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Mechanical and Bond Properties of Lightweight Concrete Incorporating Coconut Shell as Coarse Aggregate

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Abstract The demand of concrete is growing enormously now-a-days due to the increase of huge number of constructions all over the world. Therefore, the widespread research and development efforts towards discovering new constituents are essential to produce sustainable as well as environmental-friendly construction materials. The usage of waste materials such as coconut shell (CS) as a replacement of coarse aggregate is a prospective alternative in the arena of construction industries due to the continuous diminution of natural resources as well as increase of the cost of raw materials. This paper highlights the experimental outcomes of a research carried out on the mechanical (such as compressive strength and splitting tensile strength) properties as well as bond behavior of concrete encompassing crushed coconut shells as various percentage replacement of coarse aggregates. The cylindrical specimens (100 mm x 200 mm) were prepared and tested in accordance with ASTM standards. Concrete cylinder specimens incorporating different percentage replacement of coarse aggregates using coconut shells with rebar were constructed and performed pullout testing to evaluate the bond behavior of concrete containing natural stone chips and crushed coconut shells as a partial replacement of coarse aggregates. The effect of bond stress-slip behavior for various percentage replacement of coarse aggregates with crushed coconut shells were also evaluated in this research. Based on the compression and splitting tensile strength of concrete, it can be established that the concrete containing 10% and 25% crushed coconut shell aggregates with the replacement of stone chips as coarse aggregates fulfills the requirements of the lightweight structural grade concrete. There is no significant variation of bond strength observed up to 25% replacement of coarse aggregates using crushed coconut shells. Moreover, the failure behavior for CS concrete and control concrete is almost identical to other lightweight structural aggregate concretes. Therefore, it can be concluded that up to 25% natural coarse aggregates (stone chips) can be replaced in concrete production using crushed coconut shells. In addition, a strong correlation (R^2 = 0.99) has been developed between the bond strength and compressive strength for natural weight aggregate and CS concrete under normal water curing conditions.

Keywords: *sustainable materials, coconut shell, compressive strength test, splitting tensile strength test, pullout test; bond behavior, lightweight concrete*

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1. Introduction

Concrete is one of the main components in the construction arena. Meyer [1] reported that about 10 billion tons of concrete are produced in each year, and hence, concrete is taken into account of the most essential building material. Furthermore, the necessity for concrete is anticipated to propagate near about 18 billion tons annually by 2050 [2]. Amarnath and Ramachandrudu [3] stated that the production of concrete is growing very rapidly due to larger development of infrastructure as well as construction activities all over the world. Due to rising environmental issues, waste materials are currently being used as aggregates for construction in different parts of the world [4].

Coconut shells (CS) are obtainable in huge amounts in the humid areas of the world particularly Asia and East Africa [5,6]. In Bangladesh, CS are obtainable in enormous quantities in the southern zone of the country. Though coconut shells are using in manufacture of fiber-roofing material, however, the other prospect of using coconut shells as the aggregates in concrete manufacture have not been provided any crucial responsiveness [4]. According to Kanojia and Jain [7], coconut shell possesses some crucial properties such are coconut shell has high strength and modulus properties, coconut shell encompasses high lignin content which makes the composites more weather resistant. Moreover, due to lower cellulose content in coconut shell causes absorption of less moisture in comparison with other agriculture waste. In addition, coconut shell concrete shows good impact resistance [7]. Adeyemi [8] concluded that the CSs were more appropriate as low strength-providing lightweight aggregates when used to substitute common coarse aggregate in concrete production. Based on the research conducted on the flexural and impact resistance of concrete containing coconut shells as the coarse aggregates, Gunasekaran et al. [9] specified that coconut shells can be used as lightweight aggregates in producing structural lightweight concrete. According to Gunasekaran et al. [10], the flexural behavior of coconut shells reinforced concrete beam provides the satisfactory performance in comparison with other categories of lightweight concrete. Adebakin et al. [11] studied the development of self-compacting lightweight concrete using crushed coconut shells, and concluded that coconut shell aggregates blended with fly ash is a favorable indigenous technology for the development of structural lightweight concrete. Chandar et al. [12] investigated the applicability of quarry dust as an alternate material for river sand in coconut shell concrete and found that the durability properties of coconut shell concrete containing quarry dust are almost analogous to that of other typical lightweight aggregate concretes. The addition of coconut fiber improves the properties of conventional as well as coconut shell concrete [13].

