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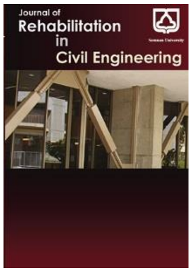

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A Rehabilitation Experimental Program on Low-Strength Concrete with Steel Bar Planting

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ABSTRACT

Many concrete structures need rehabilitation during their service life for different reasons; poor quality of construction, relatively lower compressive strength of concrete, non-compliance with existing or updated design codes, and buildings that experienced an intensive earthquake are to name but a few. One of the solutions to strengthen concrete structures is to install rebar inside the structural components. In this paper, the effect of steel rebar planting with a constant nominal diameter of 8 mm along with two different lengths (i.e., 35 and 55 mm) as well as two different planting angles (i.e., 0 and 45 degrees) have considered as variables. Therefore, the rebar planting process has conducted on 12 low-strength cylindrical concrete specimens with an initial compressive strength of 15.5 MPa. The concrete column specimens were tested under uniaxial compressive load after rebar planting. The results of this study indicated that rebar planting leads to an increase in the initial compressive strength of the concrete specimens in general. The specimens with 35 mm and 55 mm planted length witnessed an average enhancement of 17% and 23%, respectively. Moreover, considering the angle of planted rebar as another variable parameter, the obtained results revealed that the maximum compressive load for both 35 mm and 55 mm specimens with a planting angle of 0-degree and 45-degree almost followed the same increase and improved by an average of 5%.

1. Introduction

Some existed concrete structures require retrofitting due to many reasons; poor quality of materials, practical defects, damaging because of natural disasters like earthquake, construction errors, and non-compliance with the updated design codes, are to name but a few [1–3]. So far, various methods have been proposed to measure damage level and strengthen concrete structural components. Confinement plays a key role in the enhancement of axial structural elements such as columns [4]. It is proven that confinement is an efficient and popular method for this aim [5]. The procedure of confining structural elements like columns could be done in different ways. To illustrate, adding steel cage, concrete jacketing [6,7], and using fiber reinforced polymer (FRP) wrapping are common methods [4,8–13].

Concrete jacketing and using steel cage could be considered as the first methods and effective way to strengthen concrete structures [8,14,15]. Another development in this method is using a new strengthening approach of RC columns by applying fiber reinforced cementitious composites (HPFRC) sprayed mortar combined with additional reinforcing bars [16,17] the results demonstrated that the cyclic response of column specimens strengthened with HPFRC sprayed mortar enhance the hysteretic absorbed energy in comparison with conventional concrete. It is also proved in other studies that using fiber reinforced concrete significantly increases energy absorption as well as minimizing crack width [18,19]. Although It is proven in the previous researches that concrete jacketing was an effective solution to improve and restore the axial and lateral load capacity of damaged columns [20–23], an increase of columns dimension could impose limitations in terms of aesthetic and architectural concerns. Hence, using other methods might be a proper alternative in these cases.

Using FRP sheets as an external confinement is a popular method among others. It is also suggested by many researchers [4,10]. Xiau and wo [24] conducted an experimental program by testing 27 cylindrical concrete specimens under compression. The specimens were confined by carbon fiber reinforced polymer (CFRP) and the results revealed that using FRP confinement leads to an increase in both ductility and maximum strength. There are several studies [25–28] conducted on the effect of FRP wrapping which have proven the applicability of using FRP confinement on rehabilitation of damaged concrete columns. It is worth mentioning that the major drawback in this method is the high dependency of column shape on the effectiveness of strengthening, Yan et al. [29] conducted a series of experiment on cylindrical and rectangular concrete column specimens. The results indicated that FRP external jackets for square and rectangular columns are not as effective as they are for circular columns.

