Journal of King Saud University – Engineering Sciences 29 (2017) 365–372

Contents lists available at ScienceDirect

Journal of King Saud University – Engineering Sciences

journal homepage: www.sciencedirect.com

Original article

Bond behavior of steel bars embedded in concretes made with natural lightweight aggregates

Mohammad Jamal Al-Shannag *, Abdelhamid Charif

Department of Civil Engineering, King Saud University, Riyadh 11421, Saudi Arabia

ARTICLE INFO

Article history:
Received 31 March 2017
Accepted 30 May 2017
Available online 6 June 2017

Keywords:
Reinforced concrete
Lightweight
Pull-out
Bond strength
Steel bars
Load-slip behavior

ABSTRACT

The bond properties of reinforcing steel bars embedded in structural concrete made with locally available natural lightweight aggregates, was studied using pull-out tests on cubic specimens of 150 × 150 × 150 mm. A series of 30 specimens were cast considering the effect of bar diameter, and concrete compressive strength. Test results showed that the load-slip behavior of the structural lightweight concretes (SLWCs) investigated compare reasonably well with the behavior of concretes reported in the literature, and is dependent upon the compressive strength, bar size and the embedded length. The bond strength of SLWCs increased with a higher concrete compression strength but decreased as the bar diameter was increased. Comparisons of measured bond strength with the ACI bond equations showed that for all cases the experimental bond strength values were higher than the design ones. However, the results indicate use of caution when applying bond formulas of normal weight concrete to lightweight concretes. Furthermore, this study has revealed that locally available natural lightweight aggregates could be considered as a promising, and cost effective material for designing reinforced concrete members.

1. Introduction

Lightweight concrete has established itself as a suitable construction material whenever savings in the dead-loads in structures and energy conservations are required, and whenever there is an abundance of natural lightweight aggregates. Some geological surveys indicated that Saudi Arabia possesses huge deposits of the volcanic scoria rocks shown in Fig. 1, which are not utilized effectively (Sabtan and Shehata, 2000; Moufti et al., 2000). They extend in north-south direction and cover an area of 180,000 km^2 distributed among separate lava fields called harrats. The estimated reserves of scoria in some of these harrats amount to 5 million m^3. Recent investigations confirmed that the scoria deposits can be used for producing structural lightweight concrete 25% lighter than normal weight concrete (Shannag et al., 2014; Charif et al., 2014). Scarcity of information on bond behavior of deformed steel bars embedded in structural lightweight concrete limited the acceptance of this material in construction industry.

Bond of reinforcing steel bars and concrete is a major characteristic of reinforced concrete. In structural concrete design, perfect bond between the reinforcing steel and concrete is assumed. The existence of the bond is the basic condition for concrete and steel to work together as a kind of composite material. Without bond, the rebar would not be able to resist any external load, and the RC beam would behave exactly like a plain concrete member does. For instance, this type of beam would fracture quickly under a small tensile load.

There is huge information on bond behavior between reinforcing bar and normal weight aggregate concrete available in the literature, and some model equations were developed by a number of researchers (Gjørv et al., 1990; Valcuende and Parra, 2009; Lundgren, 1999; Elfgren and Noghabai, 2002; Sancak et al., 2011; Mor, 1992; Orangun, 1967; Kayali and Yeomans, 2000; Hassan et al., 2010). They clarified the effect of the bar diameter, embedded length in concrete, concrete strength, cover thickness and crack spacing on the bond strength. (Sancak et al., 2011), reported lower bond strength for deformed bars in structural lightweight concrete (SLWC) as compared with that of normal weight aggregate concrete (NWAC). They also observed that at the ultimate load the slip of ribbed bars for both NWAC and SLWAC specimens was not very different. Field performance has demonstrated

* Corresponding author.
E-mail addresses: mjshanag@ksu.edu.sa, shannag95@yahoo.com (M.J. Al-Shannag).

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jksues.2017.05.002
1018-3639/

Fig. 1. Natural Lightweight Rocks used in this investigation.

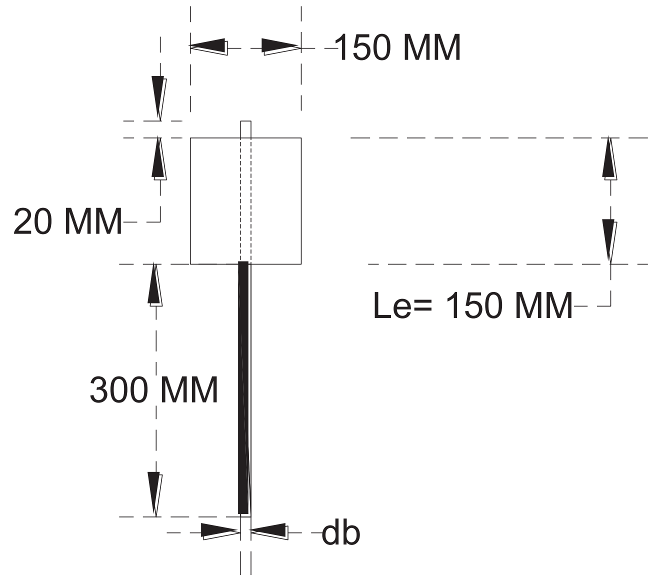

Fig. 2. Details of pull-out specimen.

satisfactory performance for bond and development length, of light density concrete (LDC) with concrete strength ranging from 20 to 35 MPa. The lower particle strength in LDC resulted in lower bond splitting strengths and reduced post-elastic straining as compared to normal density concrete (NDC). ACI 318-08 recommends a 1.3 increase factor for lightweight concrete compared to a factor of 1 for normal weight concrete (Holm and Bremner, 2000). Hossain (2008) reported lower bond strength of steel bars when used in volcanic pumice concrete (VPC) as compared to normal concrete (NC). NC specimens developed a normalized bond strength about 1.12 (ranging from 1.08 to 1.14) times that obtained with VPC counterparts. This lower bond strength for a lightweight concrete is understandable and the reduction is reasonable.

