Innovative Infrastructure Solutions (2023) 8:184
https://doi.org/10.1007/s41062-023-01153-2

PRACTICE-ORIENTED PAPER

Bond strength behaviour of high strength structural lightweight concrete containing steel fibres with different geometries

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Received: 17 March 2023 / Accepted: 19 May 2023 / Published online: 30 May 2023

Abstract

This study was undertaken to investigate the bond strength behaviour of high strength lightweight concrete containing steel fibres in different geometries throughout a comprehensive experimental programme. Four lightweight concrete mixes were prepared and tested for the preliminary mechanical properties and pullout feature. In addition to the reference mix, the other three mixes incorporated micro, hook end and hybrid steel fibres at 1.5% by volume of the concrete mix. To evaluate the bond strength aspect, block specimens were reinforced with deformed steel bars of two diameters (12 or 25 mm). A comparison has been made with some relevant empirical formulas and codes of practice. The results obtained revealed superior performance for the fibrous lightweight concrete mixes in terms of the mechanical properties. The highest improvement in the compressive, tensile and pullout strengths reached 28, 163 and 225%, respectively. For the preliminary mechanical tests (i.e., compressive, tensile strengths), hybrid lightweight concrete mix showed the highest values, while hook end lightweight concrete mix seem to be the optimal for the case of pullout feature. Regardless of the geometry, the steel fibres increase the interior bond and prevent the propagation of cracks throughout tailoring mechanism. Most of the suggested formulas to predict the tensile and bond strengths need for amendments to be used for the case of high strength lightweight concrete.

Keywords Lightweight concrete · Bond strength · Pullout test · Fibre reinforcement

List of symbol

f_{lctm}	The tensile strength of the lightweight concrete (MPa)
f_{ctm}	The tensile strength of the normal weight concrete (MPa)
f_{ck}	The compressive strength of normal weight concrete (MPa)
η_1	Coefficient
ρ	The density of lightweight concrete in (kg/m^3)
f_{lck}	The compressive strength of lightweight concrete (MPa)
σ_{sflc}	The contribution of an individual steel fibre in the maximum residual stress (MPa)
σ_f	The fibre stress (MPa)
V_f	The volume of added fibre (mm^3)
$P_{\max}$	The maximum pullout force in (N)
A_c	The area of concrete surrounding the fibre dosage (mm^2)
τ_b	The bond strength (MPa)
d_f	The diameter of steel fibre (mm)
L_E	The embedment fibre length which is recommended to be $> 5d_f$ to obtain the maximum pullout strength (mm)
σ_{lc}	The net residual tensile stress of the plain lightweight concrete with a strength level of 30 to 40 MPa (MPa)
τ_{sp}	The slipping bond strength (MPa)
f_c	The compressive strength (MPa)
c	The thickness of concrete cover (mm)
d_b	The diameter of rebar (mm)

Introduction

The use of lightweight concrete is back to more than 50 years ago when its structural applications appeared for the first time in countries such as US, UK, Sweden, and Italy [1]. In recent years, such applications showed a sharp increase in a global basis. For example, in the UK, the production of lightweight concrete in the field of block application reached 20,625 thousand square meters in 2019 [2–4]. The reason

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for this is related to the potency of lightweight concrete in the criteria of weight, resistance to weathering and sustainability. Accordingly, many pros can be achieved with the use of lightweight concrete such as reduce the total load of the entire structure, saving the overall cost of the construction, increase the speed of work and lowering the handling cost, lowering the thermal conductivity, greater fire resistance, higher sound absorption and ability to consume recycled materials. With the enhancing of the ultimate strength, lightweight aggregate concrete has exceptional appeal for use in a wide range of offshore and maritime building projects, bridges with lengthy spans, and rising structures [5–8].

Basically, structural lightweight concrete is defined as a concrete made of either lightweight aggregate or expanding agent [9–11] with a dry density does not exceed 1840 kg/m^3 and 28-day compressive strength greater than 17 MPa. Increasing strength without increasing density, or decreasing density without decreasing strength, in combination with adequate durability, can lead to cost-effective engineering solutions [12]. Both natural and artificial lightweight aggregates (LWAs) can be used in production of structural lightweight aggregates. However, because artificial LWAs are formed by certain processes, their physical and microstructural features may be precisely controlled. Among the available artificial LWAs, expanded clay is considered the common type which can be used in a wide range of structural applications.

Fibres as an additional element inside the concrete mix are considered for improving various engineering qualities of concrete [13]. Fibre-reinforced systems have improved flexural capacity, durability, post-failure ductility, and cracking control [14, 15]. As the brittleness behaviour of LWAC diminishes the intended role of LWAC, which is the ductile performance under various stresses, this drawback can be solved by using the number and proper type of fibres [16]. The former effect of reinforcing fibre on the compressive, tensile, and flexural strengths and plasticity of normal weight concrete has been demonstrated in several previous experimental studies [17]. In terms of structural quality, a high proportion of the technical qualities of concrete, such as ductility, impact resistance, and hardness, are considerably improved by the inclusion steel fibres.

