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Bond properties of reinforcing bars embedded in brick aggregate concrete

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Abstract

The composite behaviour of reinforced concrete has always been an essential aspect of structural engineering research. The transfer of bond stress in concrete surrounding reinforcing steel is very important phenomena. By evaluating cylindrical BAC specimens, this study evaluates the bond behaviour between reinforcing bars and brick aggregate concrete (BAC). Direct pull-out experiments have been performed to evaluate the effect of numerous characteristics, including bar diameter, bond length, concrete confinement, embedment length, and concrete compressive strength. A review of the bond characteristics of reinforcing bars implanted in BAC as well as in SAC has been made. To examine the effect of the factors on bond strength such as concrete compressive strength, bar diameter, concrete cover, c/d_b ratio, reinforcing bar development length are all elements that affect bond characteristics. The bond strength between bars and BAC differs from that of reinforcing bars embedded in SAC due to the lower modulus of elasticity, larger absorption capacity, and lower unit weight of brick aggregate, and it has been demonstrated that bond strength in BAC is lower than in SAC. Since much of the work has been done on SAC, descriptive equations have been utilized to forecast the bond strength of SAC in some of the existing design provisions, which are primarily for unconfined concrete or concrete that is not confined by transverse reinforcements. The bond strength of BAC is predicted using a researcher-recommended equation and compared to the experimental bond strength in BAC. This study's conclusion is based on test results on brick aggregates and pull-out test on BAC. Based on the extensive experimental outcome, it is found that the different parameters including bar diameter, types of bars, compressive strength, embedment length, confinement, aggregate properties and concrete cover have influence on bond strength.

Keywords: Concrete, brick aggregate, compressive strength, reinforcement, bond strength, steel bars.

1. Introduction

Concrete is the prime component and most widely utilized building material in the world's construction sector. Concrete is made up mostly of gravel, cement, and water. The aggregate is often made up of coarse gravel or crushed rocks which include limestone or granite, as well as fine aggregate like sand. The usage of aggregate raises the tensile strength of concrete over that of cement, which is otherwise fragile. As a result, aggregate, particularly coarse aggregate, plays a vital role in the strength and durability of concrete.

Crushed burned clay bricks are often utilized as a cost - effective alternative to coarse aggregate in the making of concrete in countries such as Bangladesh and portions of India where natural stone is rare and hence unaffordable. Concrete made from brick aggregate is extensively utilized in the construction of up to six-story structures, stiff pavements, and short and medium span bridges and culverts in this region.

Despite the widespread usage of brick aggregate concrete in these areas and the apparent excellent performance of the structures that have previously been constructed, no systematic examination of its qualities and behavior has been done and adequately recorded. Current designs for brick aggregate concretes are based on subjective judgment rather than strong experimental data. Practical experience has shown that the greatest range of compressive strength of concretes built using brick aggregate but without the use of admixtures is about 3000 psi. Higher strength concrete (f'c much larger than 3000psi) can, on the other hand, be utilized to benefit in compression members such as columns and piles. The reduction in size will result in less dead load and, as a result, less overall load on the foundations system. Furthermore, higher strength concrete with a thick microstructure is anticipated to improve the structure's long-term endurance.

Typically, the ACI method (1994) or the BS (1985) technique are used to determine the concrete mix percentage. The coarse aggregate in both methods is crushed natural stone, and the unit weight of this concrete ranges from 140 to 152 pounds per cubic foot (pcf) (Nilson and Darwin, 1997), whereas brick aggregate concrete weighing between 125 and 130 pcf is considered medium weight concrete when compared to normal weight and light weight concrete (Akhteruzzaman and Hasnat, 1983). Furthermore, brick aggregate concrete has a distinct texture and surface roughness than stone aggregate concrete. As a result, the characteristics of brick aggregate concrete may differ somewhat from those of stone aggregate concrete. So, the current code standards for stone aggregate concrete could not be relevant to brick aggregate concrete. However, one of the most evident disadvantages of utilizing brick is that it is not ecologically friendly because it is made from topsoil, which is fast decreasing. Using topsoil from agricultural regions also lowers fertility.