The bond behavior and strength between reinforcing steel bars and LWC is still not fully understood, and more research work on the bond characteristics of steel bars in lightweight aggregate concrete is required. Further research on bond behavior of LWC should contribute to the enhancement of existing code provisions for lightweight concrete. The main objective of this research is to investigate the bond behavior of reinforcing steel bars embedded in concrete made with locally available natural lightweight aggregates, using the pullout test setup presented in (ASTM C 234 specifications, 1991). The influence of matrix compressive strength and deformed steel bar size on bond strength is studied. Furthermore, the performance of the existing code provisions for predicting the bond strength of normal and lightweight concrete will be studied and compared with the data obtained from this investigation. This paper is part of a large scale research project aimed at investigating the possibility of producing structural lightweight concrete using locally available natural lightweight aggregates.

2. Experimental investigation

The experimental investigation was designed to study the influence of two main parameters on bond strength between steel bars and structural lightweight concrete: concrete strength and rebar diameter. A total of 30 pull-out specimens were cast using lightweight scoria aggregates. Two different concrete mixes were prepared namely M350, and M500 wherein the letter indicates Madina lightweight aggregates (LWA) and the numeral indicates the cement quantity. Deformed reinforcing bars having nominal diameters of 12, 14, 16, 20 and 25 mm were then embedded in each of the LW concrete mixes. Each concrete mix comprised of 15 specimens with 3 specimens each belonging to the five diameters of rebars. The details of the pull-out specimens are shown in Fig. 2. The cross-section of the pull-out specimens is square 150 mm × 150 mm and the embedment length of the bar is l_e = 150 mm. As it can be seen in Fig. 2, the steel rebar was embedded in the center of concrete with 300 mm of the rebar length projecting out on one end and 20 mm of the rebar on the other end. This was done to make sure that the measurements for rebar slip can be obtained and the rebar can be easily gripped for pull-out tests. Table 1 shows the test matrix used in this study. All pull-out specimens were tested at the end of 28 days after casting.

Table 1
Test-Matrix for pull-out specimens and properties of materials used.

Mix Designation	Embedment Length = 150 mm Rebar Diameter (mm)				
	12	14	16	20	25
	Number of Pull-out Specimens				
M350	3	3	3	3	3
M500	3	3	3	3	3
Total	6	6	6	6	6

Proportions of Concrete Mixes in (kg/m^3)

	Cement	Silica Fume	Water	LWCA	LWFA	Silica Sand	Superplasticizer
M350	350	40	240	450	400	240	8
M500	500	40	240	415	368	221	10

Properties of Concrete Mixes

Material Parameter	Compressive strength f'_c (MPa)	Air dry Unit weight (kg/m^3)	Modulus of Elasticity (MPa)	Slump
Mix M350	34	1860	15214	65
Mix M500	48	1925	20210	50

Properties of Steel rebars

Nominal Diameter	Yield Strength (MPa)	Ultimate strength (MPa)	Modulus of Elasticity (GPa)
12	428	668	192.4
14	430	667	196.5
16	425	686	201.2
20	423	708	202
25	424	686	196.4

2.1. Material properties and concrete mix proportions

The materials used in this investigation include Type I cement, silica sand, locally available scoria natural lightweight aggregates, microsilica, water, and superplasticizer. Two different lightweight concrete Mixes of 30 and 45 MPa compressive strength were designed and used. The concrete mix proportions and the basic properties of these mixes were determined following ASTM standards and presented in Table 1; further details are given by Shannag et al. (2014).

2.1.1. Steel rebars

The steel bar properties such as stress-strain curve, yield stress, ultimate stress and elongation was obtained from axial tension tests as per (ASTM A615, 2013) on five steel coupon specimens selected from the same rebar batch used in the pullout tests. The values of the yield and ultimate tensile strengths of the rebars are presented in Table 1.

2.1.2. Specimen preparation

Wooden formwork was first prepared to the required sizes. Two holes of diameter close to the diameter of steel rebar to be placed, were cut on opposite side of the wood panel exactly in the center to make way for the steel rebar. The steel rebar was then passed through the holes on each end, thereby ensuring its placement in the center of the mold. The holes were then sealed using silicone adhesive which prevented any movement of the rebar during concrete placement.

The preparation of the concrete mixes was performed using tilting drum mixers of 0.05 m^3 and 0.15 m^3 capacity. The lightweight aggregates were wetted for 10 min prior to mixing to minimize the large variation in the workability of the mixes. After mixing, concrete was poured into the pullout molds and into standard cylinders for compressive strength testing (ASTM C39, 1991). The molds were filled in three layers and vibrated using a table vibrator. The pullout specimens and cylinders were covered and left at room temperature for the next 24 h and then demolded. The steel reinforcing bars projecting out of concrete specimens were then coated with three layers of an anti-corrosive paint. After demolding, both the pull-out specimens and concrete cylinders were placed in tanks filled with lime-saturated water until the age of testing of 28 days.