Based on the relative analysis of concrete properties using coconut shell and palm kernel shell as coarse aggregates, Olanipekun et al. [5] reported that there is a cost decline of approximately 30% and 42% for concrete incorporating coconut shells and palm kernel shells, correspondingly. Moreover, according to the strength/economy ratio, coconut shells concrete exhibit higher behavior compared to palm kernel shells concrete when replace typical aggregates in concrete manufacture [5]. Concrete containing coconut shell aggregate possesses good quality of compressive strength even at long-term (365 days) ages [14]. In developing countries like Bangladesh where huge quantities of agricultural wastes are released in surrounding environment, these wastes can be used as prospective material or partial substitute material in construction industries. This leads to not only the reduction of the cost of construction material but also assist to the dumping of waste in addition to the production of the sustainable as well as environment friendly construction [4]. Bharat et al. [15] examined physical and mechanical characteristics of concrete containing coconut fiber in addition to the replacement of coarse aggregate with crushed coconut shells and suggested that the utilization of coconut shells and fiber in concrete not only provides as viable materials, but also assist to decrease the quantity of environmental waste. Paramsivam and Loke [16] investigated the bond behavior of lightweight concrete encompassing sawdust through pull-out tests with 152mm cube specimen for 20mm diameter deformed bars and obtained that the ultimate bond strength is approximately 8 MPa, which is nearby 27% of its compressive strength. Mor [17] conducted pull-out tests for specimen with 12mm diameter rebar on high-strength lightweight concrete incorporating expanded shale as coarse aggregate and found that the bond strength is ranging from 19-24% of the compressive strength.

This paper explores the performance of the strength behavior of concrete incorporating crushed coconut shells as the substitute of conventional coarse aggregates. Therefore, this study presents the outcomes of the experimental investigation performed on the mechanical (compressive strength and tensile strength) properties as well as bond behavior of concrete encompassing crushed coconut shells as various percentage replacement of coarse aggregates.

2. Experimental Program

This research mainly investigates the performance of concrete containing crushed coconut shells as a replacement of natural coarse aggregates. The experimental program in this study include assessment of physical properties of materials, mechanical properties (such as compressive strength, splitting tensile strength), and bond characteristics of concrete with 12mm deformed bar incorporating coconut shell as coarse aggregate. The mixing proportion of concrete for each batch is 1 (cement): 1.5 (fine aggregate): 3 (coarse aggregate) with a constant water/cement ratio of 0.48. In this research, the stone chips were replaced volumetrically by 0%, 10%, 25% and 50% with crushed coconut shells to produce the concrete. The cylindrical specimens (100 mm x 200 mm) were prepared compliant with ASTM testing standards.

2.1. Materials and Methodology

Fine Aggregate

Sylhet sand was used as fine aggregate. Specific gravity, absorption, unit weight and moisture content of sand were measured in accordance with corresponding ASTM standards, and found to be 2.63, 2.8%, 1627 kg/m^3 and 1.3%, respectively. Sieve analysis has been performed according to ASTM C136 [18] to determine the fineness modulus of sand used in this study as presented in Table 1.

Table 1. Sieve analysis of sand

Sieve No. (ASTM)	Sieve opening (mm)	Wt. retained (gm)	Cumulative wt. retained (gm)	Cumulative wt. retained (%)	% Finer	F.M. value
No. 4	4.75	2.4	2.4	0.5	99.5	2.55
No. 8	2.36	24.7	27.1	5.4	94.6	
No. 16	1.18	89.4	116.5	23.3	76.7	
No. 30	0.60	140.5	257.0	51.4	48.6	
No. 50	0.30	129.9	386.9	77.4	22.6	
No. 100	0.15	97.5	484.4	96.9	3.1	
Summation of cumulative weight retained (%) =				254.9		

Binder

Portland cement was used as binder. Specific gravity, initial setting time and final setting time of Portland cement were measured in accordance with corresponding testing standards, and found to be 3.15, 145 minute and 255 minute, respectively.