To determine the best performance of reinforced concrete buildings, a strong link between the concrete and the reinforcement is essential. Steel, on the other hand, is strong in both tension and compression, and the combined action of the two resists external stresses. Effective load transmission is ensured by proper bonding between these two. It's also critical for determining fracture pattern and anchoring capacity, as well as splice length and bar development length (Kabir et. al, 2014). Frictional forces, adhesion, and mechanical interaction contribute to load transmission in deformed bars, whereas adhesion and mechanical interlock contribute to load transfer in plain bars. Chemical bonds form during the concrete curing process, resulting in adhesion. In the event of a deformed bar that is quickly drained, adhesion conveys a minimal amount of force. Adhesive failures can be identified by the beginning and development of fractures at the interaction. The mechanical anchoring progressively transmits force after an adhesive failure. Frictional forces are influenced by surface roughness, slip between concrete and bar, and forces perpendicular to the bar surface. The rib arrangement as well as the mechanical characteristics of reinforcing bars and concrete impact mechanical interface and friction (Hoque et al., 2020 and ACI 408, 2003). Mechanical interlock, however, contributes the most to bond strength among these three (Diab et al., 2014). Concrete compressive strength, tensile strength, fracture energy, modulus of elasticity, bar diameter, surface condition of bar, and mechanical characteristics of concrete are all elements that determine bond strength. The mechanical qualities of concrete are primarily determined by aggregate type and size, unit weight, density, and other variables (ACI 408, 2003). The bonding strength of BAC with reinforcing bar differs from that of SAC (Hoque et. al, 2020). The bond strength of BAC is reduced because of low modulus of elasticity, lower compressive strength, and increased absorption capacity. Lightweight concrete made with brick aggregates has a unit weight ranging from 1685 kg/m3 to 1760 kg/m3 (Ooja and Zayia, 2017). Furthermore, according to Neville, the unit weight fluctuates between 2200 and 2600 kg/m3 (Neville, 1995). Unit weight of BAC is found in between normal-weight concrete and lightweight concrete, so brick aggregate produces concrete of medium unit weight. When both have the same workability, crushed BAC has a compressive strength of around 61% that of natural aggregate concrete, and the compressive strength of BAC increases as the cement concentration and age increases. The flexural strength of crushed BAC is around 70% that of natural aggregate concrete, resulting in higher performance (Ooja and Zayia, 2017). Because low-density BAC was utilized, Khalaf claimed that BAC has a lower flexural strength than SAC. The tensile strength of BAC is proven to be greater when first quality bricks are utilized in various studies (Khalaf, 2006).

Extensive research has been done on the bond-slip behavior between reinforcing bars and concrete over the last several decades, and most of the formulas provided by Darwin et al., Zou et al., Chapman et al., as well as code provisions such as ACI 318, AS 3600, CEB FIP, ACI 408, are suitable to present the bond-slip behavior for SAC. Because BAC is now extensively utilized as a substitute for SAC in many countries, it is critical to understand bond behavior and the elements that determine bond strength in BAC in order to assure good performance. Using the SAC code requirements to determine BAC bond strength may result in an overestimation or underestimation of bond strength.

Concrete cracks when reinforcing bar is embedded in concrete and tested in tension pull out due to the failure of chemical adhesion formed during concrete hardening (Tastani and Pantazopoulou, 2009). To ensure the composite action of reinforced concrete sections, proper concrete-steel bonding is essential. Chemical adhesion and mechanical interlock play a role in plain bar, whereas surface roughness and closely spaced ribs play a role in deformed bar interlocking with bearing against the key formed between concrete and ribs (Kabir et al., 2014). Figure 1 depicts a typical bond stress slips relationship that demonstrates how plain bar pull-out behavior differs from deformed bar pull-out behavior. Splitting failure allows for just rebar deformation and is a common occurrence in low-strength concrete. Rebar embedded in high-strength concrete, on the other hand, experiences significant deformation and is prone to pull-out failure. In today's world, a large number of brick manufacturing industries have sprouted up around major cities. Because of the high cost and scarcity of stone aggregates, clay burned bricks are extremely popular. Bricks are frequently broken into coarse aggregate for concrete projects, either manually or with the help of a brick crusher. Construction also includes the use of stone chips and shingles.