2.1.3. Pull-out test setup and procedure

The INSTRON tensile testing machine used and its schematic diagram are shown in Figs. 3 and 4. The loading machine was capable of applying 600 kN of force in uniaxial tension and also allowed displacement controlled tests. In this study, modified ASTM C234, pullout specimens were used. The reinforcing steel bars had different nominal diameters instead of the fixed No. 6 (19 mm) bar specified in ASTM C234. As seen in Fig. 4, the test set-up comprised of an assembly on which the pull-out specimen could be mounted. The concrete cube was rested against the steel plate of the assembly which had a central hole through which the rebar could be passed as shown in Fig. 4.

This actually provided the required resistance against the loading thereby inducing the pull-out mechanism. Slip in the rebar was measured using an LVDT (linear variable differential transformer) which was mounted on top of the rebar free end as shown in Fig. 4. The LVDTs were then connected to a Tokyo Sokki data acquisition system to record the load of the machine versus slip relationship until failure of the specimen. 25 MPa/min loading rate was used in compliance with the maximum rate of (ASTM C 234, 1991) limited to 34.5 MPa/min. The recorded displacements were corrected to account for the elastic elongation of the steel bar, and the final results showed that the bar elongation was much smaller compared to the actual slip.

Fig. 3. INSTRON testing machine showing a tested specimen.

3. Results and discussion

Results for all test specimens for different concrete mixes, and varying bar diameters are tabulated in Table 2. The results of the pull-out tests in terms of peak load, calculated bond strength, slip at peak load and the failure type are presented in the same Table. The measured bond strength was calculated using Eq. (1) given below:

$$\tau = \frac{F}{\pi\, d_b l_e} \quad (1)$$

where:

τ = experimental bond strength (MPa)
F = ultimate axial tension force (kN)
d_b = nominal rebar diameter (mm)
l_e = embedment length (mm).

According to various code provisions including ACI 318-08, the bond strength and the corresponding development length are related, as tension and shear strengths, to the square root of the concrete compressive strength. This implies that a linear relation between bond strength and the square root of compressive strength is to be expected. For the purpose of comparison between bond strengths of different mixes, the normalized bond strength

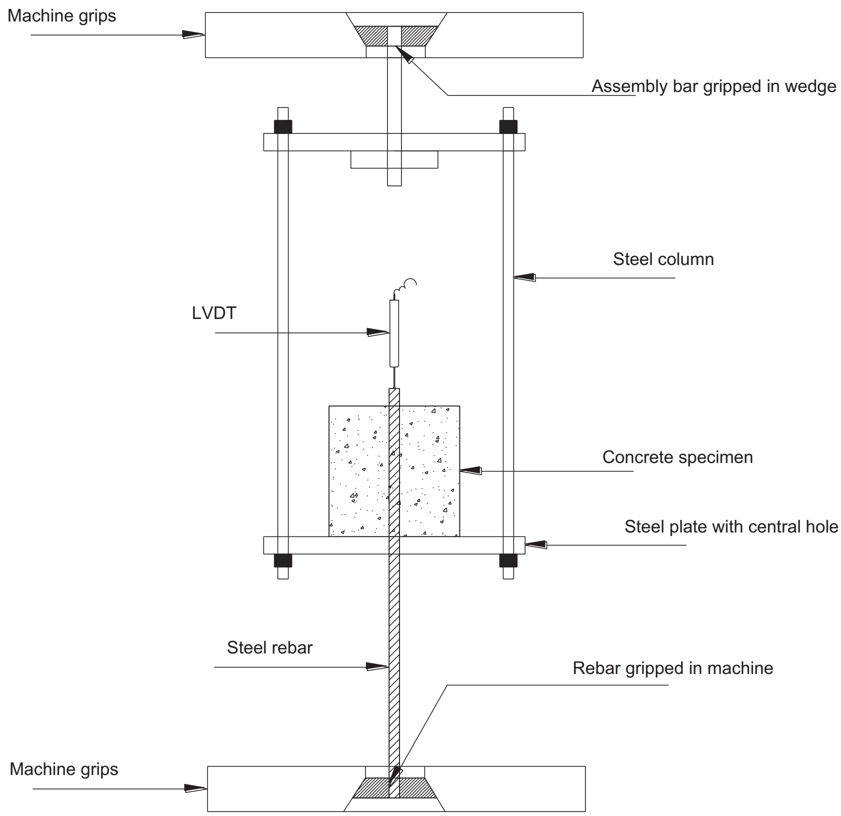

Fig. 4. Schematic for details of Test set-up.

Table 2
Results of Pull-out tests for embedment length of 150 mm.

Specimen & Mix Designation	*Compressive Strength (f'_c) (MPa)*	*Nominal Bar Diameter (mm)*	*Peak Axial Load (kN)*	*Max. Bond Strength τ (MPa)*	*Normalized Bond Strength τ_{nz} (MPa)*	*Slip at Peak Load (mm)*	*Mode of Failure*
M350	34	12	37.92	6.70	1.15	1.51	Splitting
		14	34.94	5.29	0.91	1.58	Splitting
		16	32.41	4.29	0.74	1.48	Splitting
		20	29.51	3.13	0.54	1.22	Splitting
		25	30.59	2.60	0.45	1.25	Splitting
M500	48	12	47.93	8.47	1.22	1.61	Splitting
		14	43.14	6.54	0.94	1.52	Splitting
		16	50.56	6.71	0.97	1.75	Splitting
		20	49.31	5.23	0.76	1.26	Splitting
		25	51.77	4.39	0.63	1.82	Splitting

concept has been introduced and used in this work. The normalized bond-strength is obtained by dividing the calculated experimental bond strength by $\sqrt{f'_c}$. The normalized bond strength (τ_{nz}) can be expressed as given in equation (2) :

$$\tau_{nz} = \frac{\tau}{\sqrt{f'_c}} \tag{2}$$

From the experimental results shown in Table 2, it can be observed that for the same embedment length, the bond strength of M350 concrete ranged from 6.7 MPa to 2.6 MPa, whereas the bond strength for M500 concrete ranged from 8.4 to 4.4 MPa.

