Effect of Maximum Aggregate Size on the Bond Strength of Reinforcements in Concrete

Shahid Iqbal
Department of Civil Engineering
CECOS University of IT and
Emerging Sciences
Peshawar, Pakistan
shahid.iqbalmce@gmail.com

Naqeeb Ullah
Department of Civil Engineering
CECOS University of IT and
Emerging Sciences
Peshawar, Pakistan
naqibmarwat@hotmail.com

Ahsan Ali
Department of Civil Engineering
Quaid-e-Awam University
College of Engineering, Science
& Technology
Larkana, Pakistan
ahsanone@gmail.com

Abstract-**The bond between reinforcements and concrete is the only mechanism that transfers the tensile stresses from concrete to reinforcements. Several factors including chemical adhesion, roughness and reinforcement interface and bar bearing affect the bond strength of reinforcements with concrete. This work was carried out considering another varying factor which is maximum aggregate size. Four mixes of concrete with similar compressive strengths but different maximum aggregate sizes of 25.4mm, 19.05mm, 12.7mm and 9.53mm were used with the same bar size of 16mm. Compressive strength, splitting tensile strength and bond strength for each concrete mix were studied. Test results depict a slight increase in compressive and splitting tensile strength with decrease in maximum aggregate size. The bond strength remained at the same level with decrease in maximum aggregate size except at maximum aggregate size of 9.53mm when there was a drop in bond strength, despite better compressive and splitting tensile strengths. ACI-318 and FIB-2010 codes equation for bond strength calculation work well only when the maximum aggregate size is 12.7mm and above. Therefore, maximum aggregate size is critical for bond strength when smaller size aggregates are used.**

Keywords-concrete; aggregate size; pullout test; bond strength

I.   INTRODUCTION

The role of the bond of reinforcement in concrete is of great importance. When the concrete member is loaded, tensile stresses from steel to concrete are transferred through the bond. Therefore, to ensure the safety of concrete, proper bonding between reinforcing steel and concrete is essential When the concrete member cracks, tensile stresses are resisted by the reinforcement, reinforcement slip occurs which is resisted by friction and reinforcement bearing producing bond stresses [1]. Bond behavior of steel reinforcements with concrete is an important aspect which affects the performance of reinforced concrete [2-6]. There are three main components of bond between reinforcements and concrete: friction, chemical adhesion and mechanical interlocking of deformations in steel bars. The factors affecting bond strength include strength and cover of concrete around reinforcement, geometry and yielding strength of reinforcement, embedded length, type of aggregates and admixtures used [1, 7-10]

An increase of up to 20% in pullout load is reported with increase of concrete cover depth from 40mm to 70mm [9]. Studying the effect of concrete cover on bond behavior, it is reported that the bond strength increases but the rate of increase decreases with the increase of concrete cover [10]. Thus when concrete cover increases, initially the increase in bond strength is more pronounced to further increase in concrete cover. Authors in [11] investigated the bond behavior of reinforcements in lightweight self-compacting concrete and reported 30% lower bond strength for all lightweight SCC compared to normal weight concrete. Corrosion also plays an import role in the bond performance. It is reported that there is a decrease in bond strength when corroded reinforcements are used [12]. For this purpose protective layers against corrosion may be used. It is reported that, galvanization of reinforcements can improve its resistance against carbonation and can extend the life of reinforced concrete structures [13]. Investigating the effect of bar size on the bond strength of reinforcements in concrete, it is reported that bond strength of smaller bars (10mm diameter) is 21% higher than that of the larger bars (20mm) [1]. Size of aggregate may be another bond influencing factor. To the best of our knowledge, there is limited literature available on the effect of aggregate size on the bond strength. Therefore, this study is conducted to investigate the effect of aggregate size on the bond behavior of reinforcements in concrete. Bond strength is calculated by dividing the maximum pullout load by the surface are of the reinforcement bar given by (1).

$$\mu = \frac{P}{\pi l_d d_b} \qquad (1)$$

where μ is bond strength, P is the maximum pullout load, l_d and d_b are embedded length and diameter of bar used.