According to a series of studies, the bond strength and bond-slip behavior of reinforcing bars inserted in SAC have been studied extensively over the last several decades (Diab et al., 2014, Mor, 1992, Robins et al., 1982, Harajli, 2004 and Chen et al., 2004), but these areas have not been explored for BAC. Furthermore, investigations have revealed considerable differences in tensile strength and elastic modulus between BAC and SAC. As a result, the bond strength and/or bond-slip behavior of reinforcing bars placed in the two types of concretes may change. In Bangladesh and many other nations, however, BAC is widely utilized to construct buildings and small-span bridges (Rashid, 2009). Separate formulae to forecast bond strength, development length, or anchorage length for reinforcing bars inserted in BAC are not recommended by design codes such as BNBC 2006. Based on the history, the goal of this study is to determine the behavior of Bond- slip of BAC experimentally.

This study will evaluate the bonding behavior between reinforcing bars of both types (deformed and plain) and brick aggregate concrete (BAC) by performing pullout tests on cylindrical BAC specimens. Several characteristics will be studied using direct pull-out tests, including bar diameter, bond length, concrete confinement, concrete over and concrete compressive strength.

2. Review on bond properties of concrete

Brick is widely used as a coarse aggregate in Bangladesh because of its availability and comparatively low-cost. Natural aggregates such as stones with high crushing strength and low absorptive properties are only present in small quantities in the Northern Sylhet and Dinajpur areas of Bangladesh. Due to a scarcity of this conventional natural aggregates crushed bricks are being used in construction of low to medium rise buildings, and small-span bridges etc. To evaluate the performance of reinforced concrete structures the bond between concrete and reinforcement is considered as one of the most important factors. Normally concrete is weak in tension and strong in compression on the other hand steel is strong in both tension and compression. The combined action of these two resists external loads. Proper bonding between these two ensures the effective load transfer.

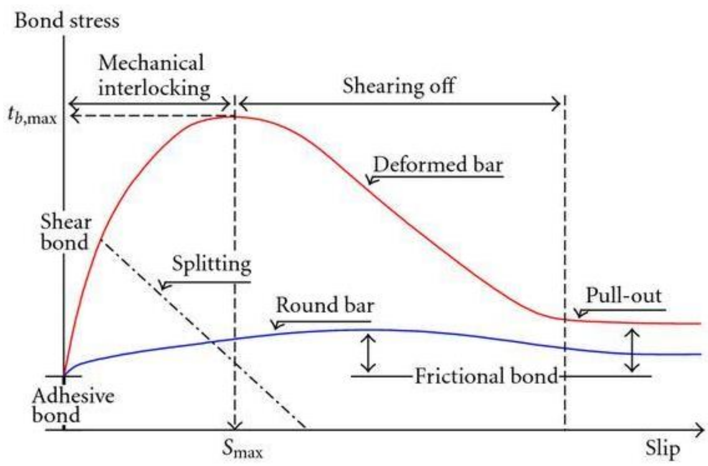

Fig. 1. Bond stress-slip relationship (Hong and Park, 2012).

So, the bond behavior between concrete and reinforcing bar is considered to be one of the most significant factors which is important for the characterization of crack pattern and anchorage capacity, splice length, and development length of the reinforcing bars (Hoque et al. 2020). For optimum performance, proper bonding between concrete and reinforcement is required to transfer load efficiently. In case of deformed bars, this load transfer occurs by frictional forces, adhesion, and mechanical interaction whereas for plain bars, adhesion and mechanical interlock contribute. During the concrete curing process chemical bonds form, for which adhesion occurs. Adhesion carries a negligible amount of force in case of deformed bar which is quickly drained. By initiation and cracks development at the interface adhesive failures can be characterized. Force is gradually transmitted following an adhesive failure by the mechanical anchorage. Roughness of the contact surface, forces transverse to the reinforcing bar surface, and relative slip between the bar and the surrounding concrete all contribute to frictional forces. Mechanical interaction and friction are influenced by the rib configuration as well as the mechanical properties of concrete and reinforcing bars. (Hoque et al. 2020, ACI 408, 2003]. However, among these three, mechanical interlock provides the greatest contribution to bond strength (Diab et al., 2014).