3.1. Load-Slip relationship and failure mode

In well confined concrete the bond strength will be governed by a pull-out failure where the concrete between the steel ribs will be sheared off and the rebar slips in a frictional mode of failure. However when the bar is embedded in concrete with low confinement, splitting through the entire concrete cover occurs. All samples of different LWC mixes and varying bar diameters, failed by cracking of the concrete cover. Splitting failure occurs when cracks in the surrounding concrete are caused by the wedging action of the lugs of the steel bar. Failures occurred suddenly with the formation of longitudinal cracks. When cracking appears, the bond forces are directed outward from the bar surface and this causes anchorage failure resulting in splitting off of the confining concrete. Fig. 5 shows the failure mode for a typical pull-out specimen for a 150-mm embedment length.

The load-slip relationships for all the specimens tested in this investigation are shown in Figs. 6 through 13. In general, for the LWC mixes studied in the present work, the specimens exhibited an initial behavior with important slip values up to 0.25 mm for low loads, followed by a stiffer part with load increasing almost linearly up to the ultimate load with a sudden failure. An ultimate

Fig. 5. Pull-out specimens after testing (l_e = 150 mm).

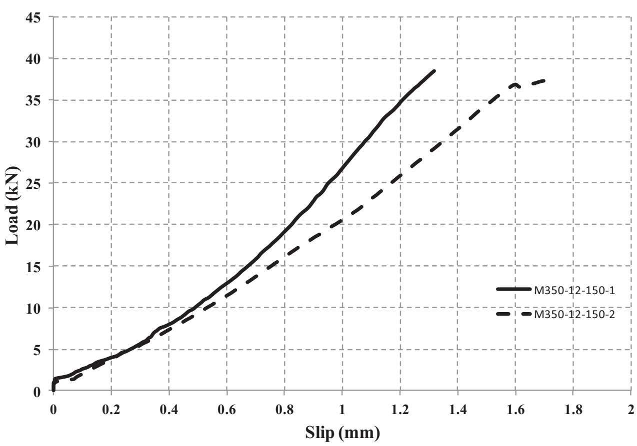

Fig. 6. Load-slip relationship for 12 mm rebar (Mix: M350) l_e = 150 mm.

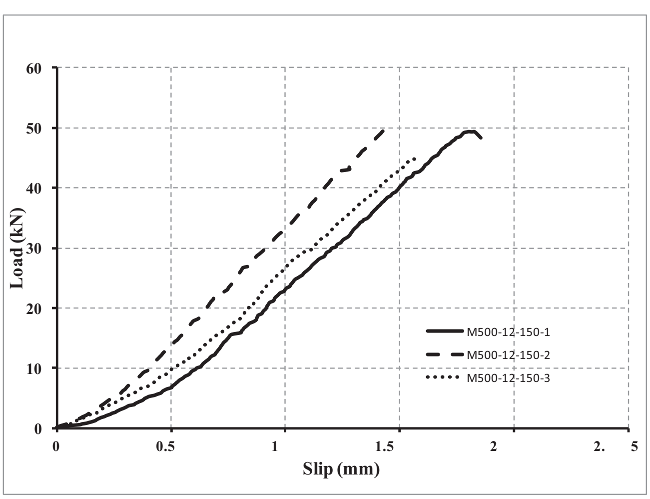

Fig. 7. Load-slip relationship for 12 mm rebar (Mix: M500) l_e = 150 mm.

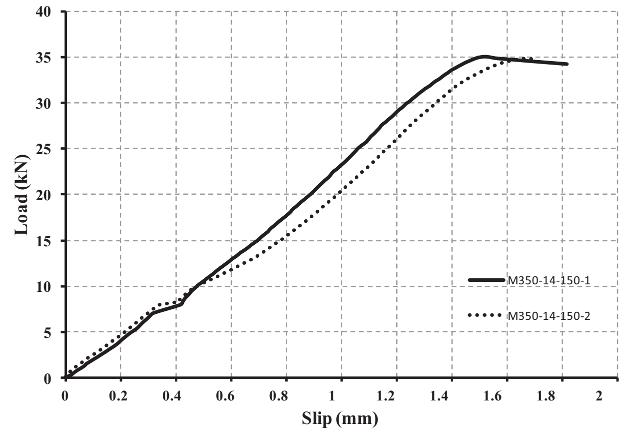

Fig. 8. Load-slip relationship for 14 mm rebar (Mix: M350) l_e = 150 mm.