In addition, inclusion steel fibres in concrete brings a dramatic enhancement in compressive ductility, toughness, and energy absorption at early ages [17]. Using the palm oil clinker (POC)-based as a lightweight aggregate, Hosen et al. [18] has found that the compression ductility, displacement ductility and energy ductility indexes increased by up to 472, 140 and 568% compared to the control specimens (concrete with 0% steel fibers), respectively. Similar results were also noted by Ye et al. [19]. Besides, longer service life has been noted for the fibre-reinforced concrete than conventional concrete due to the function of fibres in inhibiting the growth of cracks inside the concrete [13]. For the case of structural lightweight concrete, Li et al. [20] stated that the use of hook end steel fibre as well as cementitious materials increases the tensile strength of fibre reinforced LWAC. However, this inclusion reduced the workability of plain LWC and increased its density [13].

In the design of reinforced concrete structures, the characteristics of bond between the inner concrete surfaces and reinforcing bars is a critical consideration as they assumed to be integrated into one element. Previous studies [21, 22] have demonstrated that the pressure parallel to the direction of steel bars induces the crucial tension between concrete and rebar reinforced. To assess the former behaviour, pull-out test method is usually experimentally adopted. Several experimental measurements [10, 11, 23] illustrated that the bond-slip aspect is significantly affected by the variation in the concrete composition. Consequently, the calculations of lap and anchorage lengths which are the design criteria for the reinforced concrete members are changeable. Hence, employing the suggested equations indicated in the practical codes becomes unreliable.

Due to the substantial differences between the ingredients of LWAC and NWC, currently, there is no clear understanding for the bond-slip behaviour of structural LWAC [24]. Despite a lot of research works the issue of bond-slip of the reinforced concrete members have been recently published, however, to the best of the author knowledge, no investigation has been conducted on the pullout behaviour of high strength lightweight concrete (LWC) containing steel fibres in different geometries. In this study, hook end, micro and hybrid steel fibres were used to evaluate the bond strength of high strength LWC in terms of bond-slip feature using block samples. A comparison was also made with some formulas suggested by relevant studies and codes of practice.

Experimental programme

The methodology of the experimental programme adopted in this study consists of two steps: the first step is related to produce structural lightweight concrete with a strength level more than 35 MPa at age of 28-day, while the second step is designed to evaluate the preliminary mechanical properties and bond strength aspect throughout pull-out tests for the formulated lightweight concrete block samples containing steel fibres with different geometries and inclusion ratios.

Materials

The materials used in this study were ordinary Portland cement, natural sand, expanded clay, tap water, superplasticizer and steel fibres. The next sections describe the properties of the former materials.

Ordinary Portland cement

Ordinary Portland cement produced under the trademark of Al-Kufa cement factory was used as a binder for all concrete mixes. This type of cement comply with the Iraqi Standard No. 5 of 2019 [25] under the category of cement 42.5. The chemical composition and physical properties of this type of cement are illustrated in Table 1.

Aggregate

Natural sand for general purposes was used as a fine aggregate and it was consistence with the limitations of EN BS 882.1992 [26] and have a maximum particle size, fineness modulus and sulfate content of 4.75 mm, 3.1 and 0.173%, respectively. Figure 1 shows the grading of the sand used. Lightweight expanded clay aggregate commercially named LECA was used as a coarse aggregate with a maximum particle size of 8 mm, as shown in Fig. 2. It has specific gravity, absorption, and bulk density of 1.2, 12% and 650 kg/m^3, respectively. Table 2 shows the grading of LECA coarse aggregate which is consistent with the limitations of ASTM C136-06 [27].

Superplasticizer

To achieve a suitable consistency (100 ± 10 mm slump), GLENIUM 54 was used as a high-range water reducer and superplasticizer (SP) admixture based on modified polycarboxylic ether. This admixture meets the limitations of ASTM C-494, type G [28].

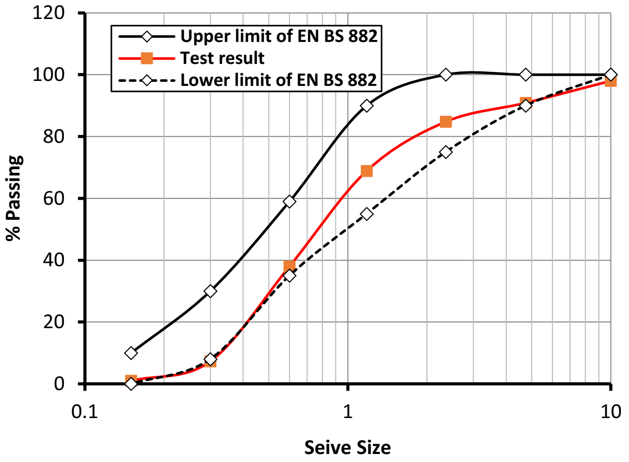


Fig. 1 Grading of the natural sand used as fine aggregate

Steel rebars

For measuring the bond-slip aspect, two deformed rebars with diameters of 12 and 25 mm were used and partially embedded in the lightweight concrete mixes. They have ultimate tensile and yield tensile strengths of 680.3 and 557.23 MPa, respectively, and they were consistent with the requirements of ASTM A615 M-12, Grade 40 [29].