There are several factors that affect bond strength such as compressive strength, tensile strength, fracture energy, modulus of elasticity, bar diameter, surface condition of bar and mechanical properties of concrete. Mechanical properties of concrete mainly depend on aggregate type and size, unit weight, density and so on. Reinforcing bars embedded in BAC have different bond strength than reinforcing bars embedded in SAC (Hoque et al., 2020). Due to its low modulus of elasticity, lower compressive strength, and higher absorption capacity bond strength of BAC is lower. Mim et. al, 2021 reviewed the bond properties in reinforcing bars embedded in BAC.

Fig. 2. Curing by ponding.

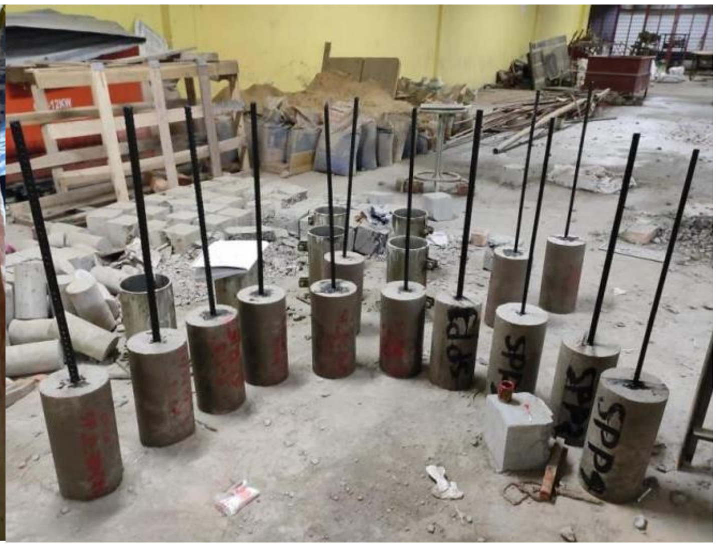

Fig. 3. Pullout specimens preparation.

Over the last several decades, extensive research works have been conducted on the bond-slip behavior between concrete and reinforcing bars and most of the formulas provided by Darwin et al. 2016, Zou and Darwin, 2000, Chapman and Shah, 1987 and code provisions such as ACI 318, CEB FIP, AS 3600, ACI 408 represent the bond-slip behavior for SAC but for BAC no such literature or code provisions can be found. Since BAC is now widely used in many countries as an alternative to SAC it is important to know about the bond behavior, the factors affecting bond strength in BAC to ensure satisfactory performance. Using those available code provisions of SAC to predict bond strength of BAC may result in overestimation or underestimation of bond strength.

Stone aggregate and brick aggregate: Concrete's core is made up of aggregates. Aggregate takes up roughly three-quarters of the volume of traditional concrete. It's necessary that a material that makes up so much of the volume provides key qualities to both the fresh and hardened product. Yet, the aggregate is not really inert in the sense that it can influence the performance of concrete due to physical, thermal, and, in certain cases, chemical quality (Neville, 1995). The grading or particle size distribution of an aggregate supply is significant because it dictates the paste requirements for workable concrete. Because the amount of paste required is determined by the aggregate grade, it is preferable economically by decreasing the quantity of paste used; however, the paste should be consistent, easily operated, compacted, and completed, and give the required strength and longevity (Mindess, 2003). Aggregate grading and fine content have an impact on the water/cement ratio and workability, which can affect compaction; hence these aggregate qualities have an indirect impact on concrete strength (Hewlett, 1998). The fine aggregate's pattern and surface affected just workability, while the coarse aggregate's properties may also affect the mechanical parameters of concrete through influencing the mechanical bond (Mindess, 2003). So, types of coarse aggregate have the major impact on concrete strength. Two most commonly used coarse aggregate are stone and brick aggregate concrete. Most of the research conducted on SAC and BAC has shown that SAC has more bond strength than BAC provided that all the material proportioning is same (Rahman et. al, 2019).

3. Materials used and experimental data

3.1 Materials used

- Cement: Portland cement is the basic component of concrete. Cement refers to all adhesive compounds but in more specifically it refers to the binding materials used in construction.
- Water: Water is one of the key ingredients of concrete for hydration reaction, workability, strength etc. Throughout the mixing process, ordinary tap water was used as the mixing water.
- Aggregate: Aggregates are inert granular materials that are mixed with water and cement to make concrete. There are various types of coarse aggregates like stone chips, brick aggregates etc. For this study brick aggregates were used as coarse aggregate.