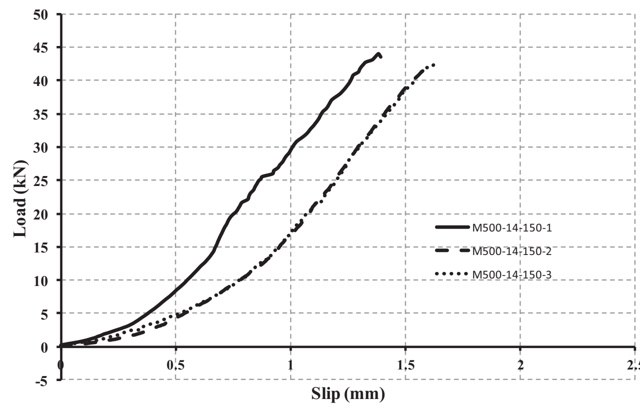

Fig. 9. Load-slip relationship for 14 mm rebar (Mix: M500) l_e = 150 mm.

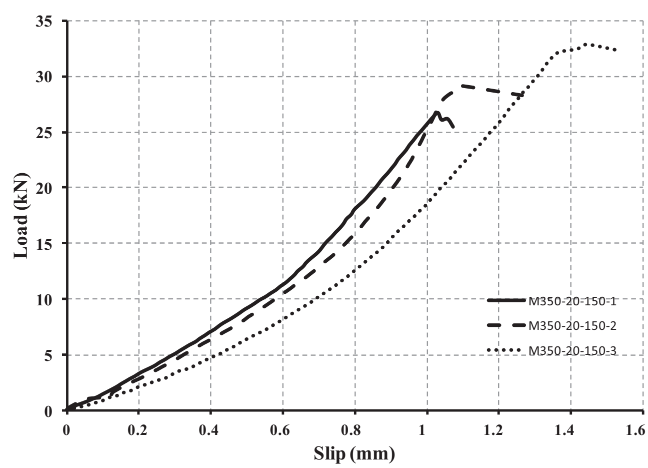

Fig. 10. Load-slip relationship for 20 mm rebar (Mix: M350) l_e = 150 mm.

slip value of 0.8 to 2.15 mm was observed for all the LWC mixes. As per the basic rules of bond stress distribution, usually a plateau exists for the bond-slip curve after the peak load is reached, followed by a linear line which decreases to the maximum frictional bond strength at a slip value approximately equal to the clear distance between the lugs of the deformed steel bars, (Lundgren, 1999). Furthermore, the pullout load-slip curves shown in Figs. 6 through 13 compare reasonably well with those reported in the literature, (Sancak et al., 2011; Hossain, 2008), for normal and lightweight concretes. Therefore, the test results presented in this investigation are expected to motivate the structural engineers to explore the potential applications of the huge deposits of volcanic scoria aggregates available in the Kingdom for structural applications.

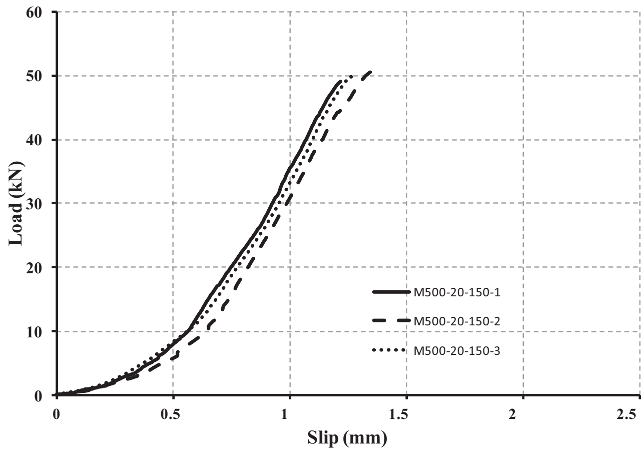

Fig. 11. Load-slip relationship for 20 mm rebar (Mix: M500) l_e = 150 mm.

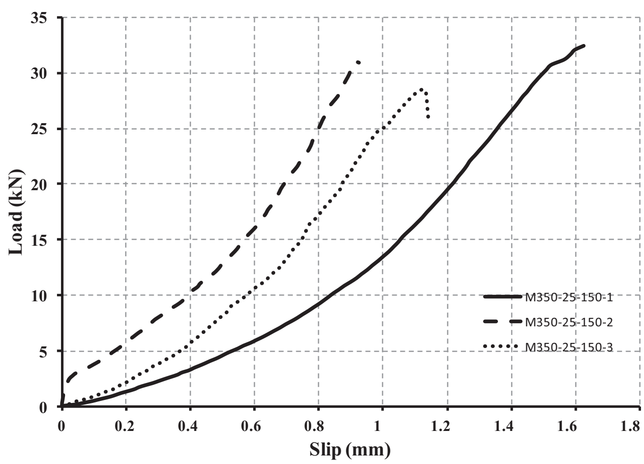

Fig. 12. Load-slip relationship for 25 mm rebar (Mix: M350) l_e = 150 mm.

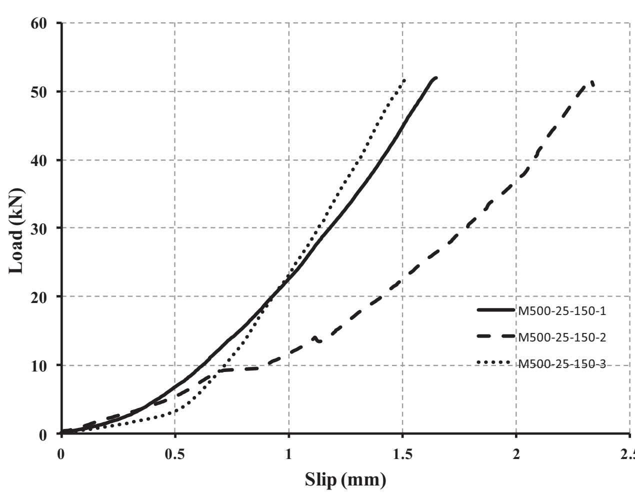

Fig. 13. Load-slip relationship for 25 mm rebar (Mix: M500) l_e = 150 mm.

