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Aggregate concrete factor (λ) for burnt clay brick aggregate concrete

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Keywords: aggregate, rebar geometries, pull-out test, bond strength, aggregate concrete factor.

Abstract. This research aims to evaluate the lightweight burnt clay brick aggregate concrete factor (λ) which is commonly used as coarse aggregate in Bangladesh as well as Asia regions. The pull-out tests were carried out on four different types of concrete cylinder specimens (100 mm by 200 mm) made with natural crushed stone and first class burnt clay brick aggregates to determine the aggregate concrete factor (λ) and bond strength. Three different rebar diameter of 8 mm, 10 mm, and 12 mm with two different embedded lengths of 100 mm and 200 mm were investigated. In addition, compressive and splitting tensile strength tests were also performed to calculate bond strength and then λ. The experimental results showed that bond strength of 10 mm diameter rebar is higher compared to other bar diameter for both aggregates and both embedded length of 100 and 200 mm. While the bond strength of 200 mm embedded length rebar is higher than the embedded length of 100 mm. From this research study, it has been found that the average λ equal to 0.88 for Bangladeshi burnt clay brick aggregate. However, based on the test results a new equation is proposed for the lightweight brick aggregate concrete factor (λ).

1. Introduction

According to ACI code, it is necessary to unite the reinforcement properly into the concrete for a finite length in order to confirm a good bonding. This sufficient length to anchor bars near the end of connections is referred to as the development length (l_d) [1]. According to ACI committee 408 (2003), the development length concept is based on the attainable average bond stress over the length of embedment of the reinforcement [2]. In reinforced cement concrete (RCC) bonding between concrete and steel is very important because inadequate development length is one of the major reasons for bond failure. If the tensile force on the bar is increased, friction between sufficiently bonded by a mass of surrounding concrete and bar can overcome the situation of bond failure of structural element [3–5]. The surrounding concrete remains intact except the crushing that takes place ahead of the ribs immediately adjacent to the bar interface [6–7]. According to ACI-318, section 12.2.3 (2001), the basic equation (Eq. 1) for development of tension bars (deformed) is as follows:

$$l_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f_c'}} \frac{\alpha\beta\gamma\lambda}{\left(\frac{C + K_{tr}}{d_b} \right)} \right) d_b, \tag{1}$$

where l_d is development length,

α is reinforcement location factor,

β is coating factor,

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γ is reinforcement size factor,

λ is light weight aggregate concrete factor,

C is concrete covering,

K_{tr} is transverse reinforcement index,

d_b is diameter of bar,

f_y is ultimate strength of steel,

f'_c is compressive strength of concrete.

However, for lightweight concretes, the tensile strength is usually less than from normal density concrete having the same compressive strength. Hence, the development length must be increased [1]. According to ACI-318-02, section 12.2.4 (2001) λ (lambda) is a lightweight aggregate concrete factor. For normal weight concrete, λ = 1.0, sand-lightweight concrete, λ = 0.85, and all lightweight concrete, λ = 0.75.

When f_{ct} is specified,

$$\lambda = 6.7\frac{\sqrt{f'_c}}{f_{ct}} \leq 1.0, \qquad (2)$$

where f'_c is compressive strength of concrete, f_{ct} is splitting tensile strength of concrete.

According to Nadir and Sujatha (2018) "Bond strength is responsible for the transfer of forces between the two materials ensuring strain compatibility and composite action" [9]. Ganesan et al. 2014, Steele (2014) and A.V. Benin et al. (2013) concluded that the bond strength depends on its development length, types and size of aggregates, mild steel surface geometry, diameter and spacing of reinforcement bar and so on [10–12]. The bond strength between reinforcing bar as well as concrete can be estimated by different test methods such as pull-out test, beam-end test, splice beam test, anchorage test and so on [11]. Among all test methods, pull-out test is the most popular and effective method to calculate the bond strength due to its ease of fabrication. In the pullout test, major load is transmitted by surface friction and mechanical interlocking of ribs in the deformed bars against the concrete. When the external load is applied to the pull-out specimen, tangential stresses i.e., tensile stresses act along the bar and at that time some new stresses develop in the concrete which is radial stress and it is perpendicular to the bar axis [13]. This radial stress surrounding the concrete performs as a thick walled concrete ring subjected to internal pressure. Therefore, tangential ring stress i.e., hoop stress as well as radial compressive stress grow in the concrete cover. But slip of the bar occurs when tensile stress exceeds the tensile strength due to radially developed cracks in the concrete cover which is also shown in Figure 1 [14].

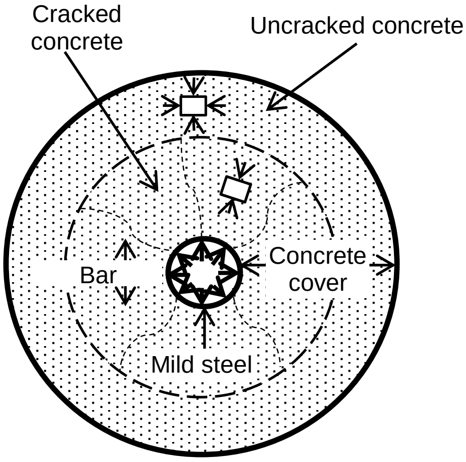


Figure 1. Transverse stresses around a pulled bar in the plan view of concrete cylinder [14].

Although numerous experimental and numerical studies have been conducted in order to gain a better understanding of the bond strength of concrete made with different types of aggregate, but almost no research is found on Bangladeshi burnt clay brick aggregate concrete factor (λ). Since Bangladesh has very limited availability of natural stones, therefore, the construction industries are mostly dependent on burnt clay brick aggregates due to cheap and availability. Indeed, in the past and even today, most of the buildings in Bangladesh are made of concrete with burnt clay brick aggregate [15]. Therefore, aggregate concrete factor (λ) has been an important issue for Bangladeshi clay brick aggregate.

In summary, the main objectives of the present study are to evaluate the aggregate concrete factor (λ) for burnt clay brick aggregate commonly used as coarse aggregate in Bangladesh by experimentally and then develop a relationship between experimental results and equation from ACI-318 (2001). To this aim, bond strength of concrete made with both burnt clay brick and natural crushed stone aggregate is observed for different bar diameter and bonding depth. Moreover, the measured bond strength has also been verified with the results found in the literature.

