregate (C.A)	2.58
Dry Rodded Bulk density of F.A (Kg/m^3)	1693
Dry Rodded Bulk density of C.A (Kg/m^3)	1619
Water-cementitious ratio	0.3169
Specific gravity of RHA	1.56

Due to their observed optimum percentage replacement performance, the 10% and 20% RHA-Cement mixes were used to prepare 78 beams for fracture parameter test. A modified Three Point Bending Test (TPBT) technique was adopted due to laboratory set up limitations. Of the 78 beams prepared, 18 beams were used as control while 30 beams each were the 10% RHA – Cement mix and 20% RHA – Cement mix respectively. The 78 beams were all air cured. The table below shows the beam specimen classification used:

Table 2: Beam Specimen Classification

Group	Wi(mm)	S(mm)	L(mm)	b(mm)	a0(mm)/W	a0(mm)
1	102.00	381.00	481.00	76.00	0.290	29.580
2	102.00	381.00	481.00	76.00	0.320	32.640
3	102.00	381.00	481.00	76.00	0.460	46.920
4	102.00	381.00	481.00	76.00	0.520	53.040
5	102.00	381.00	481.00	76.00	0.620	63.240
6	102.00	381.00	481.00	76.00	0.670	68.340

Notches were then cut into the beams using a concrete saw (as indicated in the 3 and 4 below) and were set up as indicated in the figure below and the maximum load was recorded.

Table 3: Control Mix Design (Grade M60)

		Volume
Fractional volume of oven dry rodded C.A for 12.5 mm size aggregate		-
Based on a slump of 25 – 50 mm estimated mixing water content (kg/m^3)	174	-
Void content of FA %	35.59	-
Adjustment in mixing water	2.80	-
Total water required(kg)	176.80	0.1768
Cementitious materials content(kg)	557.84	0.1771
Coarse aggregate content (kg)	1100.65	0.4267
Entrapped air content	2.00	0.0200
Fine aggregate content(kg)	524.10	0.1994
HRWR Dosage as per manufacturer recommendation (volume/cementitious content)	1Ltr/100kg	

Table 4: Lab Trial Mix (0.05062 m^3) 15 cubes per mix with 25% allowance for wastage

	Control Mix(kg/m^3)	% Replacement		Beams	
		10	20	Control	Specimen
Cement	35	32	28	47	157
RHA	0	4	7	0	17
Sand	33	30	27	45	149
Stone	70	70	70	94	344
Water (plus HRWR)	11	11	11	15	55
HRWR (ml)	353	353	353	474	1743

III. RESULTS AND DISCUSSION

The "Simple Method for Determining Material Fracture Parameters from Peak Loads" by Tang, et al [11] was adopted for the determination of the fracture parameters for the given concrete structure. As stated in the previous section, 78 beams were prepared and divided into six groups based on recommendations by Rafai and Swartz [9] with reference to three - point bending testing. The table below shows the beam classifications:

Table 5: Beam classification

Group	W_i(mm)	S(mm)	L(mm)	b(mm)	a_0(mm)/W	a_0(mm)
1	102.00	381.00	481.00	76.00	0.290	29.580
2	102.00	381.00	481.00	76.00	0.320	32.640
3	102.00	381.00	481.00	76.00	0.460	46.920
4	102.00	381.00	481.00	76.00	0.520	53.040
5	102.00	381.00	481.00	76.00	0.620	63.240
6	102.00	381.00	481.00	76.00	0.670	68.340

The beams were then subjected to load according to standard three-point bending test and the peak load responsible for each beam were recorded and shown in Table 6 below:

Table 6: Beam Peak load

Sample Classification	*P_{max} (N)* 1	*2*	*3*	*4*	*5*	*P_{max} (N)Avg*
A1	2567.49	2576.81	2593.43	2425.37	2526.95	2538.01
A2	2569.67	2664.60	2528.04	2580.24	2527.61	2574.03
A3	1689.53	1405.58	1371.80	1550.05	1417.27	1486.84
A4	1027.40	969.31	938.87	900.84	925.43	952.37
A5	775.01	783.59	752.01	814.93	674.69	760.05
A6	281.18	409.91	352.76	297.72	390.05	346.32
B1	2484.84	2360.14	2517.22	2328.24	2481.28	2434.34
B2	2437.33	2493.70	2537.11	2394.55	2552.28	2482.99
B3	1370.98	1440.91	1493.69	1462.61	1342.14	1422.07
B4	765.93	706.21	699.75	715.49	706.04	718.68
B5	632.16	597.48	541.77	671.49	505.57	589.69
B6	270.12	297.38	299.88	340.90	257.76	293.21
C1	-	-	2416.07	2346.89	2377.27	2380.08
C2	-	-	2485.95	2491.73	2365.28	2447.65
C3	-	-	1421.28	1412.53	1437.96	1423.92
C4	-	-	1005.96	971.10	1013.09	996.71
C5	-	-	695.04	719.31	743.60	719.32
C6	-	-	341.23	372.58	300.30	338.04