3.2. Effect of strength of concrete

Two different concrete mixes, M350 and M500, were used in this study with average compressive strengths of 34 and 48 MPa respectively. As observed from the results in Table 2, for 150 mm embedment length the bond strength increases with the increase in concrete strength. It was also noticed that as the concrete strength increases, the slip at peak load also increases slightly. Fig. 14 shows the relationship between concrete strength and bond strength for the mixes and bar diameters used in this study. The variation of the normalized bond stress (τ_{nz}) presented in Table 2 confirms the previous result. Clearly, the bond strength between LWC and the deformed bars is considerably affected by the concrete strength.

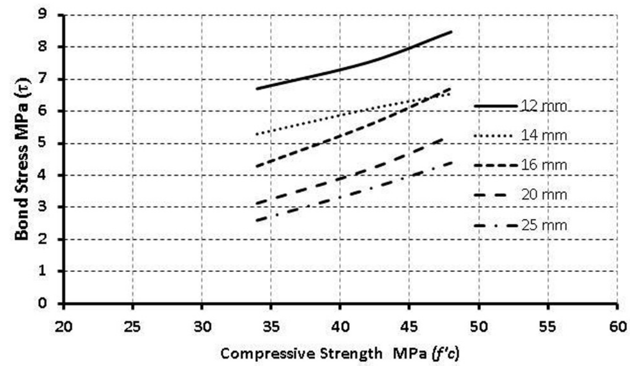

Fig. 14. Relationship between Bond stress and Compressive strength for embedment length of 150 mm.

3.3. Effect of rebar diameter

Fig. 14 showed that the maximum bond stress decreases with the increase in bar diameter. Furthermore the initial part of the load-slip curves shown in Figs. 6 through 13 had relatively higher stiffness whereas the ultimate bond strength is achieved at relatively smaller slip. The maximum bond stress for 20 and 25 mm diameter bars was achieved at a larger slip than that for bars with smaller diameters (16, 14 and 12 mm), which demonstrates that the slip at the maximum load increases with the increase in rebar diameter. In some cases the reduction in bond strength was high, which could be attributed to the splitting failure of concrete within the specimens affecting the measured pull-out load.

4. Comparison with code recommendations and predicting equations

The bond strengths that were measured in the current tests are compared in the following section with the design bond strengths specified in ACI 318-08, and in the European code EC2, 2003. Two expressions to calculate the development length L_d are offered in Sections 12.2.2 and 12.2.3 in ACI 318-08 (Eqs. (3) and (4), respectively). Here, the bond strength f_b has been derived from these expressions for the ultimate state conditions, (White and MacGregor, 2008)

$$f_b = (f_y/4)/(L_d/d_b)$$

,where f_y is the steel yield strength.

For 19 bars and smaller :

$$l_{d=}\left(\frac{f_y\psi_t\psi_e}{1.4\lambda\sqrt{f'_c}}\right)d_b$$

For 22 bars and larger :

$$l_{d=}\left(\frac{f_y\psi_t\psi_e}{1.7\lambda\sqrt{f'_c}}\right)d_b$$

$$l_{d=}\left(\frac{f_y}{1.1\lambda\sqrt{f'_c}}\frac{\psi_t\psi_e\psi_s}{\left(\frac{c_b+K_{tr}}{d_b}\right)}\right)d_b \tag{4}$$

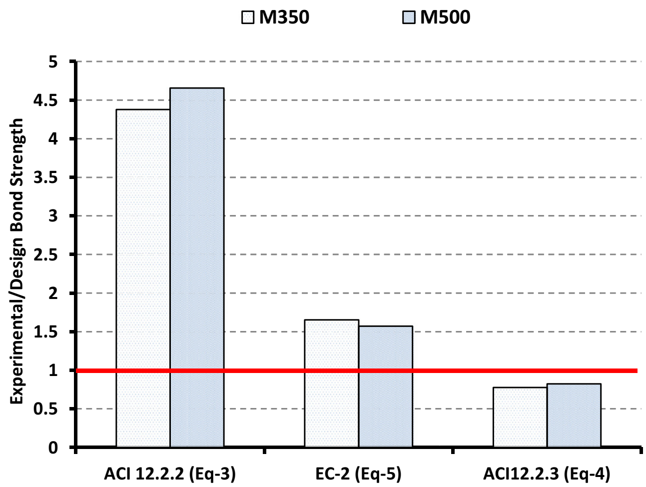

Fig. 15. Experimental to Design bond strength ratio (EDR) for all LWC mixes (Rebar diameter = 12 mm).

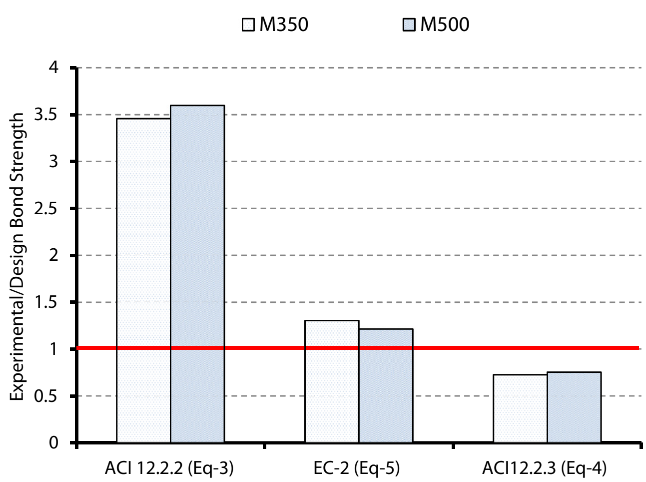

Fig. 16. Experimental to Design bond strength ratio (EDR) for all LWC mixes (Rebar diameter = 14 mm).