Table 1 The chemical composition and physical properties of the ordinary Portland cement

Chemical composition	Weight (%)	Limits of Iraqi specification No. 5-2019 [25]
CaO	63.73	–
SiO_2	20.69	–
$Al2O_3$	5.65	–
$Fe2O_3$	3.38	–
MgO	3.66	≤ 5
SO_3	2.58	≤ 2.5
L.O. I	1.28	≤ 4
I.R	0.54	≤ 1.5
L.S.F	0.90	0.66–1.02
C3S	42.26	–
C2S	36.36	–
C3A	9.25	–
C4AF	12.13	–
Property	**Test result**	
Fineness	1.97%	< 5%
Initial setting time, min	90	> 45
Final setting time, h: min	2:35	≤ 10:00

Fig. 2 Expanded clay LACA used as coarse aggregate

Table 2 Grading of the LECA coarse aggregate

Sieve size	Cumulative passing %	Limits of ASTM C136-06 [27]
1 in	100	100
¾ in	100	90–100
3/8 in	90	80–100
No. 4	42	5–40
No. 8	13	0–20
No. 16	7	0–10
No. 50	1	–
No. 100	0	–

Steel fibres

Two types of steel fibres were used, namely micro and hook end, as shown in Fig. 3. Moreover, hybridization technique was followed using combination between the former steel fibres (i.e., 50% micro steel fibres and 50% hook end steel fibres). The steel fibres were added as a ratio of the total volume of the mix and their orientations were randomly distributed within the lightweight concrete mixes. Both micro and hook end steel fibres have an aspect ratio of 60 and their other engineering properties are shown in Table 3.

Selection and mix design of the lightweight concrete mixes

The mix design calculations for the reference lightweight concrete mix were carried out based on the procedure suggested by [30] in addition to the previous studies [5, 6, 31, 32]. After multi trial mixes with the variation of the *W/C* ratio to get the desired slump value (90 mm), the mix proportions of the reference lightweight concrete mix (L–R) are 425.6 kg/m^3 cement: 447.58 kg/m^3 sand: 259.72 kg/m^3 LECA and *W/C* = 0.38. Thereafter, steel fibres were added to the selected lightweight concrete mix with a total ratio of 1.5% by volume of the concrete mix. This implies producing a further three lightweight concrete mixes. Some guidelines have stated that the total maximum ratio of the added steel fibres should not exceed 2% by volume of concrete mix [33, 34]. Besides, due to the limitation of the experimental work and focusing on the structural behaviour of full-scale beam elements which is the topic of the second phase of this study, so us the current investigation was limited to only eight combinations of steel fibres. To compromise the consistency of the lightweight concrete mixes containing steel fibres, the superplasticizer (SP) admixture was used with a dosage of 1% from the cement weight implying reduction to the original *W/C* to be 0.35. Incorporating the steel rebars into the developed lightweight concrete mixes gives eight different samples, two of them are reference lightweight concrete mixes: one of those containing rebar of Ø12mm (i.e.,

(a)

(b)

Fig. 3 Steel fibres; **a** micro steel fibre, **b** hook end steel fibre

Table 3 Properties of steel fibres

Type of steel fibre	Length (mm)	Dimeter (mm)	Aspect ratio	Tensile strength (MPa)	Density (kg/m^3)
Micro steel fibre	13.01	0.22	60	2850	7848
hook end steel fibre	30.48	0.51	60	1300	7844

L-R-12) and the other for those containing rebar of Ø25 mm (i.e., L-R-25), as shown in Table 4.

Preliminary mechanical tests

Prior performing the pullout test, the preliminary mechanical properties of the reference and fibre reinforced lightweight concrete mixes were measured. These involved measuring density, compressive and splitting tensile strengths at 7 and 28-day age according to the BS EN12390-7 [35], BS EN 12390-3 [36] and BS EN 12390-6 [37], respectively. Cube and cylinder specimens with dimensions of 150 × 150 × 150 mm and 100 × 200 mm, respectively were used in these tests. For each testing case, two specimens were measured, and the average reading was considered.

Preparing the block samples

In order to cast lightweight concrete block samples used for the pullout test, play-wood molds were formulated. These molds were made in two different configurations to suit the diameter of the reinforced steel bar based on the Technical Recommendations for the Testing and Use of Construction Materials, RILEM RC 6, Bond Test for Reinforcement Steel. 2. Pull-Out Test [38] in addition to previous research works [39, 40]. The dimensions of the first molds group were 200 × 120 × 120 mm ($l \times w \times h$), which is designed for conducting the pullout tests on lightweight concrete blocks reinforced with steel bar of 12 mm. The second molds group were made with dimensions of 375 × 250 × 250 mm ($l \times w \times h$) suite the pullout tests on the lightweight concrete blocks reinforced with steel bar of 25 mm. The embedded lengths of the reinforced steel bars were 250 and 140 mm for the first and second mold groups, respectively. Figure 4 shows the details of the block samples with their wooden molds, while Fig. 5 presents these molds ready for casting.