II.   MATERIALS AND METHODOLOGY

A. Materials Used

Normal weight fine aggregates and crushed coarse aggregates, supplied by a local material supplier, were used. Four different coarse aggregates having different maximum aggregate sizes i.e. 9.5mm, 12.5mm, 19mm, and 25mm were used (Figure 1). The maximum sizes of the aggregates were

selected on the basis of ASTM standard sieves. CEM-I 42.5N cement, supplied by a local cement manufacturer (Cherat cement) was used for all the concrete mixes.

Fig. 1.   Coarse aggregates

B. Experimental Program

Fresh and hardened concrete properties were investigated for each mix. Workability and density were investigated on the fresh concrete while compressive strength, splitting tensile strength and bond strength were studied on the hardened concrete. Workability and density were found using [14] and [15] standards. Six cylinder specimens 100mm in diameter and 200mm in height were casted from each concrete mix and cured in water tank as defined in [16]. Three cylinders of each mix were tested for compressive strength as per [17] at 28 days concrete age, by application of constant loading rate of 0.25MPa/sec. Three cylinder specimens of each concrete were tested for splitting tensile strength as per [18] at the concrete age of 28 days by load application at constant rate of 1MPa/min. Three cube samples were casted embedded with 16mm diameter bars to test the bond strength as per [19]. The size of cube was kept at 150mmx150mmx150mm which is the most common cube size in concrete tests. These samples were cured in water tank for 28 days and tested in pullout test with pullout load applied at a constant rate of 0.1KN/sec. Pullout test is a widely practiced and easy to perform test used to investigate the bond strength. It has been used by different researchers to study the factors affecting bond strength i.e. concrete compressive strength, size and geometry of reinforcement bars and active and passive confinement [20, 21]. The pull-out sample and testing assembly are shown in Figure 2.

III. RESULTS AND DISCUSSION

A. Concrete Mix Design

Trial mixes were conducted to finalize the concrete mix with maximum aggregate size of 25mm and target 28 day compressive strength of 20MPa. From previous studies [22-24] and trials of concrete compressive strength tests of each mix, it was observed that with the decrease in maximum aggregate size of coarse aggregates the compressive strength of concrete increases. The study aims at investigating the effect of aggregate size on the bond strength keeping all the other parameters constant. Therefore, to achieve similar compressive strengths and compensate for this variation of compressive

strength due to change in maximum aggregate size, the cement quantity was reduced by 2% for every consecutive reduction of coarse aggregate maximum size with increase in w/c ratio by 0.005. Mix compositions for all the mixes are summarized in Table I. The concrete mixes containing maximum aggregate sizes of 25mm, 19mm, 12.5mm and 9.5mm were nominated as Mix-25, Mix-19, Mix-12.5 and Mix-9.5 respectively.
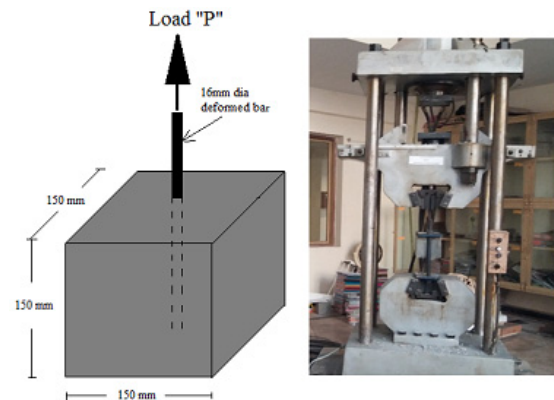

Fig. 2.   Pull-out specimen and testing arrangement

TABLE I.   CONCRETE MIX COMPOSITION

Concrete type	Cement (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)	Water (kg/m³)	w/c ratio
Mix-25	400	800	880	192	0.48
Mix-19	392	800	880	190	0.485
Mix-12.5	384	800	880	188	0.49
Mix-9.5	376	800	880	186	0.495

B. Fresh Concrete Properties

The test results for fresh concrete properties are presented in Table II. Test results for fresh concrete properties indicate decrease in slump with decrease in maximum aggregate size while concrete density remains unchanged. The relation is graphically represented in Figure 3.