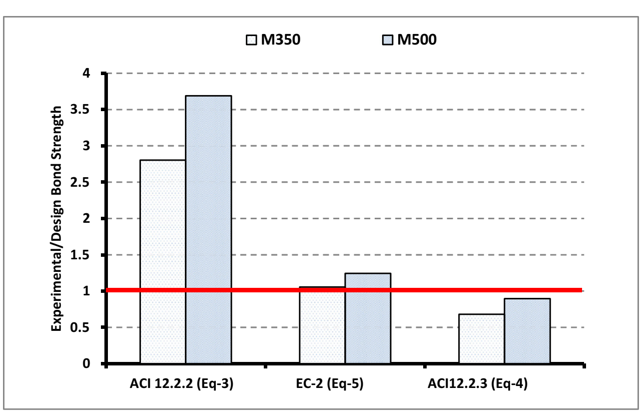

Fig. 17. Experimental to Design bond strength ratio (EDR) for all LWC mixes (Rebar diameter = 16 mm).

where
ψ_t = reinforcement location factor
ψ_e = coating factor
ψ_s = reinforcement size factor

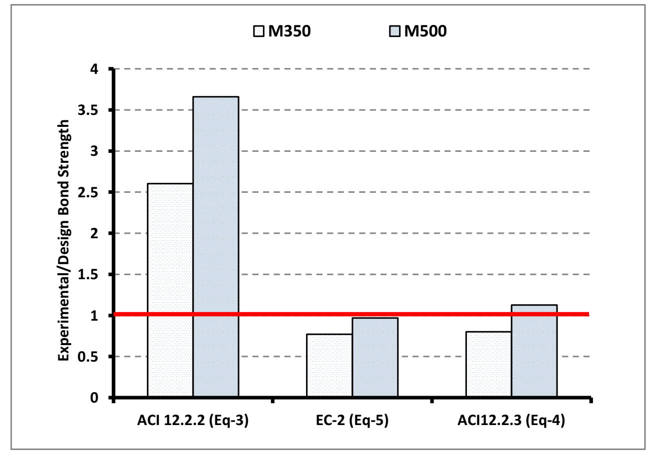

Fig. 18. Experimental to Design bond strength ratio (EDR) for all LWC mixes (Rebar diameter = 20 mm.

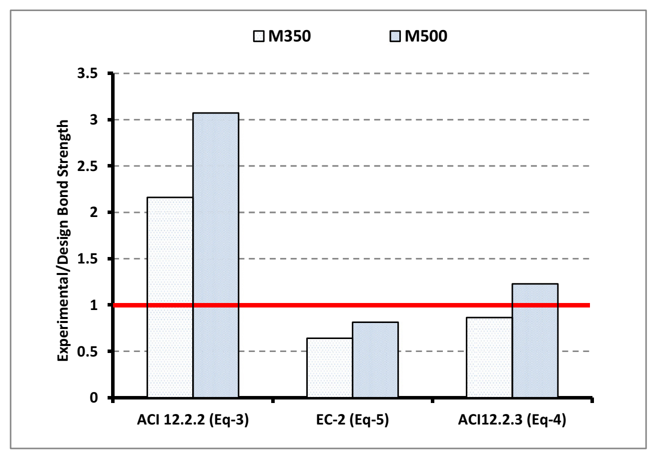

Fig. 19. Experimental to Design bond strength ratio (EDR) for all LWC mixes (Rebar diameter = 25 mm).

λ = light weight aggregate factor (0.75)
c_b = spacing or cover dimension, mm
K_{tr} = transverse reinforcement index,

Eq. (3) is intended for many practical construction cases and it yields bond strengths that are 25–40% lower than those predicted by Eq. (4), which allows the designer to account for the actual values of the variables that control the development length. These expressions and their factors were determined in accordance with the conditions that pertain to the current tests.

The European code EC2, 2003, specifies the following expression for determining the ultimate bond stress:

$$f_b = 2.25\eta_1\eta_2 f_{ctd} \tag{5}$$

where coefficient η_1 is related to the quality of the bond condition and bar location during concreting and η_2 is related to the rebar size. Here, both these coefficients are equal to unity ('good' bond conditions and diameters are less than 32 mm). The concrete design tensile strength f_{ctd} is defined in the European code as:

$$f_{ctd} = \alpha_{ct} f_{ctk,0.05}/\gamma_c$$

where α_{ct} is a coefficient accounting for long term effects with a recommended value of 1.0 and γ_c is a partial safety factor, which was set to 1.0 for the purpose of comparison with actual test results. The concrete characteristic axial tensile strength $f_{ctk,0.05}$ (5% fractile) is defined as:

$$f_{ctk,0.05} = 0.7 * f_{ck}^{\frac{2}{3}}$$

and f_{ck} is the 28 days characteristic compressive cylinder strength of concrete. The European code limits the use of the equation to a maximum strength f_{ck} of 60 MPa (a similar limitation is set also in ACI 318-08).