Mixing, casting, and curing operations

In this study, the instructions described in the BS EN12390-2 [41] were followed for the mixing, casting, and curing operations for both specimens used in the preliminary mechanical tests and concrete blocks. The steps of mixing operation can be summarized as follows:

1. The LECA and sand were mixed in dry situation for two minutes then with the half of the mixing water for another 2 min.
2. The cement powder was added and the whole mixture was mixed for additional 60 s.
3. The steel fibres were added, and mixing operation was done until reaching a homogenous composition.
4. The superplasticizer was added to the remaining water then to the mixture, and thoroughly blended for 7 min.

Figure 6 shows the block samples after completing the casting process. All lightweight concrete blocks were cured in tap water for a period of 28 days.

Table 4 Details of the lightweight concrete mixes used in this study

Mix category	Micro steel fibre (%)	Hook end steel fibre (%)	Diameter of the steel bar (mm)	Cement (kg/m^3)	Sand (kg/m^3)	LECA (kg/m^3)	Water (kg/m^3)	SP (%) from cement weight
L–R-12	0	0	12	425.6	447.58	259.72	161.73	0
L–R-25	0	0	25					
L–M-12	1.5	0	12	425.6	447.58	259.72	149.00	1
L–M-25	1.5	0	25					
L–H-12	0	1.5	12					
L–H-25	0	1.5	25					
L–HY-12	0.75	0.75	12					
L–HY-25	0.75	0.75	25					

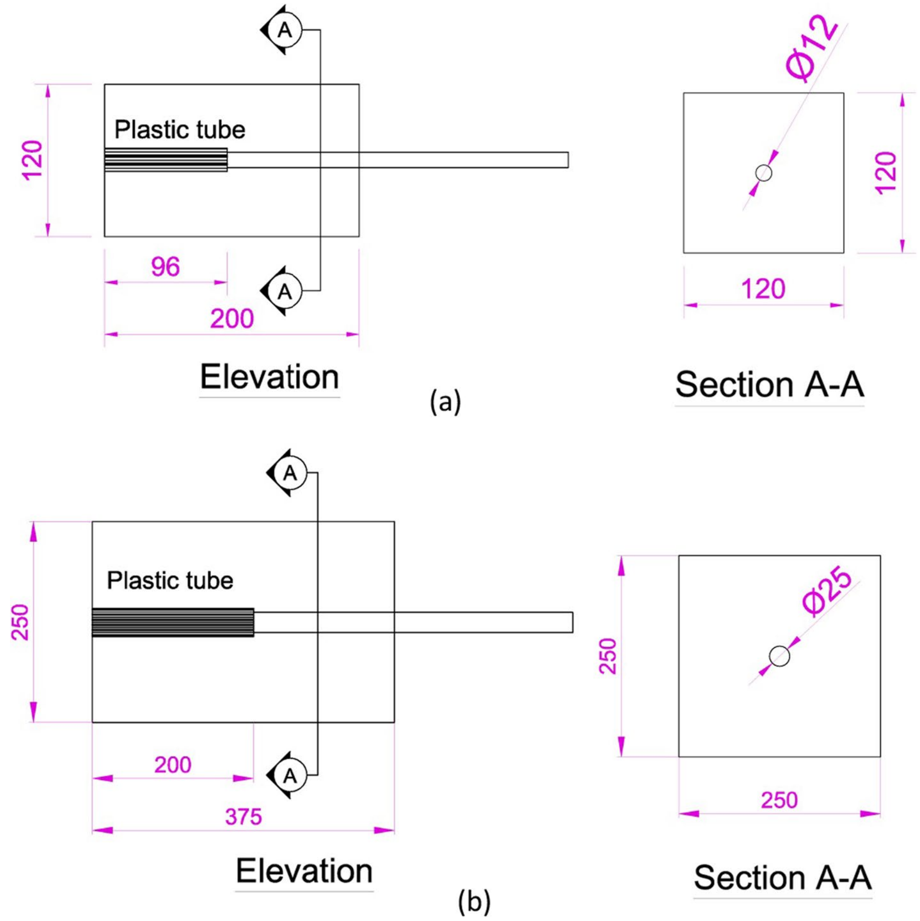


Fig. 4 Details of the wooden molds used for casting the lightweight concrete blocks: **a** molds of 12 mm steel bars; **b** molds of 25 mm steel bars

Fig. 5 The wooden molds are ready for casting the lightweight concrete blocks

Setup of the test and the measured parameters

The target of this investigation is to evaluate the bond strength of the developed lightweight concrete mixes via pullout tests based on the Technical Recommendations for the Testing and Use of Construction Materials, RILEM RC 6, Bond Test for Reinforcement Steel. 2. Pull-Out Test [38] in addition to previous research works [39, 40]. For this, universal tensile test machine with capacity of 50 Tons has been used. Aa universal jacket was prepared and used at each test for the purpose of holding the block samples within the tensile machine, as shown in Fig. 7. This also allows for applying pure tensile force on the steel bar while the upper concrete surface kept holding under compression. The adopted loading rate was 0.5 MPa/s. The applied load was continued either for completely slip out the reinforced steel bar or failure of the block sample. During performing the test, bond-slip parameters were measured throughout recording the tensile load and the corresponding slip displacement using dial gauge. The failure modes were also observed for each testing case. Two specimens were considered for each testing case and the average value was taken.