TABLE II.   FRESH CONCRETE PROPERTIES

Concrete type	Maximum Coarse Aggregate Size (mm)	Slump (mm)	Concrete density (Kg/m3)
Mix-25	25	89	2421
Mix-19	19	83	2417
Mix-12.5	12.5	78	2412
Mix-9.5	9.5	65	2408

C. Hardened Concrete properties

The test results for hardened concrete properties of all the concrete types are presented in Table III. Instances of the tests of compressive strength, splitting tensile strength and pull-out strength tests that were conducted in the lab are shown in Figure 4.

1) Compressive Strength

The tests results for compressive strength of all concrete mixes are summarized in Table III. Although the cement

content decreased intentionally with decrease in maximum aggregate size to keep the compressive strengths of all concretes at the same level in order to study only the effect of maximum aggregate size on bond strength, there is still indication of increase in concrete compressive strength when the maximum aggregate size in concrete reduces. The relation is graphically shown in Figure 5.
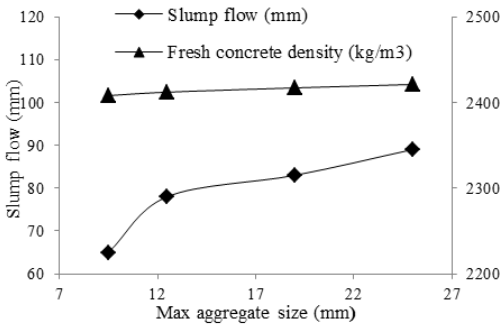

Fig. 3.   Fresh concrete properties variation

TABLE III.   HARDENED CONCRETE PROPERTIES

Concrete type	Maximum Coarse Aggregate Size (mm)	Compressive Strength (Mpa)	Splitting Tensile strength (Mpa)	Bond strength (Mpa)
Mix-25	25	21.22	2.76	7.76
Mix-19	19	21.82	2.78	7.93
Mix-12.5	12.5	21.95	2.97	7.88
Mix-9.5	9.5	22.02	3.11	7.15

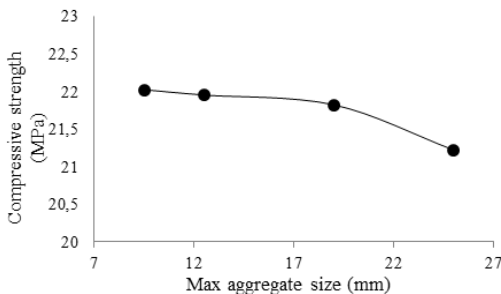Fig. 4.   Hardened concrete tests

Fig. 5.   Compressive strength variation

2)   Splitting Tensile Strength

The test results for all concrete types are presented in Table III. Similar to compressive strength, there is an increasing trend in splitting tensile strength with decrease in maximum

aggregate size used despite the decrease in cement content. This trend is graphically presented in Figure 6.
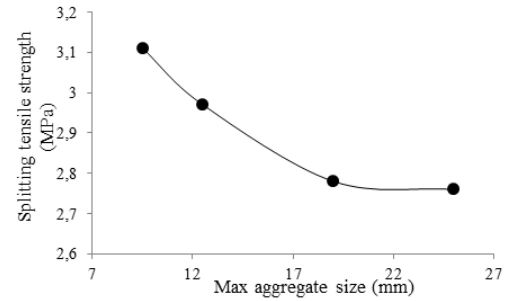