Rebar planting is usually utilized in structures to connect a concrete section to a new element; it should be noted that it can be done in both fresh and hardened concrete [30–33]. Rebar planting after concrete curing is usually carried out, using one of the following methods: 1) planting by glue 2) mechanical planting. In the first one, after boring a hole in the concrete and filling it with a special type of glue, which is usually epoxy resin or cement, rebar planting is performed. It should be considered that this method is more common since it is exerted at the project site easily [33]. Rebar planting by chemical glue has gradually replaced the planting by cement materials since 1990, with the enhancement and development of various types of polyester, vinyl ester, and epoxy glue [31,32,34]. Chemical glues are made of a special polymer, mixed filler, and usually a synthetic silica type. Very low contraction, very high fatigue resistance, acceptable performance against corrosion, as well as quick and easy installation, and utilization are some advantages of the aforementioned glues [35]. In this method, the overall strength of the planted rebar and concrete highly depends on the bond between the rebar and glue, as well as the bond between the concrete and glue. After loading a structural member, the tensile force is created in the concrete component that separates the glue from the concrete and it leads to the failure. In fact, in the aforementioned method, the shear strength of the glue is the main factor in achieving the desired failure mode [33]. It should be noted that there are three failure modes for concrete members strengthen with planting rebar method: a) steel bar rupture, b) glue rupture and rebar separation from concrete, and c) concrete fracture along with the removal of the rebar imbued with glue from concrete which is known as the desired failure mode. There are some parameters affecting rebar planting, among which are rebar diameter, bonding conditions of the planted rebar, and planting depth. It is worth mentioning that the rebar diameter is the most effective parameter in improving the performance of this method. Indeed, the increase of rebar diameter leads to the significant enhancement of strength [36].

On the other hand, one of the most common methods of stabilizing soil cuts is nailing (micro-pile nailing), the design of which is according to providing the arrangement of nails in the depth of the wall. By using trial and error method, nails arrangement should be chosen among the various layouts which meet the criteria of allowable safety factors of stability and displacement. It is worth mentioning that the length of a nail decreases from the top to the bottom of the wall. Nails are able to withstand tensile and shear forces, bending moments, and soil displacements. In the mentioned method, the major concept of design depends on the transfer of the tensile force created at the nail by the frictional or adhesion force in the joint area of the soil and nail. In the nailing system, by putting inactive nails together and forming a composite cohesive material, the soil is reinforced [37]. The behavior of reinforced soil depends on various parameters of reinforcing materials, nails' angles relative to the rupture surface, and magnitude of the force caused by friction and adhesion of nails in soil and mortar. [38].

It is tried to optimize the angle of nail planting and assess its effect on the pull-out capacity of the nails, by changing the nail angle. This can be carried out, using three-dimensional numerical modeling. Jewll et al. [39] investigated the impact of nails' angles on the shear strength of soil, utilizing the direct shear test. The results showed that to reach maximum shear strength, the optimal angle relative to the direction perpendicular to the shear area is approximately 30 degrees relative to the horizon [39].

So far, many research studies have carried out regarding the effective parameters on increasing the bond strength between the bar and concrete, considering different types of steel bars (Iranian standard steel bar types of A2 and A3) as well as various types of concrete (light-weight concrete, self-compacted concrete, high strength concrete, and so on) [23-31]. However, few studies are done about rebar planting and effective parameters on its performance on increasing ultimate compressive strength, considering different types of concrete [40–43].

In this study, as well as presenting a novel method to strengthen concrete components, the factors affecting the performance of rebar planting, such as rebar length and rebar planting angle, are evaluated. Therefore, the variable parameters in this research are the length of planted rebar and the angle of planting rebar. In fact, the proposed method to improve the axial capacity of concrete columns in this research is based on imposing confinement by planting steel rebar in hardened concrete. The main advantage of using rebar planting as a strengthening method is keeping the initial dimension of columns constant. besides, in the present study the impact of rebar planting on the concrete specimens with compressive strengths of less than 17 MPa, which are not considered structural concrete according to various design codes and consequently are not capable of being strengthened, is investigated [35]. It is worth mentioning that as the proposed method in this study is suggested by the authors; hence, the variables and obtained results are not comparative with previous researches quantitatively. Therefore, the most recent new approaches in concrete column rehabilitation are presented in Table 1 to clarify the main differences such as specimen type, rehabilitation method, and obtain results in literature review and research background qualitatively.

Table 1. Summary of most recent methods conducted on concrete column rehabilitation

Researcher(s)	Method	Specimen type	Main variables	Results
Jian Xie et al. [7]	Concrete jacketing by ultra-high performance concrete (UHPC).	cylindrical and square shaped column	thickness of UHPC jacket and the shapes of specimens	Increasing the thickness of UHPC jacket remarkably enhance the compressive strength of concrete columns for cylindrical shaped column; while, this influence on that of square shaped columns was less significant
Chang-Geun Cho et al. [16]	Applying High-Performance Fiber-Reinforced Cementitious Composites (HPFRC) sprayed mortar combined with additional reinforcing steel bars.	square shaped reinforced column	Longitudinal and transverse reinforcement	The proposed strengthening method was sufficient to improve the overall load-carrying and deformation capacities of conventional reinforced concrete columns under cyclic loadings. Moreover, it could enhance the hysteretic damping energy of the strengthened column during cyclic load reversals.
M.C. Sathwik et al. [9]	Wrapping with CFRP sheets.	cylindrical concrete specimens	Pre-loading condition	The specimens wrapped with a single layer of CFRP have an average of 55% increase in ultimate strength in comparison with unwrapped specimens (control).