2. *Experimental Methods*

2.1. Materials

An extensive laboratory testing has been carried out to obtain the value of aggregate concrete factor (λ) for burnt clay brick aggregate found in Bangladesh. In the present study, burnt clay brick chips from local market and stone chips were used as coarse aggregate, locally available Sylhet sand as fine aggregate and Portland composite cement as a binding material and also mild steel have been used for pull-out test which are discussed in next subsection 2.1.1.

2.1.1 Coarse aggregate (CA), Fine aggregate (FA), and Cement (C):

Crushed first class brick and stone chips are commonly used in Bangladesh as coarse aggregate (CA) and in the present study, both of the aggregates have been used to determine the value of λ. Collected samples were broken into pieces manually having a sieve size of 19 mm downgraded and retained on 4.75 mm (sieve #4). The aggregates were then sieved to control a standard grading. In addition, unit weight, void content, specific gravity and absorption capacity of the coarse aggregate were determined according to the ASTM standard. However, fineness modulus of the brick aggregate (BA) and stone aggregate (SA) was obtained 6.58 and 6.64 respectively. On the other hand, sand as Fine Aggregate (FA) was collected from the river in Sylhet district of Bangladesh called «Sylhet sand» ensuring no big particle or no clay were present into the present samples. Table 1 presents the properties of all types of aggregates that have been tested in the laboratory. Portland composite cement containing 70–79 % clinker, 21–25 % fly ash, slag, limestone, and 0–5 % gypsum (CEM II/B-M) and fresh drinking water have been used in this study. Deform mild steel bar of 8 mm, 10 mm, and 12 mm in diameter have been used in order to determine the shear strength from pull out test of concrete.

Table 1. Physical properties of fine and coarse aggregates.

Sample	Fineness Modulus, (FM)	Unit Weight (Kg/m^3)	% Voids	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (OD)	Apparent Specific Gravity (OD)	Absorption Capacity (%)	Abrasion test (%)
CA (Brick Chips)	6.58	1102	40	2.02	1.75	2.40	15.37	34
CA (Stone Chips)	6.64	1645	36.90	2.63	2.31	2.67	0.85	22
FA (Sand)	2.912	1664	32.78	2.54	2.48	2.66	2.65	-

2.2. Mix proportion:

The concrete mixes were divided into two groups: Brick aggregate concrete (BAC) and Stone aggregate concrete (SAC) as control case. In order to get the similar compressive strength of both BAC and SAC, a trial mix has been carried out with different water to cement (w/c) ratio as presented in Table 2. Sand to total aggregate volume ratio (s/a) was 0.42 and air volume in the mixes was considered 2 %. No chemical admixtures were used to the concrete during mixing. It has been found that the compressive strength of brick aggregate concrete (BAC1) having the w/c ratio of 0.38 is 16.70 MPa at 7 days. On the other hand, almost similar compressive strength has been found for stone aggregate concrete (SAC3) having the w/c of 0.5 is 17.19 MPa which is around 3 % more than that of BAC1. In the other case, compressive strength of BAC4 having the w/c ratio of 0.44 at 7 days is 20.96 MPa which is much closer to SAC4 with have been w/c ratio of 0.52. It is also about 3 % more than that of SAC4 (20.39 MPa). Therefore, both case selected for the final casting to determine the value of λ for BAC as shown in Table 3.

Table 2. Details of concrete mixing for Trial Casting.

Trial No.	Cases	Cement (Kg/m^3)	BA (Kg/m^3)	SA (Kg/m^3)	FA (Sylhet sand) (Kg/m^3)	Water (Kg/m^3)	Water to Cement ratio (w/c)	Compressive strength (MPa)
1.	BAC1	390	793.87	–	784.33	148.20	0.38	16.70
2.	BAC2	390	785.05	–	775.61	156.00	0.40	21.25
3.	BAC3	390	776.22	–	766.89	163.80	0.42	24.00
4.	BAC4	390	767.40	–	758.17	171.60	0.44	20.96
5.	BAC5	390	758.58	–	749.46	179.40	0.46	18.02
6.	SAC1	390	–	958.00	775.00	280.00	0.46	15.40
7.	SAC2	390	–	976.17	740.74	187.20	0.48	16.06
8.	SAC3	390	–	964.68	732.02	195.00	0.50	17.19
9.	SAC4	390	–	953.19	723.31	202.80	0.52	20.39
10.	SAC5	390	–	935.96	710.23	214.50	0.55	9.760

Table 3. Details of concrete mixing for final casting of concrete.

Final casting No.	Cases	Cement (Kg/m^3)	BA (Kg/m^3)	SA (Kg/m^3)	FA (Kg/m^3)	Weight of water (Kg/m^3)	Water to Cement (w/c)	Crushing strength (MPa)
1.	BAC1	390	793.87	–	784.33	148.20	0.38	16.70
2.	SAC3	390	–	964.68	732.02	195.00	0.50	17.19
3.	BAC4	390	767.40	–	758.17	171.60	0.44	20.96
4.	SAC4	390	–	953.19	723.31	202.80	0.52	20.39

2.2.1 Sample Preparation, mixing, casting, and curing of concrete:

In the present study, concrete cylinder with a diameter of 100 mm and height of 200 mm is made as specimen to determine the compressive and splitting tensile strength of concrete. The same dimension is also used for the specimens to determine the shear strength from pull-out test with the full (i.e., 200 mm) and half (i.e., 100 mm) height of the specimen as development length. Automatic mixture machine having the speed 30–35 revolutions per minute is used for mixing the concrete homogeneously. Before pouring the concrete into the cylinder, deformed steel bar was placed at the center of the cylinder as shown in Figure 2a. In this study, slump test was conducted to measure the workability concrete as shown in Figure 2b. Slump cone having a dimension of 300 mm in height, 100 mm diameter in top, and 20 mm diameter in bottom is filled by 3 layers with 25 tamping on each layer following ASTM C143 [16]. Concrete specimens have been properly compacted using vibrating hammer following the specification of ASTMC 1435-99 [17]. In order to avoid the void in concrete, all concrete specimens are compacted carefully in the laboratory and after compaction of these specimens; scaling and hammering have been made (see Figure 2c). Wet water curing method is applied to ensure adequate moisture and temperature as required specification of ASTM C192/C192M-02 [18] as shown in Figure 2d.