Coarse Aggregate

Black stone chips were used as natural coarse aggregate. Specific gravity, absorption, unit weight and moisture content of black stone chips were also performed according to associated ASTM standards and found to be 2.72, 1.1%, 1520 kg/m^3 and 0.7%, respectively. Gradation of stone chips was also performed in accordance with ASTM C136 [18] and presented in Figure 1.

Crushed coconut shell aggregate

The specific gravity, unit weight, water absorption and moisture content characteristics of crushed coconut shell aggregates were determined following the similar testing procedures of coarse aggregates and obtained to be 1.23, 550 kg/m^3, 25.6%, and 7.8% respectively. The obtained gradation curves for crushed coconut shell aggregates have been presented in Figure 1. It should be noted that the gradation of crushed coconut shell aggregates were performed for three samples to ensure the consistency of the coarse aggregates that were used as normal weight aggregates in replacement of stone chips.

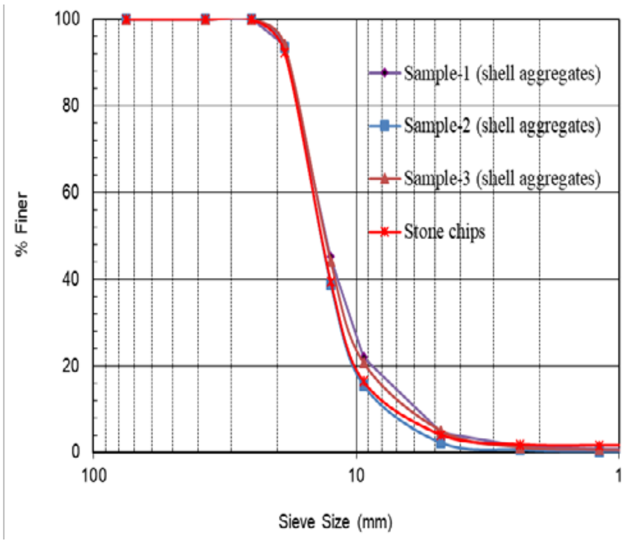

Figure 1. Grain size curves for stone chips and crushed coconut shell aggregates

2.1.1. Slump Test

In this study, the slump test has been performed according to ASTM C143 [19]. Figure 2 illustrates the technique of slump value measurement to indicate the workability of fresh concrete. It should be mentioned that the slump test was accomplished for concrete containing stone chips as well as concrete made with partial replacement of stone chips through coconut shells. The cast cylindrical specimens (100 mm x 200 mm) for the compression and tensile strength tests are presented in Figure 3. Each cast samples were demoulded after 24 hours and submerged in water for curing.

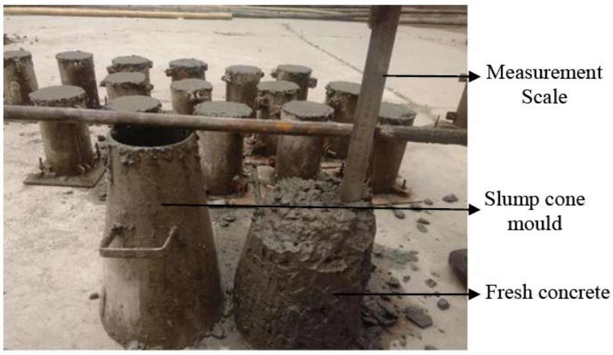

Figure 2. Slump cone test to measure the workability of concrete

Figure 3. Preparation of cylindrical specimens for compression and tension testing

2.1.2. Specimens for Bond Test

Concrete cylinder with rebar were constructed. Eight group of concrete cylinders specimens (100 mm x 200 mm) were prepared for pullout test. The prepared specimens for pull-out test is presented in Figure 4. A single 12 mm diameter rebar was embedded at the center of the vertical axis of the test cylinders (shown in Figure 4). The yield and ultimate strength of the 12 mm diameter deformed bar was determined in the laboratory and found to be 420 MPa and 512 MPa, respectively. It should be noted that rebar was cast vertically from the top of the cylinder to bottom of the cylinder.

Figure 4. Preparation of test specimens to evaluate bond properties

3. Test set-up

3.1. Compressive Strength

Total 36 specimens (three samples for each mixing batch) were cast to perform compressive strength test of concrete. The compression testing of cylindrical specimen was performed in accordance with ASTM C39 [20]. Figure 5 shows the test set-up of cylindrical concrete specimen to conduct compression test using a compression testing machine. The load was applied gradually till the failure of specimens and the ultimate load for each specimens were recorded.