Results and discussions

Preliminary mechanical properties

The results of the preliminary mechanical properties are illustrated in Table 5. It is obvious that all the density

Fig. 6 The lightweight concrete block samples after completing the casting process

Fig. 7 Setup of the pullout test

values of the tested specimens are below the maximum specified limit for the structural lightweight concrete (i.e., no more than 1800 kg/m^3). However, addition of steel fibres leads to an increase in the density of lightweight concrete samples with a value reaching 130 kg/m^3. This is clearly known, as the specific gravity of the steel fibre is higher than that of cement ingredient and the inclusion of steel fibre was carried out based on the volume substitution. Another matter to be considered is the lightweight aggregates are porous, which means they contain small air pockets or voids. These voids are usually filled with the hydration products which lead to an increase in the density value of the produced lightweight concrete sample over the summation weights of mix ingredients [42, 43].

For the compressive strength, the reference lightweight concrete recorded 37.30 MPa at 28-day age which falls within the range of the high strength concrete. The percentage increase in the strength from the age of 7–28 days was 25.5%. The corresponding percentage increases for the L–M, L–H and L–HY mixes were 9.5, 15.2 and 21%, respectively. This indicative for the effect of the steel fibre on the inner structure of concrete in which inconsistency interfacial transition zone can be obtained due to multi voids released around the steel fibre. Nevertheless, the overall strength level increased as the added fibres contributed to supporting more applied loads with tendency to achieve ductile material. Similar behaviour was also noted in previous studies [15]. Among the four tested lightweight concrete mixes, mix L–HY revealed the highest compressive strength of 47.8 MPa at 28-day age. Such an attitude explains the advantage of the hybridization technique where both adhesion and ductility characteristics can be obtained. The percentage increase in the compressive strength for former mix at 28-day age compared to the reference one is 28%.

A similar tendency to that of compressive strength was also noted for the splitting tensile feature where the L–HY mix showed the highest value at 7.2 MPa. In contrast to what was noted in the compressive strength, the growth of tensile strength from 7 to 28-day age was higher for the concrete mixes containing steel fibres. The percentage increase in the value of splitting tensile strength at 28-day age compared to those at 7 days were 18.6, 24, 24.7 and 27.2% for the L–R, L–M, L–H and L–HY mixes, respectively. This can be

Table 5 Results of the preliminary mechanical tests

No.	Mix symbol	Density (kg/m^3)	Compressive strength (MPa)		Splitting tensile strength (MPa)		Slump (mm)
			7 days	28 days	7 days	28 days	
1	L–R	1647.0	29.70	37.30	2.30	2.73	90
2	L–M	1718.5	35.70	39.10	5.40	6.70	90
3	L–H	1748.0	36.50	42.08	5.53	6.90	90
4	L–HY	1777.7	39.50	47.80	5.66	7.20	90

attributed to nature of the applied load and the role of the steel fibres in eliminating the tensile carks which normally leads to failure of concrete specimens. The failure modes shown in Fig. 8 support the former explanation where the steel fibres tailor the propagated cracks and converting the brittle attitude of reference concrete to be more ductility. Among the tested samples, the concrete mix containing hybrid steel fibres (L–HY) displayed a better tailoring process where multiple cracks with refined mechanism was achieved, hence whole mechanical properties of this lightweight concrete mix were improved, as indicated in Fig. 8d. On this basis, this approach is considered feasible for further structural applications.

It is worth mentioning that the BS EN 1992-1-1 [44] suggested the following expression to be used to foretell the tensile strength of lightweight concrete according to its density and the characteristics of normal weight concrete.

$$f_{lctm} = f_{ctm}.\eta_1 \tag{1}$$

$$f_{ctm} = 0.3 f_{ck}^{2/3} \tag{2}$$

$$\eta_1 = 0.4 + 0.6\rho/2200 \tag{3}$$

However, for simplification, the above equations linked the predicted tensile strength to the compressive strength of normal weight concrete without mentioning its strength level.

In this study, based on the results presented in Table 5, Eqs. (4) and (5) were derived to compute the splitting tensile strengths of reference and fibre reinforced lightweight concrete mixtures at any testing age directly from their compressive strength values, respectively. It is clearly shown that the constant of these equations was approximately double for the concrete mixes containing steel fibres due to the role of such kind of fibres in enhancing the tensile strength.

$$f_{lctm} = 0.075 f_{lck} \tag{4}$$

$$f_{lctm} = (0.14 - 0.15) f_{lck} \tag{5}$$

Bond-slip behaviour

Figures 9 and 10 show the test results of the pullout feature in terms of bond-slip for lightweight concrete blocks investigated in this study. For the block samples reinforced with steel bar of 12 mm diameter, the lowest force needed to pullout the embedded bar was recorded for the reference lightweight concrete mix at 26.8 kN, as shown in Fig. 9. When the steel fibres were added to lightweight concrete mix, superior performance was noted as the maximum pullout force reached 87 kN. This behaviour is associated with a notable increase in the amount of slipping out before the failure occurred reaching 66% compared to that of reference mix. The reason for this is related to the obstructions which appear when the steel fibres are added, meaning further adhesion is obtained for the inner composition of concrete. At the same slip value, lower pullout force was observed for the case of reference lightweight concrete compared to those of steel fibre samples. Moreover, the bond-slip curve converted from steep to flat nature at one-third of the ultimate load for the reference sample. The former transfer was noted at 80% of the ultimate load for the steel fibres reinforced samples.