Fig. 6.   Splitting tensile strength variation

3)   Bond Strength

The main objective of this study was to investigate the effect of maximum aggregate size on the bond strength of reinforcements with concrete. Results for bond strength are summarized in Table III calculated using (1). Results indicate no major change in bond strength with decrease in maximum aggregate size. However, surprisingly, there is a drop in bond strength when maximum aggregate size of 9.5mm was used despite possessing the highest compressive and splitting tensile strengths among all the concretes used. The reason may be the decrease in locking provided by small aggregates to the pulled out bar. The failure pattern in all pullout specimens was by splitting of the concrete cover which is caused by wedging effect of bar deformations as shown in Figure 7.
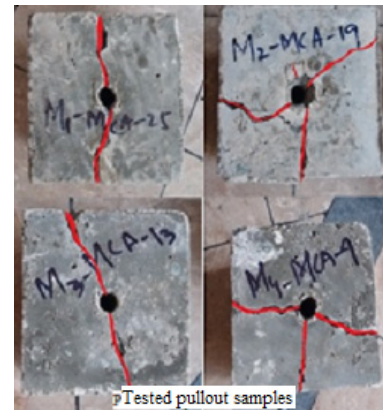

Fig. 7.   Pullout samples after bond failure

The bond strength experimental results were compared with those calculated from different equations in the literature. Four different equations were considered: (2)-(5) taken from [25-28] respectively.

$$\tau_{u,split} = \eta_2 \cdot 6.54 \cdot (f_{ck})^{0.25} \cdot (\frac{20}{\Phi})^{0.2} \cdot [(c_{max} / \Phi)^{0.33} \cdot (c_{min} / c_{max})^{0.1} + 8K_{tr}] \quad (2)$$

$$\frac{T_C}{f_C^{1/4}} = \frac{A_b f_s}{f_C^{1/4}} = [1.43l_d(C_{min} + 0.54d_b) + 57.4A_b] \cdot (0.1\frac{C_{min}}{C_{max}} + 0.9) \quad (3)$$

$$\frac{u_c}{\sqrt{f'_c}} = 0.10 + 0.25\, \frac{C_{min}}{d_b} + 4.15\, \frac{d_b}{l_d} \qquad (4)$$

$$U = u_c\, \frac{1+\frac{1}{M}}{1.85+0.024\sqrt{M}}\, (0.88 + 0.12\, \frac{C_{mid}}{C_{min}}) \qquad (5)$$

TABLE IV.   EXPERIMENT AND CALCULATED BOND STRENGTHS

Concrete type	Bond strength (Mpa)				
	experimental	(2)	(3)	(4)	(5)
Mix-25	7.76	7.87	7.83	7.34	7.25
Mix-19	7.93	7.93	7.88	7.45	7.33
Mix-12.5	7.88	7.94	7.89	7.47	7.35
Mix-9.5	7.15	7.94	7.90	7.48	7.36

Results indicate that there is no major impact of aggregate size on the bond strength of reinforcements in concrete when higher maximum aggregate sizes are used. Equations (2) and (3) (from [25, 26]) are extremely good in predicting bond strength values while (4) and (5) (from [27, 28]) give slight conservative results. However, when the size of maximum aggregate reduces below 10mm, there is drop in experimental bond strength results despite better compressive and tensile strengths which may be due to lower resistance provided by smaller size aggregates to pulled out bars. This drop is not reflected in the equations used for bond strength calculations. As all the specimens failed by splitting, this phenomenon may have been more pronounced if concrete cover was increased to initiate pure pullout instead of specimen splitting. In that case, bigger size aggregates may induce more resistance to bars pulling out by locking compared to smaller size aggregates. The comparison of all values is shown in Figure 8. The percentage variations of equation values were calculated with respect to the experimental results and are summarized in Table V. Equations (2) and (3) fit really well with the experimental values with less than 2% variation when 12.5mm and above maximum aggregate sizes are used. However, when the maximum aggregate size of 9.5mm was used, the variation was above 10%. The variations of (3), (4) with respect to the experimental values were in the range of ±5-7% for all values.
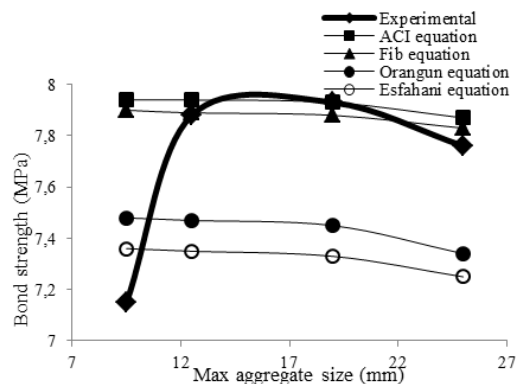