Figure 5. Placement of cylindrical specimen for compressive strength test

3.2. Splitting Tensile Strength

This test was conducted according to ASTM C496 [21]. Total 24 specimens (three samples for each mixing batch) were cast to conduct splitting tensile strength test of concrete. Cylindrical concrete specimens were placed into the compression testing machine with the bearing edges of 12 mm diameter bar in the top and bottom of the specimens as illustrated in Figure 6. The load was applied on each specimen in anticipation of failure of specimens by indirect tension in the mode of splitting takes place along the vertical diameter of cylinders and recorded the failure load for each specimens. It should be mentioned that the tensile strength of concrete can be calculated using the formula provided in the ASTM testing standard and can be expressed as T= 2P/πDL, where, T = tensile strength; P = failure load; L = length of the cylinder; and D = diameter of the cylinder.

Figure 6. Test set-up for splitting tensile strength test

3.3. Bond Strength

The direct pullout test using Universal Testing Machine (depicted in Figure 7) was implemented in this research to assess the bond behavior of steel-reinforced concrete with 12 mm diameter deformed bar. Because of the variances in boundary conditions as well as stress state, the stress values achieved from the direct pull-out tests may not be accurately the identical as the stresses achieved in real scenarios [22]. Nevertheless, this test set-up was considered in this research because the testing arrangement in this set-up is simple, more convenient and inexpensive in comparison to other testing system. Moreover, this test set-up is representing almost practical arrangement as it signifies the main longitudinal reinforcement, which is typically under tensile loads in a reinforced concrete flexural members such as slab and beam.

Figure 7. Direct pullout test set-up for the determination of bond stress-slip behavior

Prior to start the test, the specimens were positioned in a Universal Testing Machine for direct pullout test (shown in Figure 7). Concrete cylinder was kept below the fixed plate which contains a hole in the center where the rebar can be passing. The rebar was entered through the hole of the fixed plate and reached to the moving plate where it was gripped by clamp. The cylindrical samples were tested at the curing age of 7 and 28 days in a 500 kN Universal testing machine. The load was applied at a constant rate as per ASTM C234 [23] (depicted in Figure 7) until failure to obtain the ultimate load. The slip value at corresponding ultimate load was also determined for each specimen. Three replicate specimens were tested and reported the average of these three specimens.

The bond strength based on the experimental test was calculated using Equation (1).

$$\tau = \frac{P}{\pi d_b l_d} \tag{1}$$

Where,
τ = bond stress;
P = failure load;
d_b = nominal bar diameter;
l_d = embedment length.

4. Results and Discussions

4.1. Workability Measurement

In order to measure the workability of each mixing batches of concrete, slump value was measured for normal weight concrete containing stone chips only as well as each percentage replacement of normal coarse aggregates with crushed coconut shell aggregates. Table 2 presents the obtained slump value for each mixing batches of concrete. The measured slump values for the normal weight concrete, 10%, 25% and 50% replacement of natural coarse aggregates with crushed coconut shell aggregates were 110 mm, 90 mm, 80 mm and 55 mm, respectively. It can be revealed that the slump value of concrete decreases with the increase of percentage replacement of stone chips with crushed coconut shell aggregates. It should be mentioned that each mixing batches of concrete followed true slumps.

Table 2. Slump value of CS concrete

% replacement of stone chips with CS aggregates	Slump value (mm)
0%	110
10%	90
25%	80
50%	55

4.2. Compressive Strength

Compression testing was conducted for concrete containing stone chips only as well as partial replacement (such as 10%, 25% and 50%) of stone chips using crushed coconut shells. Figure 8 illustrates the variation of compressive strength for 7, 28 and 90 days with different percentage replacement of coarse aggregates by crushed coconut shells. From Figure 8 it can be stated that the compressive strength of the concrete decreases gradually as the percentage replacement of stone chips using crushed coconut shells increases in the concrete mixing. It should be mentioned that the compression capacity of cylinder specimens were reported based on three replicate samples. There is about 10%, 23% and 43% variation of compressive strength of concrete incorporating 10%, 25% and 50% crushed coconut shells respectively, in comparison to the concrete encompassing stone chips only as illustrated in Figure 8.