Fine Aggregate as Sand: 'Sylhet sand' 'which is brown in color was used as the fine aggregate. The sieve analysis of sand was carried out by ASTM C136 and Fineness modulus (F.M) of sand was found 3.06.

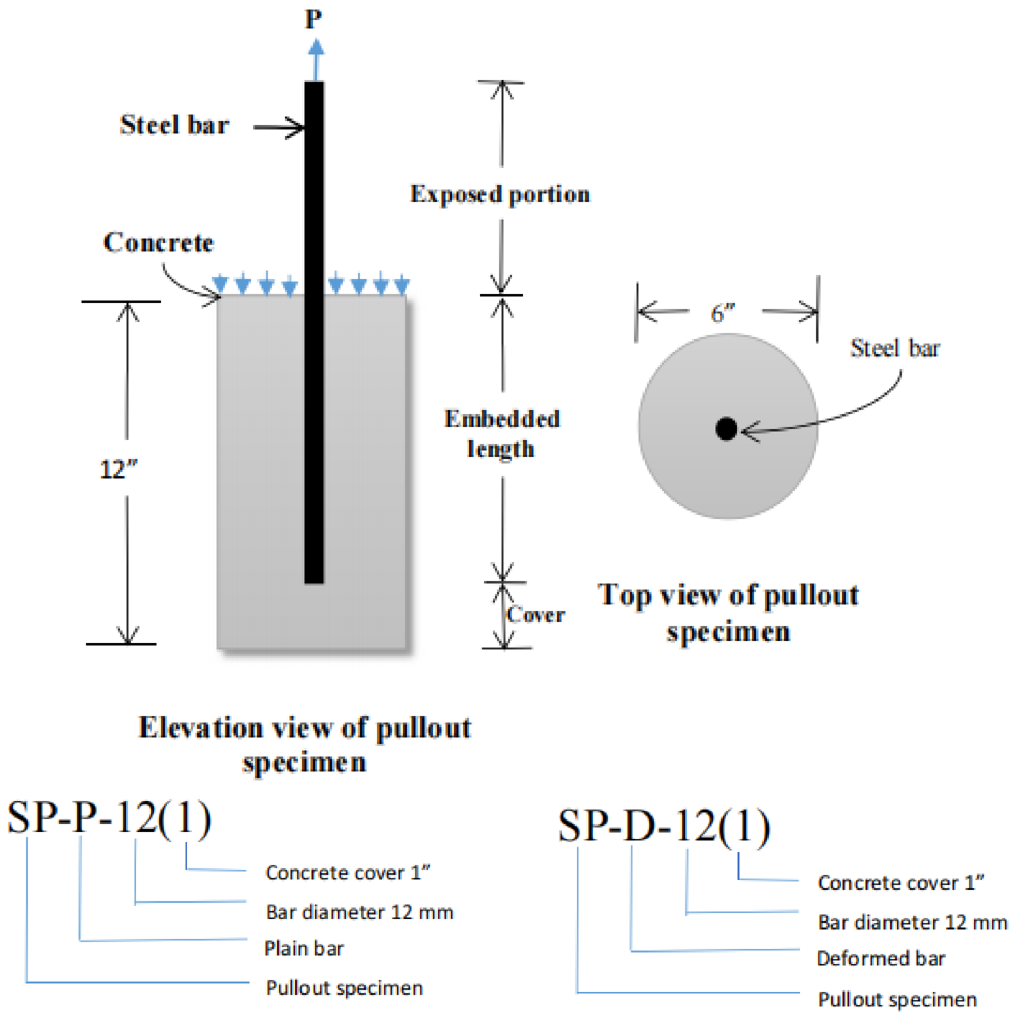

Fig. 4. Pullout specimen details and concrete cylinder specimen designation.

Coarse Aggregate as Brick Aggregate: For typical construction activities, the FM of coarse aggregate (khoa) varies in between 4-5. The brick aggregate used here was produced by breaking down whole new bricks using a hammer.

- Reinforcement: Pullout specimens were prepared using two different types of bars of different diameter such as 12mm, 16mm and 20mm bar. Steel rebars of yield strength 60ksi are used to analyze the effect of bar diameter, bar geometry on bond behavior between steel and concrete. Two types are (i) Deformed Bar and (ii) Plain Bar.
- Coating Material: To prevent corrosion and contact with curing water exposed parts of the bars were painted before curing.
- Curing Chemicals: The specimens were immersed in curing water outside the laboratory until testing. Saturated lime water was used for curing. Figure 2 shows the curing of specimens.