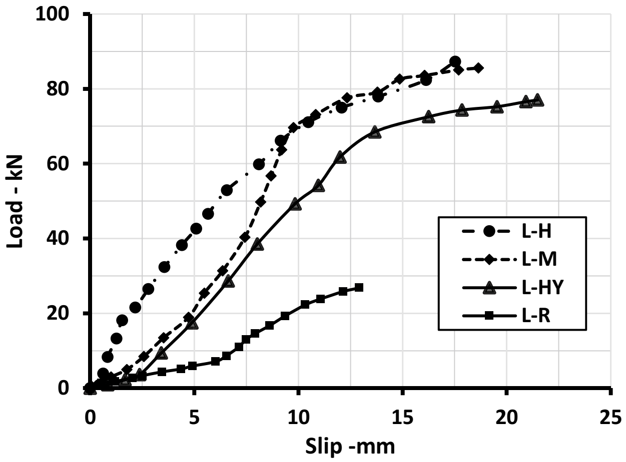
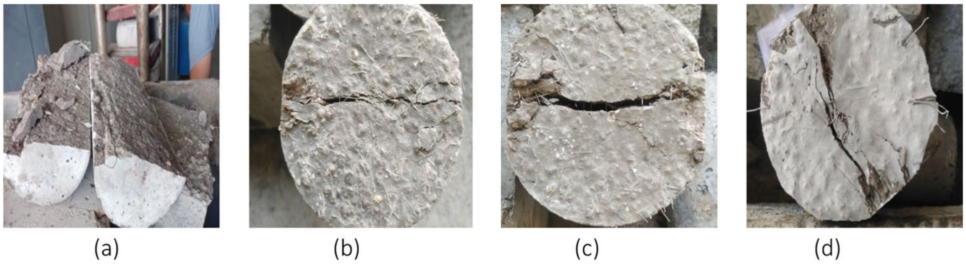


Fig. 9 Load–slip relationship for the lightweight concrete mixes reinforced with 12 mm steel bar

Fig. 8 Failure modes of the tested specimens; **a** L–R mix; **b** L–M mix; **c** L–H mix; **d** L–HY



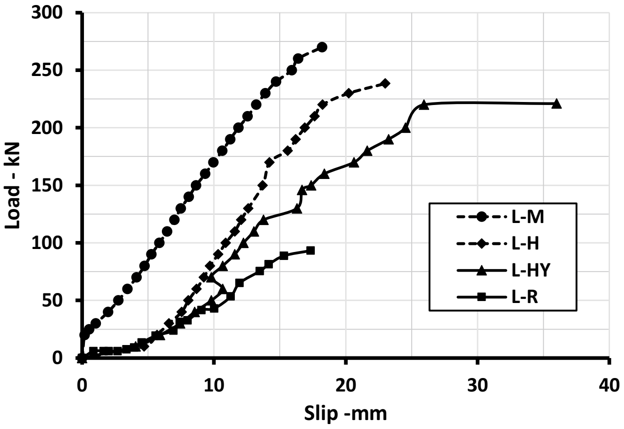


Fig. 10 Load–slip relationship for the lightweight concrete mixes reinforced with 25 mm steel bar

In terms of the core role of the different fibre geometry, contrast attitude to what was noted in the compressive strength aspect test in the preliminary mechanical properties, where the highest bond value was recorded for both hook end and micro steel fibres not for the hybrid fibre. This behaviour may be due to the interfere with the rib of steel bar in the generated obstructions, so the most homogenous fibre system could growth the highest pullout resistance. However, the overall improvement in the bond characteristic was 3.25 times when the steel fibres are added to the reference lightweight concrete mix, while it was 1.27 times in the compressive strength aspect.

Except for the order of the highest improvement in the bond behaviour due to the use of steel fibre, a similar tendency was also noted for block samples reinforced with steel bars of 25 mm, as shown in Fig. 10. However, the magnitude of the pullout load was higher. This is well understood as the geometry of the deformed steel bar of Ø25mm is different from that of Ø12mm, in addition to the differences in the embedded length of steel bar and the size of the concrete block. If these parameters are taken into consideration, reliable results can be obtained, as shown in Table 6, in which the results have been presented in terms of the bond strength rather than pullout force. It was noted that the highest percentage increase in the ultimate bond strength is recorded for L–H-12 samples at 225.6%, on the other hand, highest percentage increase in the slip value was recorded for the L–HY-25 samples at 107.5%. Such results are promotion for the superior role of steel fibres.

The failure modes of the block samples are shown in Fig. 11a–f. Splitting failure mode was observed for the reference lightweight concrete samples as the crack patterns were along the embedded part of the steel bar. Inclusion of the hybrid steel fibre enhanced the bond strength, hence slipping failure modes are taken place, as shown in Fig. 11d and g. As mentioned before, this behaviour comes from the tailoring role of hybrid steel fibres. More bond resistance was obtained for the cases of micro and hook end steel fibres which leads to cutting off the reinforced steel bars without any disintegration mark in the concrete block samples, as shown in Fig. 11a, c, e, and f.