Figs. 15 through 19 show the experimental-to-design bond strength ratios (EDR) where the design strengths were calculated according to Eqs. (3)(5). The Figures show that the experimental-to-design ratios were higher than 1.0 for all cases when the bond strength was calculated using the ACI 12.2.2 equation. Equation 12.2.3 of the ACI 308-08 and Eurocode-2 equation yields better results for bond strength as compared to experimental pull-out bond stresses, as shown in the Figures. However from the results it is clear that the development length equations which were developed using results for normal strength concrete mixes need to be re-evaluated for light weight concrete mixes, and if they are used, it has to be done with caution.

5. Conclusions

Based on the experimental test results, and the analytical investigation performed, the following conclusions can be drawn:

1. The pullout load-slip curves of deformed steel bars embedded in SLWC's reported in this investigation compare reasonably well with similar curves available in the literature for normal and lightweight concretes. This may boost the acceptance of this material by the concrete industry sector.
2. Test results indicated that the load-slip behavior of the deformed steel bars embedded in structural lightweight concrete (SLWC) is dependent upon the compressive strength, bar diameter and embedment length. Peak load rebar slip values of 1.2 mm to 2.4 mm were observed in rebars of different diameters embedded in SLWC, which is comparable to normal weight concrete
3. The bond strength of deformed steel bars embedded in structural lightweight concrete increased with the increase in compressive strength but decreased as the bar diameter was increased for the embedment length used in this study.
4. The ACI 318-08 equation 12.2.2 for calculating development length of deformed steel bars in tension can be safely used and is conservative enough for predicting the development length in tension for rebars in structural lightweight concrete.
5. The pullout test results indicated that the bond formulas of normal weight concrete can be applied to lightweight concretes with caution.

Acknowledgements

This project was supported by NPSTIP strategic technologies program number (ADV1190) in the Kingdom of Saudi Arabia. The authors are grateful to the engineers and the technicians at the concrete and structural laboratories for their assistance during the execution of the experimental program.

References

ACI 318-08. Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Detroit, Michigan.

ASTM A615/A615M, 2013. Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement, doi: http://dx.doi.org/10.1520/A0615-A0615M.

ASTM C 234, 1991. Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel. Annual Book of ASTM Standards, Vol. 4.02, pp. 153-157.

ASTM C 39, 1991. Standard Test Method for Determining the Compressive Strength of Concrete, Annual Book of ASTM Standards, vol. 4.02, pp. 20-24

Charif, A., Shannag, M., Dghaither, S., 2014. Ductility of reinforced lightweight concrete beams and columns. Lat. Am.J. Solids Struct. 11, 1251–1274.

Elfgren, L., Noghabai, K., 2002. TC 147-FMB fracture mechanics to anchorage and bond. Mater. Struct. 35, 318–325.

EC2, 2003. Design of Concrete Structures-Part 1.1: General rules and rules for buildings. European Standards.

Gjørv, O., Monteiro, P.J.M., Mehta, P.K., 1990. Effect of condensed silica fume on the steel-concrete bond. ACI Mater. J. 87 (6).

Hassan, A.A., Hossain, K.M.A., Lachemi, M., 2010. Bond strength of deformed bars in large reinforced concrete members cast with industrial self-consolidating concrete mixture. Constr. Build. Mater. 24, 520–530.

Holm, T.A., Bremner, T.W., 2000. State-of-the-art Report on High-strength, High-durability Structural Low-density, Concrete for Applications in Severe Marine Environments. U.S. Army Corps of Engineers.

Hossain, K.M.A., 2008. Bond characteristics of plain and deformed bars in lightweight pumice concrete. Constr. Build. Mater. 22, 1491–1499.

Kayali, O., Yeomans, R.S., 2000. Bond of ribbed galvanized reinforcing steel in concrete. Cem. Concr. Compos. 22 (6), 459–467.

Lundgren, K., 1999. Three-dimensional Modeling of Bond in Reinforced Concrete: Theoretical Model, Experiments and Applications (Ph.D. dissertation). Chalmers University of Technology, Sweden.

Mor, A., 1992. Steel-concrete bond in high-strength lightweight concrete. ACI Mater. J. 89 (1), 76–82.

Moufti, M.R., Sabtan, A.A., El-Mahdy, O.R., Shehata, W.M., 2000. Assessment of the industrial utilization of scoria materials in central Harrat Rahat. Saudi Arabia. Eng. Geol. 57, 155–162.

Orangun, C.O., 1967. The bond resistance between steel and lightweight-aggregate (Lytag) concrete. Build. Sci. 2 (1), 21–28.

Sabtan, A.A., Shehata, W.M., 2000. Evaluation of engineering properties of scoria in central Harrat Rahat. Saudi Arabia. Bull. Eng. Geol. Environ. 59, 219–225.

Sancak, E., Simsek, O., Apay, A., 2011. A comparative study on the bond performance between rebar and structural lightweight pumice concrete with/without admixture. Int. J. Phys. Sci. 6 (14), 3437–3454.

Shannag, M., Charif, A., Dghaither, S., 2014. Developing structural lightweight concrete using volcanic scoria available in Saudi Arabia. Arabian J. Sci. Eng. 39, 3525–3534.

Valcuende, M., Parra, C., 2009. Bond behavior of reinforcement in self-compacting concretes. Constr. Build. Mater. 23, 162–170.

White, J.K., MacGregor, J.G., 2008. Reinforced Concrete: Mechanics and Design,. Prentice-Hal, p. 1110.