The first 3 classes of beams were found to be statistically relevant and were used for the next stage of the analysis. The average peak loads for the first 3 classes of beams were calculated and then applied in accordance with the LEFM equations shown below to calculate the K_{IC}^{s} and $CTOD_c$ using series of assumed a value for a_c (*see Table 4.3*)

$$K_{Ic}^{s} = \frac{3P_{max}S}{2BW^2}\sqrt{\pi a_c}F(\alpha) \quad (1)$$

$$CTOD_c = \frac{6P_{max}Sa_c}{W^2BE}V_1(\alpha)\{(1-\beta)^2 + (-1.149\alpha + 1.081)(\beta - \beta^2)\}^{1/2} \quad (2)$$

Table 7: The calculated K_{IC}^{s} and $CTOD_c$ based on assumed a_c (Class A1)

S/N	*W(m)*	*S(m)*	*B(m)*	*f'c (MPa)*	*a₀ (m)*	*ac (m)*	*Pmax (N)Avg*	*K^s IC (MPa)*	*CTODC (mm)*
1	0.102000	0.381000	0.07600	60.15	0.029580	0.056100	2380.08	1.150960	0.019522
2	0.102000	0.381000	0.07600	60.15	0.029580	0.056233	2380.08	1.156167	0.019696
3	0.102000	0.381000	0.07600	60.15	0.029580	0.056365	2380.08	1.161410	0.019872
4	0.102000	0.381000	0.07600	60.15	0.029580	0.056498	2380.08	1.166691	0.020050
5	0.102000	0.381000	0.07600	60.15	0.029580	0.056630	2380.08	1.172009	0.020229
6	0.102000	0.381000	0.07600	60.15	0.029580	0.056763	2380.08	1.177365	0.020410
7	0.102000	0.381000	0.07600	60.15	0.029580	0.056896	2380.08	1.182759	0.020593
8	0.102000	0.381000	0.07600	60.15	0.029580	0.057028	2380.08	1.188192	0.020777
9	0.102000	0.381000	0.07600	60.15	0.029580	0.057161	2380.08	1.193665	0.020963
10	0.102000	0.381000	0.07600	60.15	0.029580	0.057293	2380.08	1.199176	0.021151

Based on the Tang et al (1996), the values of K_{IC}^{s} *and* $CTOD_c$ are modelled to find the function of $CTOD_c(K_{IC}^{s})$ and is developed using the simple linear regression model as shown below:

$$y = a + bx \quad (3)$$

$$b = \frac{N\sum xy - (\sum x)(\sum y)}{N\sum x^2 - (\sum x)^2} \quad (4)$$

$$a = \frac{\sum y - b\sum x}{N} \quad (5)$$

Taking K_{IC}^{s} to be x and $CTOD_c$ to be y, the function of $CTOD_c(K_{IC}^{s})$ for the respective classes is shown as follows;

$$CTOD_c(K_{IC}^{s}) = 0.0382K_{IC}^{s} - 0.0250 \quad (6)$$

$$CTOD_c(K_{IC}^{s}) = 0.0364K_{IC}^{s} - 0.0251 \quad (7)$$

$$CTOD_c(K_{IC}^{s}) = 0.0282K_{IC}^{s} - 0.0136 \quad (8)$$

From equations (6), (7) and (8) above, the same values of K_{IC}^{s} were substituted in the equations and average of the corresponding $CTOD_c$ and the variance (s^2) (*refer to Table 8 below*).

Table 8: Calculated Average $CTOD_c$ and variance S^2 (Partial table)

K_{IC}^{s} *(MPa)*	$CTOD_c$ *(Group 1)*	$CTOD_c$ *(Group 2)*	$CTOD_c$ *(Group 3)*	*Average*	S^2
0.6700000	0.0005940	-0.0007120	0.0052940	0.0017253	0.997794533
0.6850000	0.0011670	-0.0001660	0.0057170	0.0022393	0.951484633
0.7000000	0.0017400	0.0003800	0.0061400	0.0027533	0.906453333
0.7150000	0.0023130	0.0009260	0.0065630	0.0032673	0.862700633
0.7300000	0.0028860	0.0014720	0.0069860	0.0037813	0.820226533
0.7450000	0.0034590	0.0020180	0.0074090	0.0042953	0.779031033
0.7600000	0.0040320	0.0025640	0.0078320	0.0048093	0.739114133
0.7750000	0.0046050	0.0031100	0.0082550	0.0053233	0.700475833
0.7900000	0.0051780	0.0036560	0.0086780	0.0058373	0.663116133
0.8050000	0.0057510	0.0042020	0.0091010	0.0063513	0.627035033