For deducing the contribution of an individual steel fibre in the maximum residual stress, Eq. 6 has been suggested by Al-Naimi and Abass [45].

$$\sigma_{sflc} = \sigma_f V_f \eta_0 = \frac{P_{\max}}{A_c} \tag{6}$$

where η_0 is a factor related to the randomness of the fibre within the concrete taken as 0.5 or determined using Lee et al. chart [46] with an assumption of no size effect.

As the above expression needs more effort to identify its parameters, direct calculation from the test results considered an alternative can be used to account the residual stress as per in Eq. 7 [45].

$$\sigma_{sflc} = 4\frac{\tau_b L_E}{d_f} \tag{7}$$

For the case of hook end fibre, the embedment length should be increased by the length of hook end length.

Table 6 Bond-slip values of the lightweight concrete mixes including comparisons with the reference mix

No.	Mix symbol	Ultimate bond strength (MPa)	Ultimate slip (mm)	% Increase in the bond strength value	% Increase in the slip value
1	L–R-12	5.08	12.92	0.00	0.00
2	L–M-12	16.22	18.63	219.32	44.26
3	L–H-12	16.54	17.52	225.60	35.65
4	L–HY-12	14.60	21.49	187.39	66.30
5	L–R-25	5.94	17.35	0.00	0.00
6	L–M-25	17.20	18.20	189.42	4.90
7	L–H-25	15.18	23.00	155.55	32.56
8	L–HY-25	14.08	36.00	136.89	107.5

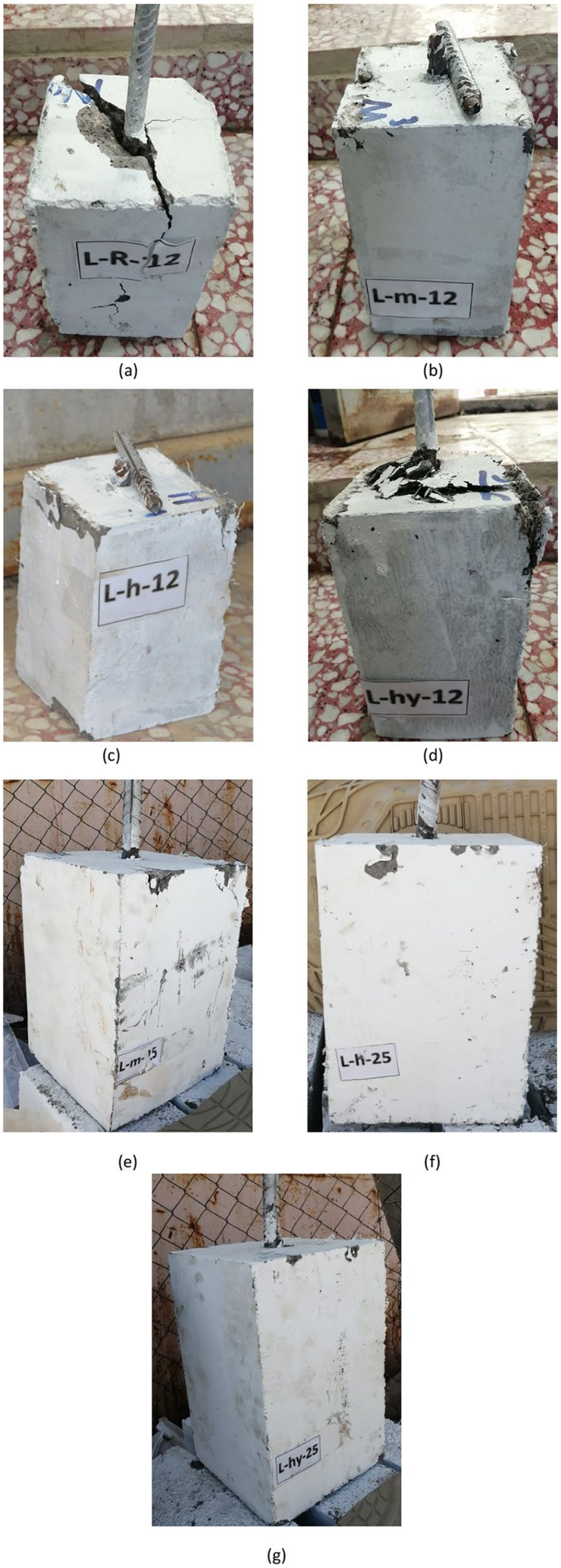


Fig. 11 Failure modes of the lightweight concrete mixes; **a** L–R; **b** L–M-12; **c** L–H-12; **d** L–HY-12; **e** L–M-25; **f** L–H-25; **g** L–HY-25