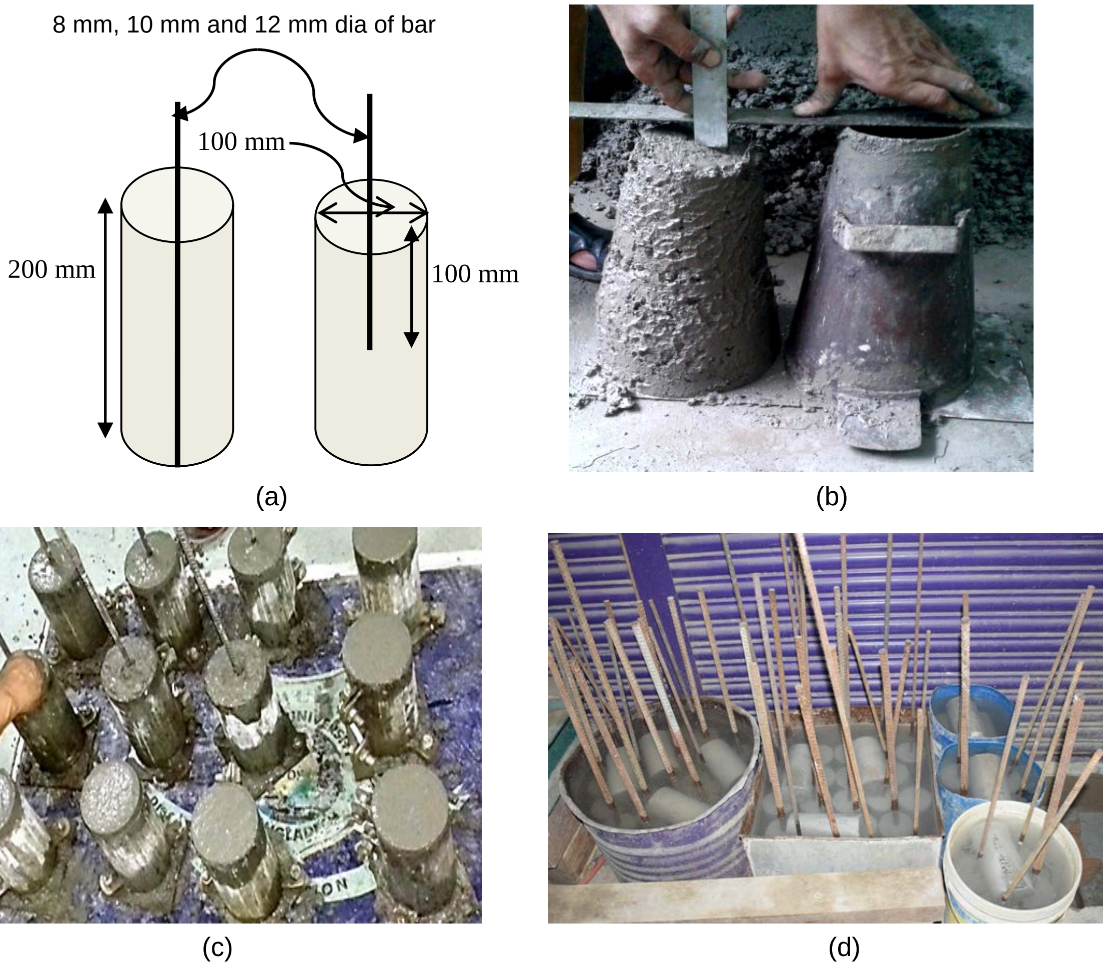


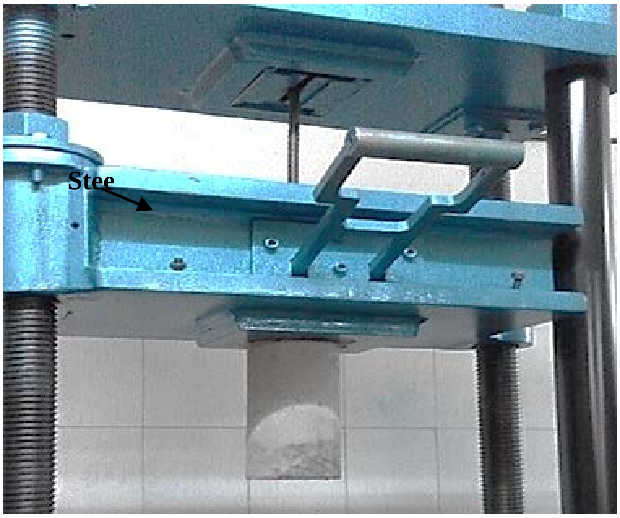
Figure 2. Preparation of concrete specimen: (a) dimension of the sample; (b) workability test by slump cone; (c) concrete casting; (d) concrete under water for curing.

2.3. Experimental plan

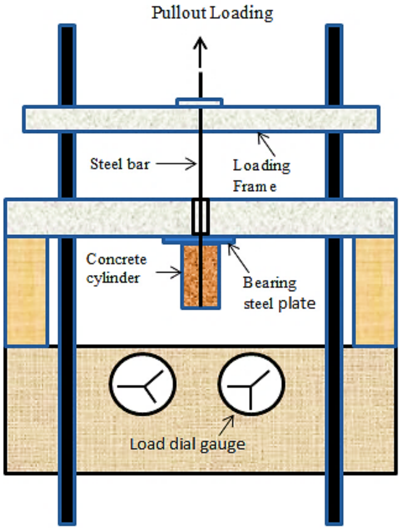
2.3.1 Test setup

An experimental study has been conducted to evaluate compressive strength, splitting tensile strength, and bond strength for determining aggregate concrete factor (λ) of brick and stone aggregate concrete. All tests were conducted at the age of 28 days. The compressive strength of concrete, splitting tensile strength, and bond strength as shear strength by pull-out test is determined by using Universal

Testing Machine (UTM) which has maximum capacity of 800 kN. In the present study, compressive strength is performed as per ASTM C39M-03 [19], indirect tensile strength test is carried out to determine the splitting tensile strength of plain concrete cylinder as per ASTM C496M-04 [20].After crushing the concrete cylinders, the failure surfaces of concrete have been observed carefully. Shear strength by pull-out test covers the determination of the strength of hardened concrete by measuring the force required to pull embedded mild steel inserted and the attached concrete fragment from a concrete test specimen (ASTM C 900-15 [21]. An embedded deformed steel bar is attached into a concrete cylinder is used for determining shear strength from pull out test is as shown in Figure 3a. and Figure 3b. A special arrangement is arranged with the UTM. Here, a cramp is being used to embay the upper portion of the steel bar in order to avoid slipping. A hollow steel ram is also used at the lower portion of the steel bar which is embedded into the concrete cylinder.