Figure 8 also illustrates the compressive strength development of both the normal weight concrete and crushed coconut shell concrete up to the curing age of 90 days. It is also examined that the compressive strength of the concrete increases with the increase of the curing days as illustrated in Figure 8. From Figure 8 it can be also stated that the rate of strength gain is enlightened for the first 28 days. There is a very slow rate of strength gaining experienced between 28 and 90 days of curing age. Due to rough surface of coconut shell, coconut shell concrete exhibits better compressive strength compare to palm oil shell concrete [5]. According to ACI 301 [24], the structural lightweight aggregate concrete must meeting the requirements of the aggregates that conforming ASTM C330 [25], and the compressive strength of concrete should be higher than 17 MPa at 28 days age [26]. Kosmatka et al. [27] stated that the typical compressive strength for structural lightweight concrete varies in the range of 20 to 35 MPa. According to ACI-213R [28], the compressive strength for structural lightweight concrete varies from 17 to 41 MPa [2]. Therefore, it can be revealed that the concrete containing 10% and 25% crushed coconut shells with the replacement of stone chips as coarse aggregates fulfills the requirements of the lightweight structural grade concrete.

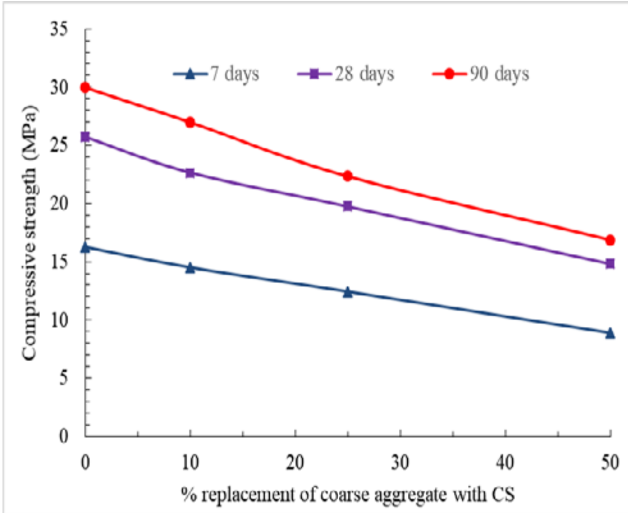

Figure 8. Comparison of compressive strength of concrete with percentage replacement of coarse aggregates by crushed coconut shells at 7, 28 and 90 curing days.

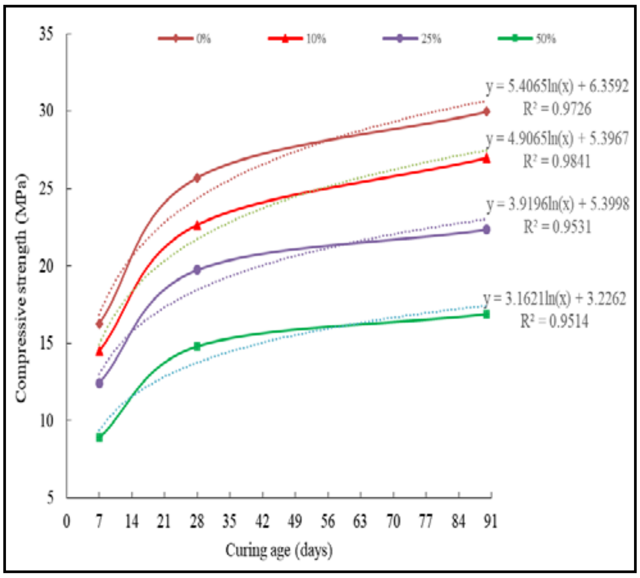

Figure 9. Development of compressive strength under 90 days water curing

To develop effective correlation among compressive strength and curing age for both control concrete and crushed coconut shell concrete, simple regression analysis were executed. Based on the regression analysis (illustrated in Figure 9), it can be specified that the compressive strength followed logarithmic manner with the curing ages. Figure 9 depicts the logarithmic correlations between compressive strength and curing time of normal weight concrete as well as concrete incorporating partial replacement of coarse aggregates using crushed coconut shell aggregates under normal water curing conditions. The optimum logarithmic relationships for 10% and 25% replacement of coarse aggregates with crushed coconut shells aggregates concrete can be expressed by the following equations:

For 10% CS aggregates concrete,

$f_{cu} = 4.9065\ln(d_{cu}) + 5.3967$ ($R^2 = 0.9531$); and

For 25% CS aggregates concrete,

$f_{cu} = 3.9196\ln(d_{cu}) + 5.3998$ ($R^2 = 0.9841$)

Where, f_{cu} is the compressive strength of cylinders in MPa, and d_{cu} is the curing ages of cylinders in days.