Fig. 8.   Bond strength variation and comparison

TABLE V.   PERCENTAGE VARIATIONS

Concrete type	Percentage variations			
	(2)	(3)	(4)	(5)
Mix-25	1.42%	1%	-5.4%	-6.6%
Mix-19	0	-0.6%	-6%	-7.6%
Mix-12.5	0.76%	0	-5.2%	-6.7%
Mix-9.5	11%	10.5%	4.6%	3%

IV. CONCLUSIONS

The following conclusions have been drawn based on the experimentally performed study:

- The workability of concrete decreases with decrease in maximum aggregate size used.

- With increase in maximum aggregate size used in concrete, the compressive strength and splitting tensile strength decrease.

- When higher maximum aggregate size of coarse aggregates values are used in concrete, there is no variation in bond strength but it reduces when maximum aggregate size of less than 10mm is used. This may be due to lower locking provided to pulled out bar by smaller aggregates. This may be more pronounced if splitting of samples is avoided by increasing concrete cover.

- Equations taken from [25, 26] for bond strength calculation work extremely well with higher maximum aggregate size concretes but do not work well when lower maximum aggregate sizes (<10mm) are used. Aggregate size effect may be introduced in these equations for lower maximum aggregate size concretes to better reflect the actual bond strength.

REFERENCEES

[1] A. Ali, S. Iqbal, K. Holschemacher, T. A. Bier, "Bond of Reinforcement with Normal-weight Fiber Reinforced Concrete", Periodica Polytechnica Civil Engineering, Vol. 61, No. 1, pp. 128-134, 2017

[2] fib, "Bond of reinforcement in concrete: state-of-art report", Bulletin No. 10, fib, 2000

[3] S. Hong, S. K. Park, "Uniaxial bond stress-slip relationship of reinforcing bars in concrete. Advances in Material Science and Engineering", Advances in Materials Science and Engineering, Vol. 2012, Article ID 328570, 2012

[4] C. Jiang, Y. F. Wu, G. Wu, "Plastic hinge length of FRP-confined square RC columns", Journal of Composites for Construction, Vol. 18, No. 4, 2014

[5] D. S. Gu, Y. F. Wu, G. Wu, Z. S. Wu, "Plastic hinge analysis of FRP confined circular concrete columns", Construction and Building Materials, Vol. 27, No. 1, pp. 223-233, 2012

[6] D. Guan, C. Jiang, Z. Guo, H. Ge, "Development and seismic behavior of precast concrete beam-to-column connections", Journal of Earthquake Engineering, Vol. 22, No. 2, pp. 234-256, 2016

[7] E. Fehling, P. Lorenz, T. Leutbecher, "Experimental Investigations on Anchorage of Rebars in UHPC", in: Proceedings of Hipermat 2012 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials, pp. 533-540, 2012

[8] A. F. Bingol, R. Gul, "Residual bond strength between steel bars and concrete after elevated temperatures", Fire Safety Journal, Vol. 44, No. 6, pp. 854–859, 2009

[9] H. S. Arel, S. Yazici, "Concrete-reinforcement bond in different concrete classes", Construction and Building Materials, Vol. 36, pp. 78–83, 2012