(a)



(b)

Figure 3. Laboratory test setup: (a) compressive strength test, (b) indirect (splitting) tensile strength test, (c) original image of shear strength by pull-out test, (d) schematic diagram of pull-out test.

3. Results and Discussion

In the present study, shear strength (i.e., bond strength) with different diameter and length of deformed mild steel has been investigated. In order to establish the aggregate concrete factor for development length equation of stone and burnt clay brick aggregate, mechanical properties of concrete have been carried out. Indeed, it is quite important to have same mechanical properties such as compressive and tensile strength as well as bond strength in order to establish aggregate concrete factor (λ) for both brick and stone aggregate concrete.

3.1. Hardened concrete properties

3.1.1 Compressive strength

Table 4 presents the compressive strength of concrete measured at 28 days. It can be seen that the compressive strength of concrete made with burnt clay brick and stone aggregates are very close to each other. For example, the compressive strength of concrete made with brick aggregate (BAC1) and stone aggregates (SAC3) are, respectively, 33 MPa and 30.49 MPa which is around 7 % higher for BAC1 than SAC3. While a little difference (5 % higher for brick aggregate) in value is found for compressive strength of BAC4 and SAC4. Though both two different mixes for two different concretes are not comparable due to same amount of cement is used, this behavior could be due to higher water to cement ratio of stone aggregate concrete (0.5 and 0.52) than the brick aggregate concretes (0.38 and 0.44). Indeed, higher amount of water causes higher amount of void in the concrete, resulting in weaker Interfacial Transition Zone (ITZ) around the stone aggregates than brick aggregates. ITZ is the weakest path for failure of concrete during mechanical loading.

Table 4. Compressive and splitting tensile strength of concrete at 28 days.

Sl No.	Name of sample	Compressive strength (MPa)	Splitting tensile strength (MPa)
1.	BAC1	33.00	3.10
2.	SAC3	30.49	2.91
3.	BAC4	36.02	3.05
4.	SAC4	34.13	3.15

3.1.2 Tensile strength

It can be seen from the experimental results that tensile strength of BAC1 and SAC3 are 3.10 MPa and 2.91 MPa accordingly which is about 6 % lower than that of BAC1 as presented in table 4. In another case, the tensile strength of BAC4 and SAC4 are 3.05 MPa and 3.15 MPa respectively. Around only 3 % discrimination in tensile strength is observed for both BAC4 and SAC4. Since the differences of tensile strength of concrete made with brick and stone aggregate are quite low (3 to 6 % in all cases), hence it is believed that the value of λ will not be affected significantly. A relationship between tensile and compressive strength of concrete is being proposed and shown in Figure 4. Depending on the experimental data, the following equation (Eq. 3) is submitted which could be valid for stone and burnt clay brick aggregate concrete made in Bangladesh.

$$f_t = 0.56\sqrt{f_c'}, \tag{3}$$

where f_c' is compressive strength of concrete in MPa and f_t is tensile strength of concrete in MPa.

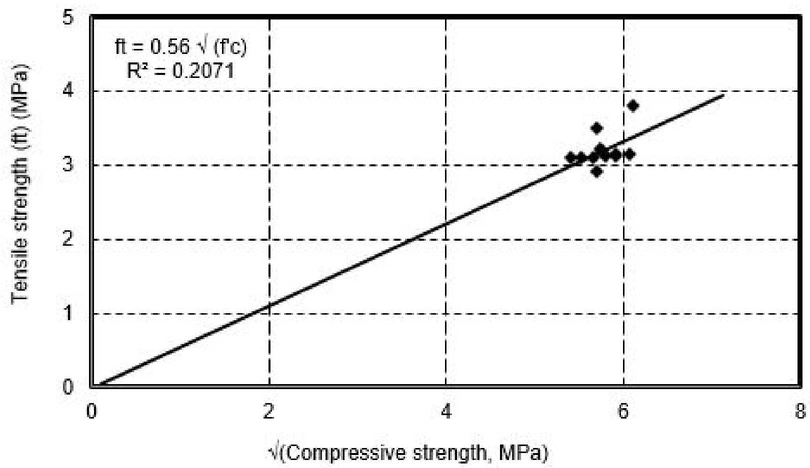


Figure 4. Relationship between tensile and compressive strength at 28 days.

3.1.3. Bond strength

In order to deeper understanding the effect of aggregate types on bond strength of concrete, the pull-out tests have been conducted at 28 days of curing. Totally, four types of concrete made with first class burnt clay brick and stone aggregate with different water to cement ratios and three different diameters of steel bars (8 mm, 10 mm, and 12 mm) have been investigated in this research project. Additionally, two different embedded lengths of 100 mm and 200 mm have been considered to investigate the bond strength behavior by pull-out test of all concretes. As concern the effect of rebar diameter, the experimental results have shown that bond strength of 10 mm diameter rebar exhibited higher strength as compared to the diameter of 8 mm and 12 mm for both aggregates and both embedded length of 100 and 200 mm as shown in Figures 5–8. For example, the average bond strength of concrete (BAC4) with rebar diameter of 8 mm, 10 mm, and 12 mm are, respectively, 7.97 MPa, 13.68 MPa (about 42 % higher than 8 mm), and 10.87 MPa for brick aggregate, while 8.76 MPa, 16.87 MPa (about 48 % higher than 8 mm), and 12.11 MPa for stone aggregate with embedded length of 100 mm. Almost similar behavior has been observed for the other concretes with embedded length of 100 mm and 200 mm. Based on the experimental results, higher surface area provides higher mechanical and physical adhesion between the concrete and rebar surface resulting in higher bond strength. Probably, because of the higher surface area, the propagation of cracks and microcracks are prevented in the plane parallel to the longitudinal axis of the rebar, thus increasing the bond force for 10 mm than 8 mm at which the bond failure occurs. On the other hand, relatively lower bond strength of 12 mm diameter deformed rebar is possibly due to size and shapes of grooves are different from 8 mm as well as 10 mm diameter deformed bar that is available in Bangladesh.