Figure 10 presents the failure patterns of cylindrical specimens under axial compression loading. It has been seen that all cylindrical specimens (containing various percentage of crushed coconut shells) under compression loading followed the similar modes that generally occurred in concrete containing natural aggregates. The failure surfaces of concrete showed fracture of the crushed coconut shell aggregates, signifying that the distinct shell strength had a robust effect on the subsequent concrete strength.

(a) Observed cracks during testing

(b) Observation of cracks after testing

Figure 10. Failure modes of cylindrical specimens under axial compression loading

4.3. Splitting Tensile Strength

The splitting tensile strength tests for different percentage replacement of stone chips using crushed coconut shells as coarse aggregates at 7 and 28 curing days have been performed and presented in Figure 11. From Figure 11 it can be stated that the tensile strength of the concrete reduces with the increase of the percentage replacement of stone chips by crushed coconut shell aggregates. The rough surface of aggregates resulting to the increase of the bond and thus increasing tensile strength [29]. From Figure 11 it can also be specified that there is approximately 11%, 24% and 37% variation of splitting tensile strength of concrete containing 10%, 25% and 50% crushed coconut shells respectively with respect to concrete containing stone chips only.

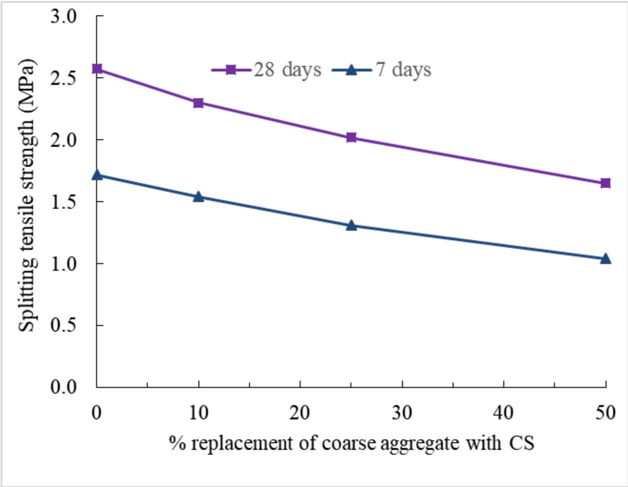

Figure 11. Variation of tensile strength with percentage replacement of coarse aggregates by crushed coconut shells at 7 and 28 curing days

(a) Splitting cracks observed during tensile loading

(b) Observation of splitting cracks after testing

Figure 12. Failure modes subjected to tensile loading

According to ACI 301 [24], the structural lightweight concrete must be in compliance with ASTM C330 [25], and the minimum requirements of splitting tensile strength for this type of concrete is 2.0 MPa. Moreover, several researchers such as Abdullah [30]; Mannan and Ganapathy [31]; Teo et al., [32]; Alengaram et al. [33] disclosed that the splitting tensile strength of the lightweight aggregates concrete at 28 days curing age generally varied from approximately 1.1 to 2.4 MPa. Hence, the concrete incorporating 10% and 25% crushed coconut shells with the replacement of stone chips as coarse aggregates fulfills the tensile strength obligations for lightweight structural grade concrete.

The failure modes of cylindrical specimens when subjected to tensile loading is depicted in Figure 12. It is evident that the behavior of CS concrete in splitting tensile strength is also almost identical to normal weight concrete. It has also been observed that all specimens under splitting tensile loading followed similar manner i.e. split into two segments through the middle of the cylinders.

4.4. Bond Behavior

The results for the pull-out test are given in Table 3. Three pull-out test specimens were tested for control concrete as well as CS concrete. Figure 13 presents the development of bond strength with curing ages for both control concretes and crushed coconut shell concretes. The 7-day and 28-day bond strength of concrete varied from 5.23 to 2.90 MPa and 8.76 to 4.74 MPa, respectively, depending on the percentage replacement of stone chips with crushed coconut shell as illustrated in Figure 13. The average values of bond strength had coefficient variation varying from 5% to 11%.