[10] B. Bai, H. K. Choi, C. S. Choi, "Bond stress between conventional reinforcement and steel fiber reinforced reactive powder concrete", Construction and Building Materials, Vol. 112, pp. 825–835, 2016

[11] M. I. Kaffetzakis, C. G. Papanicolaou, "Bond behaviour of reinforcement in lightweight aggregate self-compacting concrete", Construction and Building Materials, Vol. 113, pp. 641–652, 2016

[12] X. Fu, D. D. L. Chung, "Effect of corrosion on the bond between concrete and steel rebar", Cement and Concrete Research, Vol. 27, No. 12, pp. 1811–1815, 1997

[13] P. Pokorny, P. Tej, M. Kouril, "Evaluation of impact of corrosion of hot-dip galvanized reinforcement on bond strength with concrete – A Review", Construction and Building Materials, Vol. 132, pp. 271–289, 2017

[14] ASTM, "C143/C143M -15a: Standard test method slump of hydraulic-cement concrete", in: Annual Book of ASTM Standards, Volume 04.02 Concrete and Aggregates, ASTM International, 2012

[15] ASTM, "C138/C138M-17a: Standard test method for density (Unit weight), yield and air content (Gravimetric) of concrete", in: Annual Book of ASTM Standards, Volume 04.02 Concrete and Aggregates, ASTM International, 2012

[16] ASTM, "C192/C192M-16a, "Standard practice for making and curing concrete test specimens in the laboratory", in: Annual Book of ASTM Standards, Volume 04.02 Concrete and Aggregates, ASTM International, 2012

[17] ASTM, "C39/C39M-18, Standard test method for compressive strength of cylindrical concrete specimens", in: Annual Book of ASTM Standards, Volume 04.02 Concrete and Aggregates, ASTM International, 2012

[18] ASTM, "C496/C496M-17, Standard test method for splitting tensile strength of cylindrical concrete specimens", in: Annual Book of ASTM Standards, Volume 04.02 Concrete and Aggregates, ASTM International, 2012

[19] RILEM, "Technical Recommendations for the Testing and Use of Construction Materials", Taylor & Francis, 1994

[20] R. Eligehausen, E. P. Popov, V. V. Bertero, Local bond stress–slip relationships of deformed bars under generalized excitations, Report no. USB/EERC 83/23, Earthquake Engineering Research Center, University of California, Berkeley, California, 1983

[21] B. S. Hamad, "Bond strength improvement of reinforcing bars with specially designed rib geometries", Structural Journal, Vol. 92, No. 1, pp. 3–13, 1995

[22] M. Yaqub, I. Bukhari, "Effect of Size of Coarse Aggregate on Compressive Strength of High Strength Concrets", 31st Conference on Our World in Concrete and Structures, Singapur, August 16-17, 2006

[23] N. A. A. Hamid, N. F. Abas, "A study on effects of size coarse aggregate in concrete strength", Jurnal Teknologi, Vol. 75, No. 5, pp. 51–55, 2015

[24] A. Neville, "Aggregate bond and modulus of elasticity of concrete", Materials Journal, Vol. 94, No. 1, pp. 71–74, 1997

[25] ACI Committee 408, "Bond and Development of Straight Reinforcing Bars in Tension (ACI 408R-03)", American Concrete Institute, 2003

[26] fib, Model Code 2010 - First complete draft, Vol. 1, 2010

[27] C. O. Orangun, J. O. Jirsa, J. E. Breen, "A Reevaluation of Test Data on Development Length and Splices", ACI JOURNAL, Vol. 74, No. 3, pp. 114–122, 1977

[28] M. R. Esfahani, B. V. Rangan, "Bond between normal strength and high-strength concrete (HSC) and reinforcing bars in splices in beams", ACI Structural Journal, Vol. 95, No. 3, pp. 272–280, 1998