3.2 Experimental data

In this study, physical properties of the aggregates have been determined through ASTM standard.

3.2.1 Physical properties

The essential physical properties of aggregate like shape and texture of aggregate, specific gravity, bulk density, unit weight, and absorption capacity affect bond strength. The basic physical properties are given in the following Table 1.

Table 1
Basic physical properties of brick aggregate

Physical property	Experimental Value	Typical Value
	Brick Aggregate	Stone Aggregate
Shape and texture	Angular with rough surface	Well rounded, smooth to angular and rough
Bulk Specific gravity (SSD)	1.90	2.66
Bulk Specific gravity (OD)	1.55	2.64
Unit weight (Kg/m^3)	1150	1493
Absorption (%)	22.9	0.51

3.2.2 Concrete properties

For a mix ratio of 1:2:4 and water-cement ratio of 0.5, concrete properties are given below:

Table 2
Basic concrete properties of brick aggregate concrete

Concrete property	Experimental Value	Remarks
Slump Value	0-1inch (0-25mm)	Very Low
Compressive Strength (Average)	9.59 MPa	At 21 days
	11.26 MPa	At 28 days

4. Test results and discussion

Figure 3 shows the pull-out specimen preparation. specimens' details. Eight pull out test specimens were made to fulfill the paper objective. Six specimens consisting three diameters (12mm, 16mm and 20mm) with 1", 1.3" and 1.6" cover for both smooth and deformed bar were tested. Additional two specimens consisting 12mm diameters with 2" and 3" cover for deformed bar were tested. Pull-out specimens' detail is shown in Figure 4. Test set up is shown in Figure 5.

Fig. 5. Test Setup.

On the UTM machine with a capacity of 1000kN, single pull-out test was performed. To eliminate eccentric load on the concrete and steel joint, the pull-out specimen was placed concentrically at the test base. Special care was taken to ensure that the vertical placement was correct. Pull out specimens were placed on the upper fixed arm of the testing machine shown in Figure 5. Bottom arm of the machine was movable, and the steel bar was gripped at bottom arm. As the machine was displacement controlled a fixed displacement rate of 1.5 mm per minute was applied.

The Bond force for Brick aggregate concrete pull-out specimen were predicted from the proposed equation by Hoque et al, 2020 as given below.

$$U/\sqrt{f'_c} = 0.525\ (\frac{c}{d_b})^{0.42}$$

Table 3 shows the comparison of tested results with the predicted results used with the equation proposed by Hoque et al, 2020.

Table 3
Test results compared with predicted bond strength

Specimen	Cover, c (mm)	Embedded Length, l (mm)	Compressive Strength f'_c (MPa)	Predicted bond strength, U (MPa)	Actual bond strength (MPa)
SP-P-12 (1")	25.4	274.6	11.26	2.4138	2.94
SP-P-16 (1.3")	33.02	266.98		2.3883	2.72
SP-P-20 (1.6")	40.64	259.36		2.3728	1.39
SP-D-12 (1")	25.4	274.6		2.4138	5.29
SP-D-16 (1.3")	33.02	266.98		2.3883	5.93
SP-D-20 (1.6")	40.64	259.36		2.3728	3.16
Cover Change					
SP-D-12 (2")	50.8	249.2	11.26	3.3533	6.08
SP-D-12 (3")	76.2	223.8		3.9759	5.59

Results are reasonably well for smooth bar but for deformed bar some variations are observed.