As regards the effect of embedment length, as the embedment length increased, the average bond strength increased. Except for concrete BAC4 with a diameter of 10 mm and embedded length of 100 mm rebar, the average bond strength of 200 mm embedded length rebar is higher as compared to 100 mm embedded length for all concretes and all diameters, see Figures 5–8. This behavior could be explained by the mechanical interlocking of rebar ribs and concrete keys. Embedded length of 200 mm is double than the length of 100 mm, theoretically, it can believe that the number of ribs will be doubled for the embedded length for 200 mm than 100 mm, which provide higher strength for 200 mm than 100 mm. Moreover, this behavior also could be due to the increased bonding area between the rebar and concrete parallel to the longitudinal axis of the rebar.

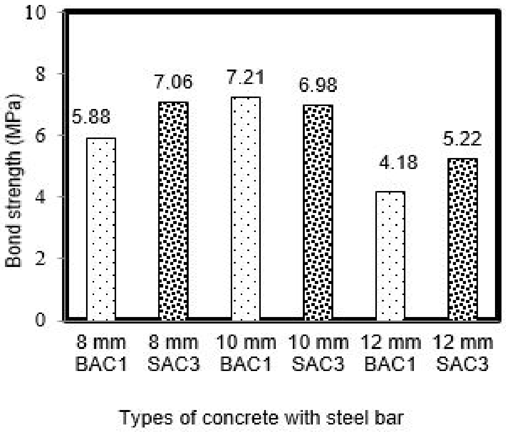


Figure 5. Bond strength of concrete with different diameters with 100 mm embedded length.

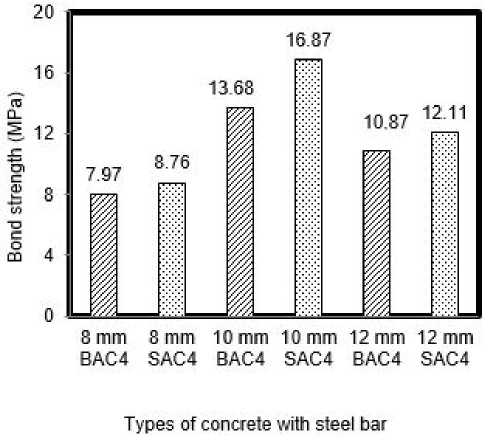


Figure 6. Bond strength of concrete with different diameters with 100 mm embedded length.

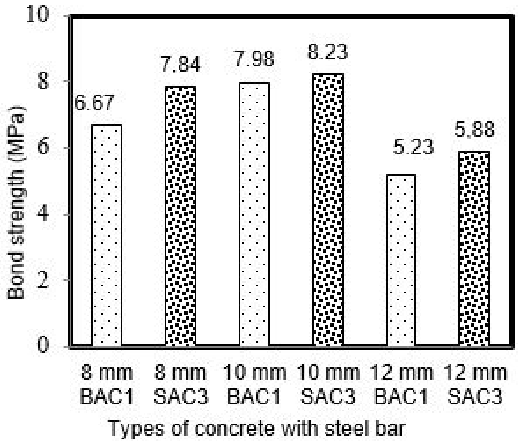


Figure 7. Bond strength of concrete with different diameters with 200 mm embedded length.

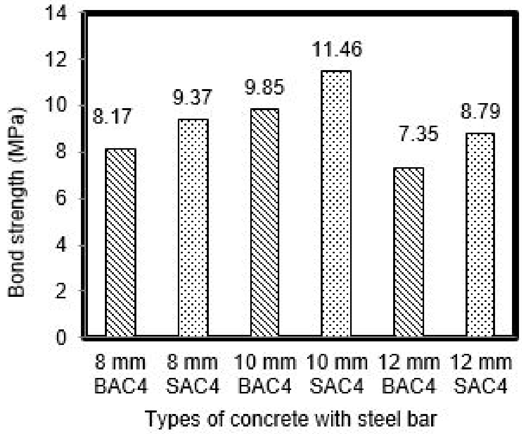


Figure 8. Bond strength of concrete with different diameters with 200 mm embedded length.

However, in most of the cases, it has been found that the bond strength of concretes made with stone aggregates are higher than the concretes made with first class burnt clay brick aggregates as shown in Figures 5–8. This behavior could be due to better interlock/stronger Interfacial Transition Zone (ITZ) around the rebar and stone aggregates than brick aggregates. This behavior also could be explained by the higher abrasion resistance of stone aggregate (abrasion = 22 %) than the brick aggregate (abrasion = 34 %) (Table 1). Indeed, the higher the abrasion resistance, the higher the strength of concrete, resulting in higher bond strength. Also, the percentage of void in stone aggregate (36.9 %) was lower than the brick aggregate (40 %) (Table 1). This higher percentage of void in brick aggregate caused higher porosity and higher permeability, meaning that weaker ITZ and then lower bond strength.

In order to deeper understanding the effect of aggregate type on bond strength of concrete, the relation between bond strength of burnt clay brick aggregate and stone aggregate is plotted and shown in Figure 9. Though almost a linear relation has been observed, it seems that the values of stone aggregate concrete are slightly above the line of equality than that of brick aggregate concrete.

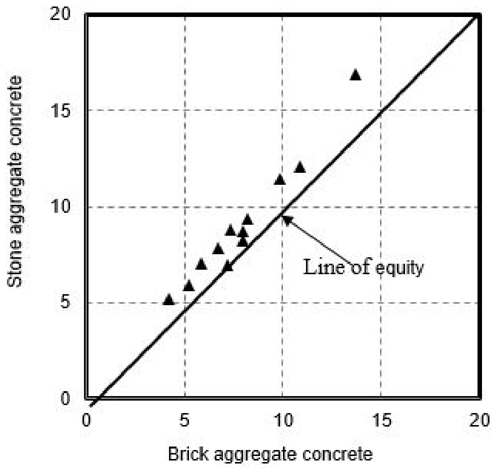


Figure 9. Bond strength of concrete made with brick and stone aggregates.