The projections on the surface of the rebars take the part of a significant role in enlightening the bond strength particularly in the existence of water. The variety of curing atmosphere also effected the bond strength of concrete containing normal weight aggregates as well as concrete incorporating crushed coconut shells. As anticipated, cylindrical specimens with deformed bars that encompasses without replacement of coarse aggregate using crushed coconut shells (i.e. normal weight concrete) experienced higher bond strength at every curing ages of concrete. For specimens with increase of percentage replacement of crushed coconut shells, the bond strength was relatively lower due to vastly uneven shape and smooth surfaces of the crushed coconut shells combined with the continuous existence of water influence to the prevention of decent bonding between rebar and concrete, which causes to the lower bond strength [34]. The average values of ultimate load, bond stress and the corresponding slip values are presented in Table 4.

It has been observed that the failure behaviour for CS concrete and control concrete is almost similar. At every ages of the pull-out test, cylindrical specimens encompassing deformed bars failed due to the cracking of the concrete cover as illustrated in Figure 14. The failure of the control concrete and CS concrete specimens were also abrupt with the creation of longitudinal cracks along the specimens and the slip behavior were not substantial throughout the preliminary stage of loading. When the cracks materialized, the bond loads were pointed towards the outside from the rebar surface and these loads caused anchorage failure through the splitting off the confined concrete. The strength is reliant on to a number of extent on the physical strength of the coarse aggregate [32]. The failure of pull-out specimens of the control concrete and CS concrete showed that there is no pull-out failure as depicted in Figure 14. Figure 14(c) shows the specimen after splitting of cylinder specimens for CS concrete.

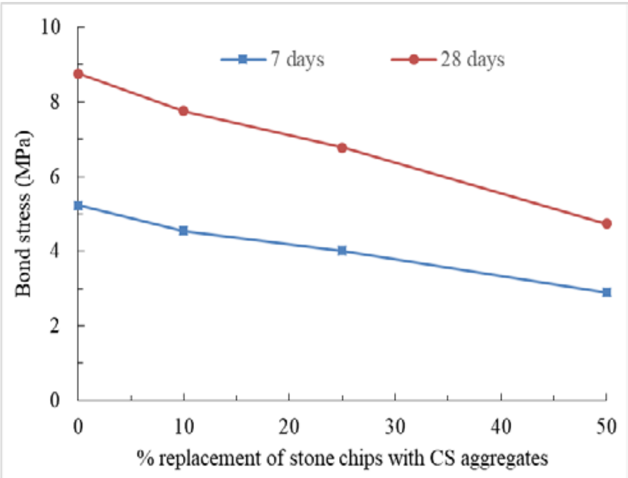

Figure 13. Bond stress of normal concrete and concrete containing different percentage of coconut shell aggregates at 7 and 28 days age

Table 3. Test results of bond strength specimens

% replacement of stone chips with CS aggregates	7 days				28 days			
	Failure load (kN)			Average failure load (kN)	Failure load (kN)			Average failure load (kN)
	S-1	S-2	S-3		S-1	S-2	S-3	
0 (Control specimen)	37.7	39.0	41.6	39.4	67.6	63.7	67.0	66.1
10	32.5	36.4	33.8	34.2	58.5	59.8	57.2	58.5
25	29.3	31.2	30.2	30.2	51.4	50.1	52.0	51.1
50	22.1	20.8	22.8	21.9	36.4	35.1	35.8	35.8

Table 4. Test results of bond stress and the ultimate end slip for control concrete and coconut shells concrete

% replacement of stone chips with CS aggregates	7 days			28 days		
	Ultimateload (kN)	Bond strength (MPa)	Maximum slip (mm)	Ultimate load (kN)	Bond strength (MPa)	Maximum slip (mm)
0 (Control specimen)	39.4	5.23	3.8	66.1	8.76	5.1
10	34.2	4.54	4.3	58.5	7.76	6.2
25	30.2	4.01	4.0	51.1	6.78	5.4
50	21.9	2.90	3.2	35.8	4.74	4.7