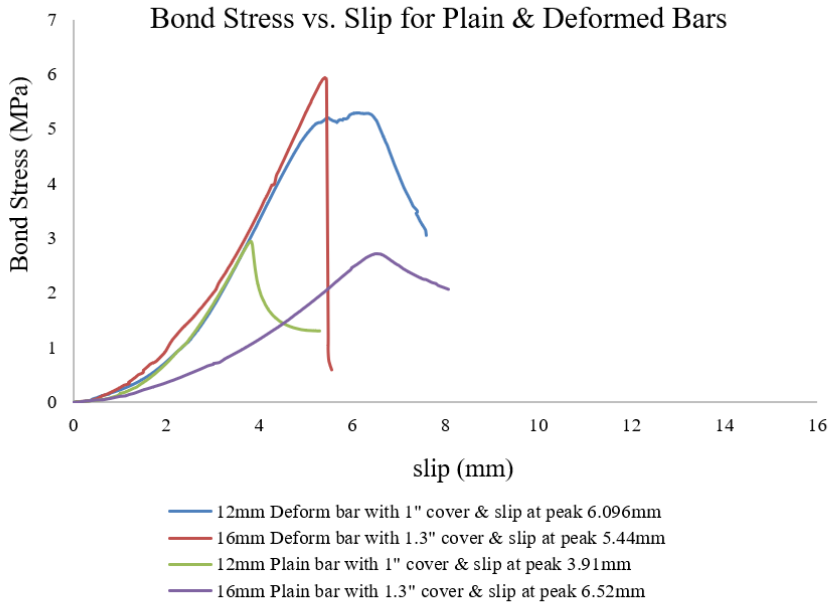

Fig. 6. Relation of bond stress with slip for deformed and smooth bar.

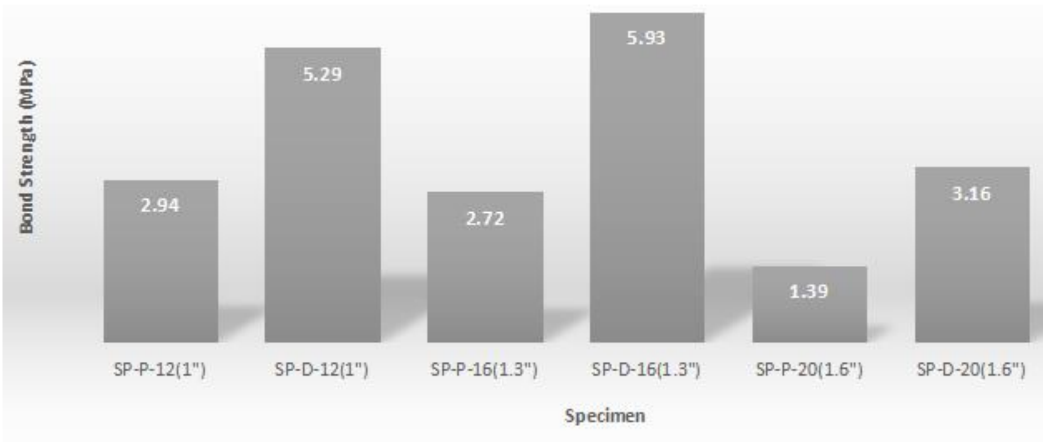

Fig. 7. Bond strength for plain and deformed bar.

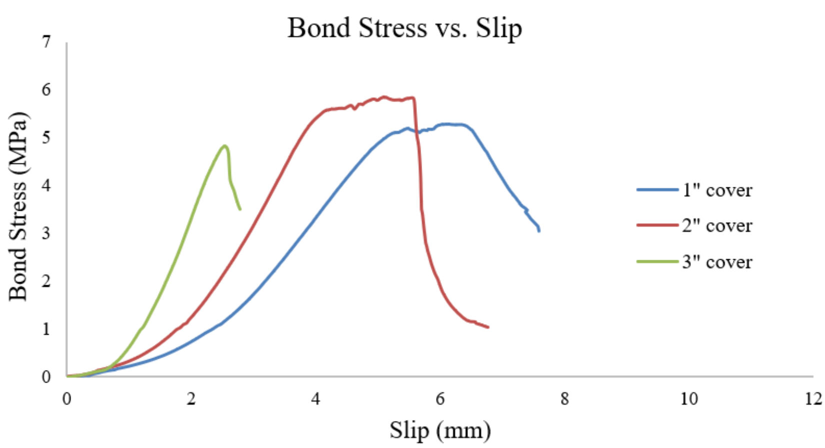

Fig. 8. Relation of bond stress with slip for 12 mm dia deformed reinforcing bar.

4.1 Type of bar

To observe the differences in bond strength, two types of reinforcing bars were used in this study: deformed bar and plain bar. The bond strength of deformed bar was found to be higher than that of plain bar, as illustrated in Figure 6.