3.1.4. Comparison of experimental bond strength with different mathematical model

However, Bond strength of concrete by pull-out tests were conducted by several researchers which can be found in literature and attempted to formulate the equation. Orangun et al., (1977) [22] carried out the tests and proposed the following Eq. 4.

$$U = 0.083045\sqrt{f_c'}\left[1.2 + 3\frac{c}{d_b} + 50\frac{d_b}{L_d}\right], \tag{4}$$

where c is minimum concrete cover,

f'_c is compressive strength in MPa,

d_b is diameter of rebar,

L_d is development length.

In order to investigate the bond strength of concrete, Australian standard, (1994) [23] recommends the following Eq. 5.

$$U = 0.265\sqrt{f_c'}\left(\frac{c}{d_b} + 0.5\right), \tag{5}$$

where d_b is diameter of rebar,

c is minimum concrete cover,

f'_c is compressive strength in MPa

M.N.S. Hadi (2008) [24] conducted research on bond strength of concrete with high strength reinforcing steel and proposed the following Eq. 6.

$$U = 0.083045\sqrt{f_c'}\left[22.8 - 0208\frac{c}{d_b} - 38.212\frac{d_b}{L_d}\right], \tag{6}$$

where c is minimum concrete cover,

f'_c is compressive strength in MPa,

d_b is diameter of rebar,

L_d is development length.

However, according to Arthur et al., (2003) [1], the measured uniform bond strength can be expressed as follows

$$U = P_{\max}/\pi d_b L_d. \tag{7}$$

where $P_{\max}$ is maximum applied load,

d_b is diameter of rebar,

L_d is development length.

In order to deeper analysis of the experimental results and to compare with proposed analytical equations found in literature, the bond strength of concretes were calculated based on the equation discussed above and compared with experimental results of concrete made with brick aggregate as shown in Figures 10–13. In Figures 10–13, different rebar diameter and embedded length were considered. In most of the cases, the bond strength of the experimental results are in good agreement, especially for the rebar diameter of 10 mm than 8 mm and 12 mm. This behavior could be due to different compressive and tensile strength of the concrete, aggregate and cement types, grade of rebar and so on considered in the proposed equations found in the literature than the experimental one.

3.1.5. Lightweight aggregate concrete factor (λ) by the equation of ACI-318 (2001)

The determination of the development length of the mild steel in tension comprises evaluating an expression that includes a modification factor that either increases or decreases the development length. That factor λ is shown in the Eq. 2 according to the specification of ACI-318 (2001), section 12.2.4 and the results obtained from that equation which is shown in Figure 14. According to the ACI-318 (2001), the λ should not less than 1.0. Except for concrete BAC4, other three concretes λ is 1.0 which is in good agreement with the λ of normal weight concrete as proposed in ACI-318 (2001).

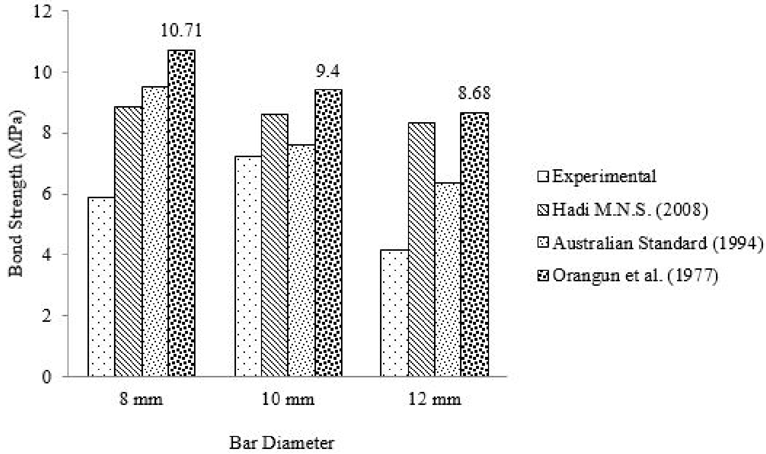


Figure 10. Rebar diameter with 100 mm embedded length of BAC1.

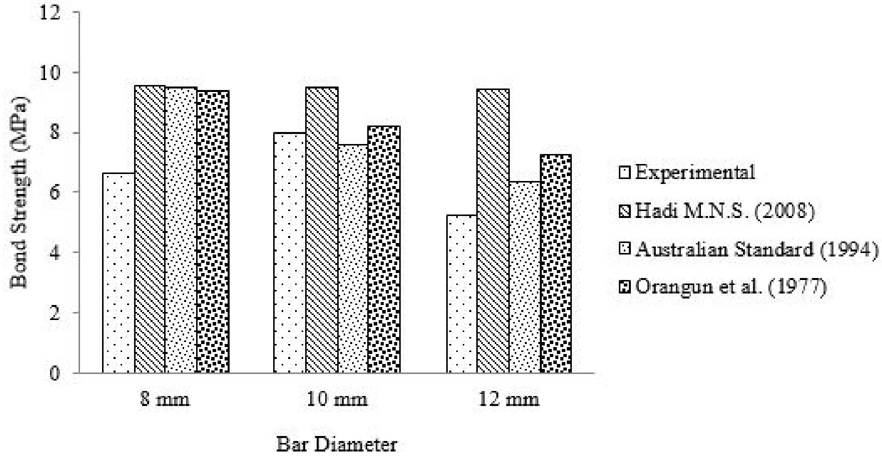


Figure 11. Rebar diameter with 200 mm embedded length of BAC1.

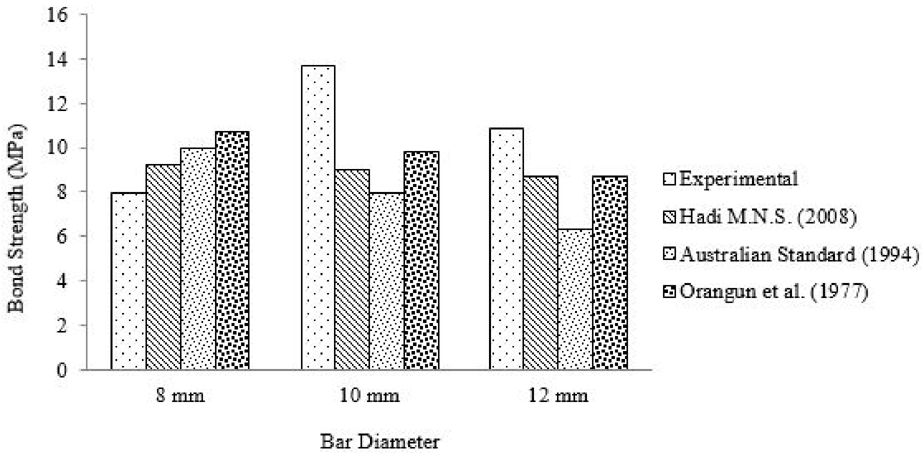


Figure 12. Rebar diameter with 100 mm embedded length of BAC4.