NB: See full table in the appendix

Furthermore, applying a multiple linear regression model, the function of $S^2(K_{IC}^s)$ was modelled using the K_{IC}^s**,** square of K_{IC}^s as variables. The equation below was derived showing a nonlinear relationship between S^2 and K_{IC}^s ***(group A)***

$$S^2(K_{IC}^s) = 2.8413(K_{IC}^s)^2 - 6.9373(K_{IC}^s) + 4.3703 \quad (9)$$

The equation above reveals that the minimum of the curve S^2– K_{IC}^s corresponds to the critical intensity factor for the whole materials as shown below. Based on the value, the linear regression model between the average $CTOD_c$ and K_{IC}^s can be used to find the corresponding $CTOD_c$ for the material.

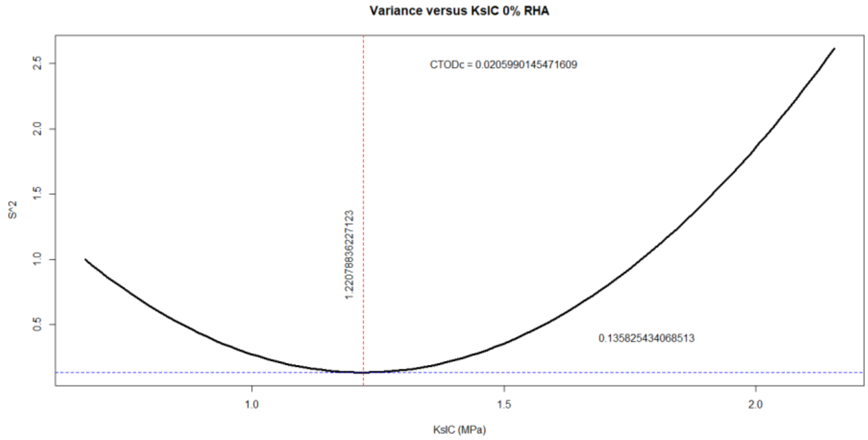

Figure 1: TOD_c and K_{IC}^s at 0% RHA

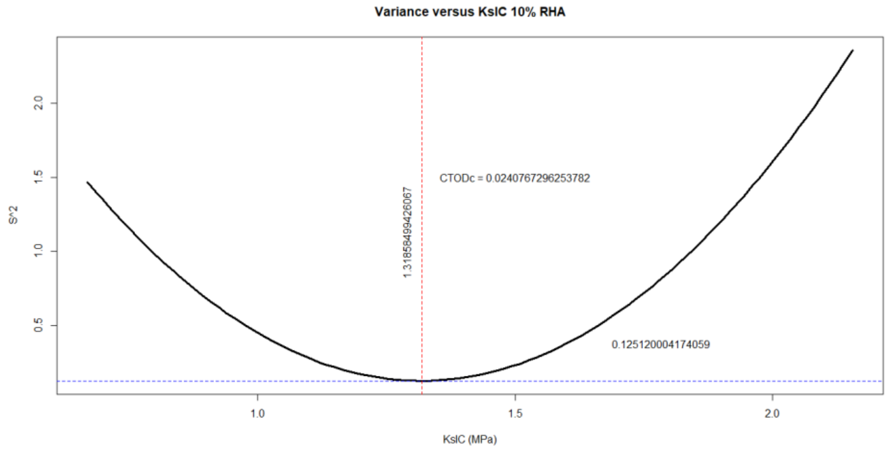

Figure 2: $CTOD_c$ and K_{IC}^s at 10% RHA

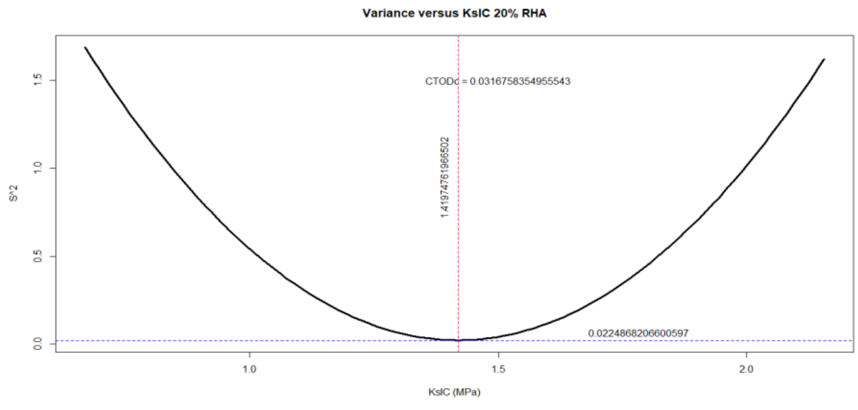

Figure 3: $CTOD_c$ and K_{IC}^s at 20% RHA

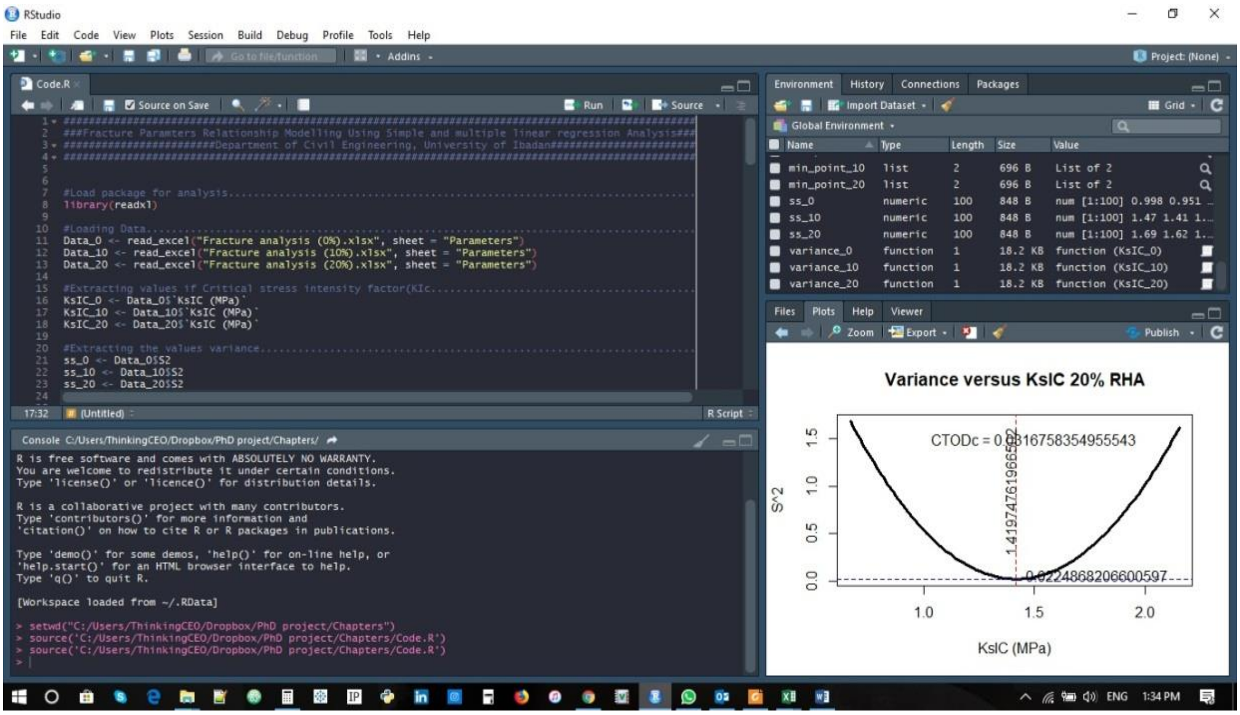

Plate I: R-studio work space

The above plate (I) reveals that the $\boldsymbol{CTOD_c}$ *and* $\boldsymbol{K_{IC}^{s}}$ increases with increase in RHA percentage with 20% recording the highest after using an R-program code to model the various linear regression relationships.

IV. CONCLUSION

From the experiment carried out, it was observed that K_{ic} increases with an increase in RHA % replacement, while CTOD increases with increase in RHA % replacement. The value of the K_{ic} and CTOD of the 20% RHA – Cement mix was higher than that of 0% and 10% replacements respectively, and thus the 20% replacement offers more resistant to crack growth propagation. Given the influence of material quality on strength of HSC, with careful quality control during concrete production the strength of HSC can be improved for 20% replacement. Thus, the 20% RHA – concrete mix is recommended as a suitable replacement for cement in HSC production. This will lead to a reduction of CO_2 emissions during the production of HSC and environmental pollution that occurs as a result of the indiscriminate disposal of Rice Husk and Rice Husk Ash.

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