From Figure 6, it is well understood that the higher the diameter, the higher the bond strength and this is applicable for both smooth and deformed bar. Also bond strength of deformed bar is higher than plain bar as compared well with literature due to ribs and straight strips on the surface, which make the surface rough and help to increase the bond between concrete and steel bars. It is also confirmed from Figure 7 which also follows the bond properties of reinforcing bars embedded in SAC.

4.2 Concrete cover and embedment length

In figure 8, it is shown for 12 mm dia deformed bar, the bond strength decreases as the concrete cover increases. Here cover is shown in figure 4. In other sense, bond strength decreases as embedment length decreases. So, for 3" cover bond strength is lowest than that of covers for 1" and 2". For slip at peak strength, the higher the embedment length (1" cover) the higher the higher the slip at peak strength.

4.3 Crack pattern in plain and deformed bar

In the case of plain bar, the sort of failure pattern discovered in the specimen was "Bond failure or pullout failure." Pullout failure usually happens when the embedded length of bar is insufficient. This form of failure can occur when the bonding resistance is insufficient. Because the bar was plain and there were no ribs, it's possible that the reduced bond strength of plain bar is to blame for this type of failure.

Fig. 9. Identification of Crack Pattern of Pullout Specimen, SP-D-20 (1.6")

Splitting failure with vertical crack and pullout failure was detected in deformed bars. When an adequate embedded length is provided, the pullout force may surpass the concrete's tensile capacity, resulting in shear failure. On the surface, a flexural crack develops, followed by a continuous longitudinal crack running the length of the rebar. This sort of failure occurs mostly on the concrete's surface and spreads longitudinally and transversely. Figure 9 shows Crack Pattern of Pullout Specimen, SP-D-20(1.6”).

5. Conclusions

The purpose of this study was to provide a rough overview of various parameters including compressive strength, bar diameter, concrete cover, aggregate properties, and embedded length influencing bond strength of reinforcing bars embedded in SAC as well as in BAC. Direct pull-out experiments for deformed as well as for plain bar were performed to evaluate the effect of numerous characteristics, including bar diameter, compressive strength, embedment length, and concrete cover on bond strength. The bond strength between bars and BAC differs from that of reinforcing bars embedded in SAC due to the lower modulus of elasticity, larger absorption capacity, and lower unit weight of brick aggregate, and it has been demonstrated that bond strength in BAC is lower than in SAC. Conclusions of this study have been described in the following points:

- Absorption capacity of sample brick aggregate was determined to be 22.9% which is comparatively higher than that of stone aggregate. Brick is more porous than stone aggregate for which brick aggregate concrete has higher absorption capability. Higher absorption makes the brick chips weaker, and concrete becomes more susceptible to aggregate failure. Alternatively, higher absorption capacity results in lower bond strength.
- Type of bar also impacts on bond strength. Experimental result shows that bond strength in plain bar is less than that of deformed bar. Several factors are involved here. Deformed bar has ribs and straight strips on the surface, which make the surface rough and help to increase the bond between concrete and steel bars. Bond strength of deformed bars significantly depends on the mechanical interlocking and this interlocking of deformed bar with ribs is much higher than adhesive stress and frictional force. For which bond strength in deformed bar is higher than that of plain bar.
- In case of deformed bar, higher bond strength was found for the 16mm bar diameter than that of 12mm. There is no linear relation found between bar diameter of deformed bar and bond strength because there are other parameters involved such as concrete cover, rib spacing, rib height etc. For plain bar the same trend of the higher the bar diameter the higher the bond strength is observed.
- In case of plain bar of different diameters, mostly pullout failure or bond failure was observed due to reduced bond strength compared to deformed bar. And for deformed bar splitting failure along with pullout failure was noticed.
- Embedded length is related to contact surface area which directly influences the bond stress-slip relation. In general, lesser the contact surface area lesser the bond strength and higher the slip. As the depth of the concrete under the bar increases, so does the bond strength.
- The bond strength of BAC is predicted using a researcher-recommended equation and while comparing to the experimental, bond strength was found reasonable for smooth bar.
- In future, concrete of more batches with different mix ratios and pull-out test with different diameter reinforcing bars may be tested to ensure a wide range of bond strength data which can be used to generate formulas for calculating bond strength of reinforcing bars embedded in BAC.

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