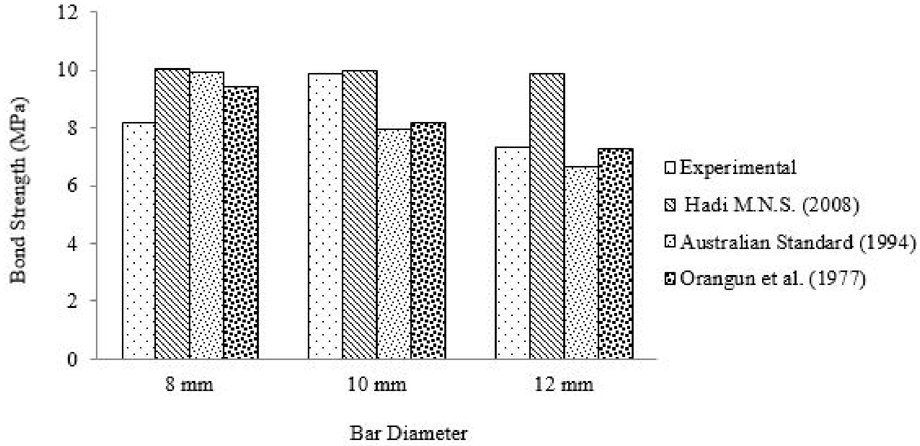


Figure 13. Rebar diameter with 200 mm embedded length of BAC4.

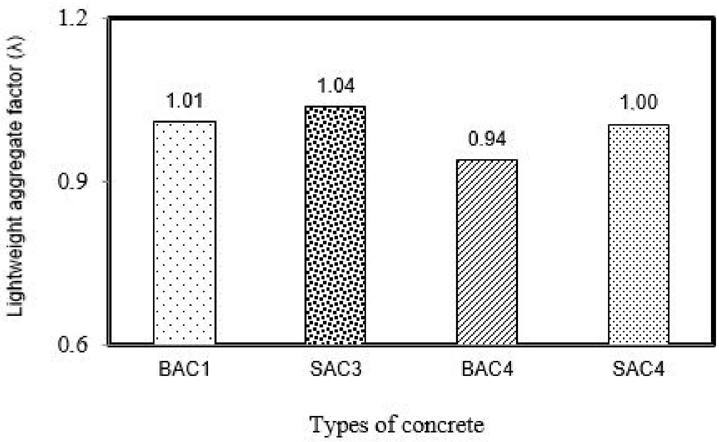


Figure 14. Lightweight aggregate concrete factor (λ_{eq}) for different w/c ratios determined from the equation of ACI-318 (2001).

3.1.6. Proposed analytical equation for lightweight brick aggregate concrete factor (λ)

According to ACI-318 (2001), section 12.2.4, the value of λ for normal-weight aggregate (i.e., stone aggregate) concrete is 1 when it is to be used for calculating development length of deformed rebars. In the present study, the value of λ for lightweight aggregate (i.e., brick aggregate which is commonly used in Bangladesh) concrete has been determined considering stone aggregate as the base line. Here, the value of bond strength of stone aggregate concrete has been considered as 100 %. Hence, the value of λ can be determined from the ratio of brick aggregate and stone aggregate concrete obtained from the experimental results. The lightweight aggregate factor (λ) of concrete made with brick aggregate (BAC1 and BAC4) with different rebar diameter and embedded length are presented in Figure 15. For the concrete type BAC1 with embedded length 100 mm and 200 mm, the value of λ is ranges 3 % to 5 % for all diameters of rebar as shown in Figure 15 (a). Similar results are also found for the concrete type BAC4 as shown in Figure 15 (b). Here, the value of λ ranges from 0.8 to 1.02 which quite satisfactory according to the ACI-318 (2001). From this research study, the average λ equal to 0.88 has been found for Bangladeshi first class burnt clay brick aggregate.

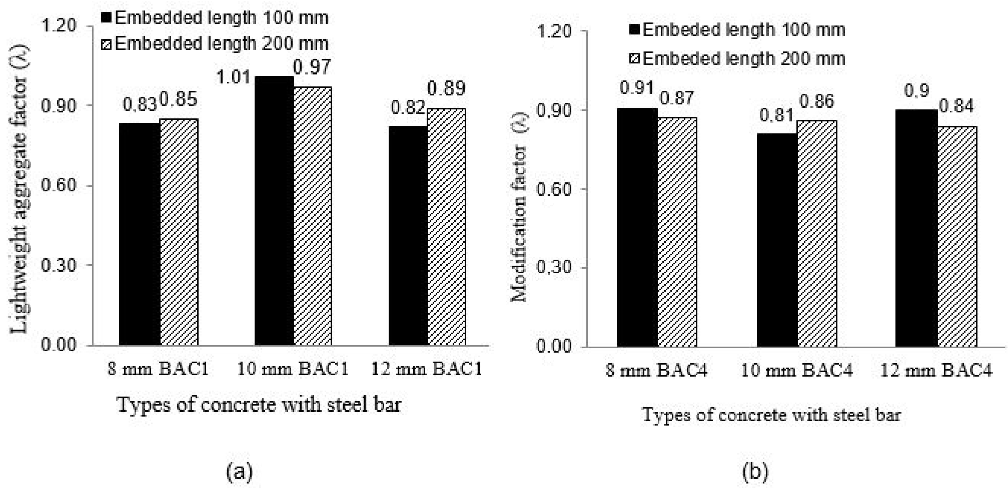


Figure 15. Aggregate concrete factor (λ) from experimental bond strength test: (a) BAC1 and (b) BAC4 with embedded length of 100 mm and 200 mm.