For the net residual tensile stress of the plain lightweight concrete with a strength level of 30–40 MPa, Eq. 8 has been proposed in the study of Al-Naimi and Abass [45]:

$$\sigma_{lc} = 0.065 f_{lcm} \tag{8}$$

For the comparison and validation purposes based on the results obtained in this study, it is obvious that Eq. 4 is more appropriate to match the measured data than what is indicated in Eq. 8. Besides, the contribution of individual steel fibre in the bond strength can be calculated using Eq. 7 where the input data are the enhancement value of steel fibre in the tensile strength (MPa) (from Table 5) as well as the properties of the steel fibres (i.e., the length and diameter). Assuming $L_E = 5d_f$ to ensure maximum pullout strength, the theoretical influence of selected numbers of steel fibres (17, 34, 51 and 68) on the bond strength are shown in Table 7. The former selected numbers were chosen as approximately an equivalent to 0.5, 1, 1.5 and 2% steel volume, respectively. Taken in consideration subtracting the net effect of plain lightweight concrete in the bond strength, it can be seen reliable result is only obtained for the contribution of micro steel fibre to the bond strength compared with the measured values presented in Table 6. Increasing the numbers of hook end and hybrid steel fibres should exhibit more bond strength than those of micro as their geometries are twice as large. However, the theoretical calculations are inconsistent with the actual action as the bond strength is related only to the active steel fibres located at the tension surface of concrete and subjected to pullout forces.

In the range of compressive strength of 30–35 MPa, it was suggested using Eq. 9 proposed by Harajli et al. [47] to evaluate the splitting bond strength of lightweight concrete mixes reinforced with different geometries of rebars.

$$\tau_{sp} = 0.75\sqrt{f_c'}\left(c/d_b\right)^{2/3} \tag{9}$$

Applying Eq. 9 using the compressive strength data presented in Table 5, the evaluation outputs are shown in Table 8. It can be noted that the above suggested equation gives an overestimation bond strength value for the reference lightweight concrete mix reaching 145%, and it was underestimating for the bond strength values of the micro and hook end fibre concrete mixes. On the other hand, close agreement was observed for the concrete mix containing hybrid steel fibre.

Conclusions

The goal of this study was to investigate the bond strength of high strength lightweight concrete containing steel fibres with different geometries through an experimental

Table 7 Theoretical contribution of fibrous in the bond strength

Mix symbol	Enhancement of steel fibre to the tensile strength (MPa) (from Table 5)	Properties of steel fibre		Bond strength τ_b (MPa) based on the number of fibres used				
		d_f	l_f	1	14	34	51	68
L–M	3.97	0.22	13.01	0.20	3.37	6.75	10.12	13.50
L–H	4.17	0.51	30.48	0.21	3.54	7.09	10.63	14.18
L–HY	4.47	0.37	21.75	0.22	3.80	7.60	11.40	15.20

Table 8 Evaluation of bond strength values of lightweight concrete mixes based on Eq. 9

No.	Mix symbol	Measured bond strength (MPa)	Calculated bond strength using Eq. 9 (MPa)	% Difference
1	L–R-12	5.08	12.47	+145.52
2	L–M-12	16.22	12.77	−21.27
3	L–H-12	16.54	13.25	−19.91
4	L–HY-12	14.60	14.12	−3.29
5	L–R-25	5.94	12.47	+109.98
6	L–M-25	17.20	12.77	−25.76
7	L–H-25	15.18	13.25	−12.73
8	L–HY-25	14.08	14.12	+0.28

programme. The core points of the results obtained can be summarized as follows:

1. Adding steel fibres increases the density of the lightweight concrete with a percentage of 7.5%. Nevertheless, the density value did not exceed the maximum limit indicated for the structural lightweight (i.e., 1850 kg/m^3).
2. The compressive strength of fibrous lightweight concrete mixes exhibited a lower rate of increase over time compared to the reference mix. This can be attributed to the limitations imposed by the matrix as well as the likelihood of voids existing in the interfacial transition zone. The feature of tensile strength cannot be characterized in the same way.
3. The hybridization technique enhanced the behaviour of lightweight concrete samples subjected to both compression and tensile loading. However, it was less effective in the pullout test compared with the block samples containing micro or hook end fibres alone.
4. The role of steel fibres was clear in the fractured specimens where they tend to tailor the propagated cracks which permit to achieve double tensile strength of the reference samples.
5. The highest bond strength was for the hook end block samples at 16.4 MPa representing a percentage increase of 66%. While the highest slip value was noted for the hybrid block samples at 36 mm with a percentage increase of 136%.
6. The bond strength values of the lightweight concrete blocks reinforced with Ø12mm and Ø25mm were similar. This indicative for a constant bond strength with the keeping of similar ratio of rebar geometry and concrete cover.
7. Splitting failure mode was noted for the reference lightweight concrete blocks and it was converted to the slipping mode for the fibrous concrete blocks due to the role of steel fibres.
8. The contribution of the steel fibres in the bond strength depends on the number of the active steel fibres working on the concrete surfaces subjected to pullout forces and this cannot be estimated based on the bulk inclusion mechanism.
9. The known formulas used for prediction of the bond strength need for amendment to be used for the case of lightweight concrete samples.

Declarations

Conflict of interest The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Ethical approval The authors further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

Informed consent The authors agree to publish potentially identifying information, such as details or the case and photographs, was obtained from the patient(s) or their legal guardian(s).

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