(a) Before bond test of specimens

(b) After bond test of specimens

(c) Specimen after splitting

Figure 14. Failure modes after split up of specimens

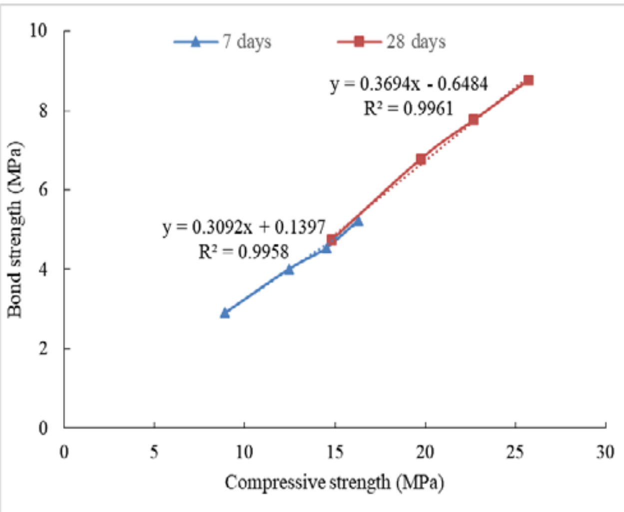

Figure 15. Relationship between bond strength and compressive strength

Figure 15 represents the correlation between the bond strength and compressive strength at the curing ages of 7 and 28 days for control concrete and CS concrete specimens under normal water curing conditions. There is a strong linear relationship with a correlation (R^2 = 0.99) between both strength properties. The best fit linear equations for the bond strength (τ_f) of CS concrete are computed based on the relationship presented in Figure 15 and can be expressed as:

$\tau_f = 0.3092 f'_c + 0.1397$ ($R^2 = 0.9958$) for 7 days

$\tau_f = 0.3694 f'_c - 0.6484$ ($R^2 = 0.9961$) for 28 days

Where τ_f is the bond strength in MPa and f'_c is the cylinder compressive strength in MPa.

This relation shows that the bond strength of CS concrete is lesser than the concrete containing natural stone chips aggregates. It has also observed that in concrete containing crushed coconut shells aggregates, the bond strength are approximately 30-35% of its compressive strength. This is supported by previous research conducted by Orangun [35] using pull-out test and reported that the bond strength of lightweight sawdust concrete encompassing 12mm diameter deformed bar inserted in 152mm cube specimen is about 25-41% of the compressive strength.

5. Summary and Conclusions

This research mainly investigates the performance and feasibility of concrete incorporating crushed coconut shells as the substitute of natural coarse aggregates. The mechanical properties such as compressive strength; splitting tensile strength as well as bond behavior of concrete with 12mm deformed bars encompassing crushed coconut shells with various percentage (such as 0%, 10%, 25% and 50%) replacement of coarse aggregates have been investigated. The cylindrical specimens (100 mm x 200 mm) were prepared using mixing proportions of 1:1.5:3 and tested in accordance with associated ASTM standards. Based on the experimental investigation of this research the following conclusions can be outlined:

- The slump value of concrete decreases with the increase of percentage replacement of stone chips using crushed coconut shell aggregates. Concrete incorporating crushed coconut shells up to 25% provide reasonable slump value for typical concreting work except pumping concrete.
- Based on the compression and splitting tensile strength of concrete, it can be stated that the compressive and splitting tensile strength of the concrete decreases gradually as the percentage replacement of stone chips using crushed coconut shells increases in the concrete mixing. However, the concrete containing 10% and 25% crushed coconut shell aggregates with the replacement of stone chips as coarse aggregates fulfills the requirements of the lightweight structural grade concrete. Therefore, it can be concluded that up to 25% natural coarse aggregates (stone chips) can be replaced in concrete production using crushed coconut shells.
- From the viewpoint of bond properties, coconut shell concrete up to 25% replacement of coarse

aggregates exhibited insignificant variation compared to concrete containing natural weight aggregates. Moreover, the failure behavior for CS concrete and control concrete is almost identical to other lightweight structural aggregate concretes.

- There is strong correlation (R^2 = 0.99) developed between the bond strength and compressive strength at the curing ages of 7 and 28 days for natural weight aggregate and CS concrete under normal water curing conditions. The design engineer can be used this linear relationship as a guideline in concrete industry.

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