However, the relationship of lightweight aggregate concrete factor (λ) obtained from the equation of ACI-318 (2001), section 12.2.4 and experimental result has been developed and shown in Figure 16. The relationship between experimental results and equation from ACI-318 (2001) which is Eq. 8 is being also proposed.

$$\lambda_{eq} = 1.15x\, \lambda_{ex}\,. \tag{8}$$

where λ_{eq} is aggregate concrete factor obtained from equation of ACI-318 (2001), section 12.2.4;

λ_{ex} is brick aggregate concrete factor obtained from experimental results.

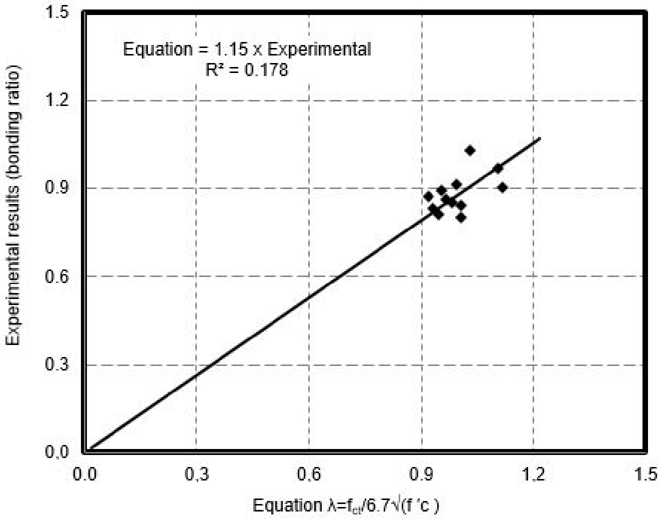
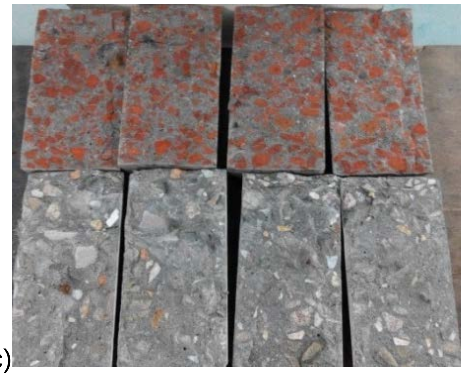
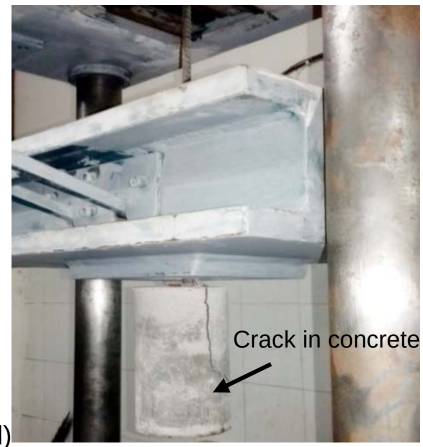


Figure 16. Relationship of lightweight aggregate concrete factor (λ) obtained from equation according to ACI-318 (2001) and experimental results.

3.1.7. Fracture surface:

Figure 17, shows the failure modes of the specimens by compressive strength, splitting tensile strength, and bond strength tests. As expected, combined failure (both mortar and aggregate failed) was observed instead of bond failure for both compressive and tensile strength test of concrete made with both stone and burnt clay brick aggregates. This behavior could be due to better interlock/bond between mortar and aggregate. The pull-out test specimens were failed in pull-out failure and splitting failure for concrete specimens made with stone and brick aggregates. The pullout failure mode occurred when the concrete provided adequate confinement, thus preventing a splitting failure of the test specimen. This was occurred by inducing cracks on the top loaded face of the specimens. While splitting mode of failure was occurred by splitting the specimens. This behavior could be explained by the initiation of a crack along the loading axis (parallel to the longitudinal axis of the rebar, see Figure 17 d.) and then reach failure by splitting the specimens. This behavior also could be due to brittleness of the concrete specimens since fibers did not use in any of the concrete mixes.

a)  b)  c) 

d) 

e) 

Figure 17. Fractured surface of specimen: (a) compressive strength; (b) & (c) splitting tensile strength; (d) & (e) pull-out and splitting failure of bond strength test.

4. Conclusions

This paper presents an experimental program to investigate the lightweight aggregate (i.e., brick aggregate) concrete factor (λ). The pull-out tests were carried out on four different types of concrete, three different types of rebar diameter, and two different types of embedded lengths. Additionally, different proposed equations for calculating the bond strength found in literation has been investigated and compared with the experimental results. While λ has been calculated according to the ACI-318 (2001), section 12.2.4 and proposed an equation for brick aggregate. The main findings regarding the bond strength and λ can be summarized as follows:

1. The bond strength of 10 mm diameter rebar is higher as compared to the diameter of 8 mm and 12 mm for both aggregates and both embedded length of 100 and 200 mm for all concretes, this is probably due to higher surface area of rebar of 10 mm than 8 mm. But relatively lower bond strength of 12 mm diameter deformed rebar is possibly due to size and shapes of grooves are different from 8 mm as well as 10 mm diameter deformed bar.

2. The embedded length of 200 mm showed higher bond strength than the embedded length of 100 mm. This is probably due to better mechanical interlocking of rebar ribs and concrete keys as well as higher ribs per unit length which can play an important role on the bond strength of concrete.

3. Based on the experimental results, the optimum diameter for both embedded length of concretes bond strength is 10 mm that gives maximum bond strength for all cases.

4. From this research study, it has been found that the average λ equal to 0.88 for Bangladeshi burnt clay brick aggregate which can be used for modeling and the development of appropriate design guidelines.

5. Based on the test results a new equation is proposed for the lightweight aggregate (i.e., brick aggregate) concrete factor (λ) which is commonly used as coarse aggregate in Bangladesh.

The proposed aggregate (i.e., brick aggregate) concrete factor (λ) value (0.88) and the equation for brick aggregate are promising that can be used to determine λ or use the proposed value in the design which deals with concrete made with brick aggregate. Nevertheless, further tests need to be carried out by taking into account different concrete grades/strength, rebar geometries (e.g., diameter and embedded length), and specimen type and dimensions to validation and calibration of the λ value and the proposed equation.

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