2. Materials

2.1. Concrete

In this paper, the specimens are made based on a mix design in which the compressive strength is less than 17 MPa. It is worth mentioning that this value is the minimum compressive strength required for structural concrete. Cylindrical concrete specimens are made by utilizing the mix design presented in Table 2. The fine aggregate was natural river sand with a fineness modulus of 2.8, and the coarse aggregate was natural gravel with a maximum size of 19 mm. The cement used in the present study was cement type II manufactured by the Tehran cement plant. In order to determine the compressive strength of the aforementioned mix design, three standard cylindrical concrete specimens are subjected to the uniaxial compression test to obtain the mechanical properties of concrete.

The average mechanical properties of concrete on the age of 28 days including compressive strength, cracking strain, and ultimate strain are presented in Table 3. In addition, Fig. 1 displays the stress-strain diagram of the concrete.

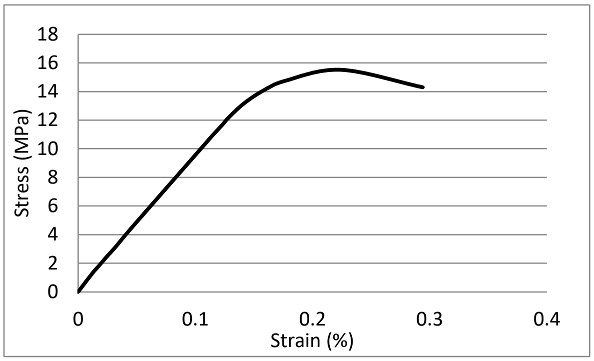


Fig.1. compressive Stress-strain diagram of the concrete.

Table 2. Mix proportion of the concrete.

Water (kg/m^3)	Cement (kg/m^3)	$\frac{w}{c}$	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
168	300	0.56	1000	850

Table 3. Mechanical properties of the concrete.

Mix code	f_c' (MPa)	ε_{cu} (%)	ε_{cr} (%)
NC	15.51	0.3	0.14

2.2. Steel rebar

Steel Rebar (type A3 based on Iranian steel bar standard) with lengths of 35 and 55 mm, and diameters of 8 mm, is used to be planted inside the concrete. Table 4 shows the average mechanical characteristics of the steel rebar.

Table 4. Mechanical characteristics of the steel rebar.

D_b (mm)	f_y (MPa)	f_u (MPa)	E (GPa)	ε_y (%)
8	400	500	200	0.2

2.3. Rebar planting glue

To plant steel rebars, first, the cylindrical specimens are drilled; then, the holes are completely cleaned, using an air pump. Afterward, the holes are filled with polyester-based glue with the commercial name of AKFIXC900. Finally, the steel rebars are placed inside the holes, as shown in Fig. 2. Moreover, mechanical and chemical characteristics of the glue, reported by the manufacturer, are presented in Table 5.

Fig. 2. Rebar planting process with glue

Table 5. Characteristics of the glue, used for the rebar planting in this study

Basis		Unsaturated polyester
Density $(^{kg}/_{L})$		1.7
Compressive strength (MPa)		65
Compressive modulus (MPa)		6000
Admissible Loads	Tensile strength (kN)	4.3
	Shear strength (kN)	5.8

3. Test preparation

3.1. Specimens description

According to ASTM C192 [44], the specimens are made in the form of a cylinder with a diameter of 150 mm and a height of 300 mm, as shown in Fig. 3. In order to determine the hole length, considering the diameter of the specimen which is equal to 150 mm, this value should not be more than half of the specimen thickness, according to ACI408R-03 [45]. As two bars are supposed to be planted in front of each other in a symmetrical way, each hole length should be less than 75 mm. One of the matters studied in this research is the effect of rebar length on the increase of compressive strength. Therefore, two different lengths of 35 and 55 mm are considered for rebar planting; and, the holes' lengths of 40 and 60 mm are drilled, respectively. According to the criteria of rebar planting glue and the required bond strength between the glue and the rebar, bar length is considered 5 mm shorter than the holes' length.

Fig. 3. Prepared specimens

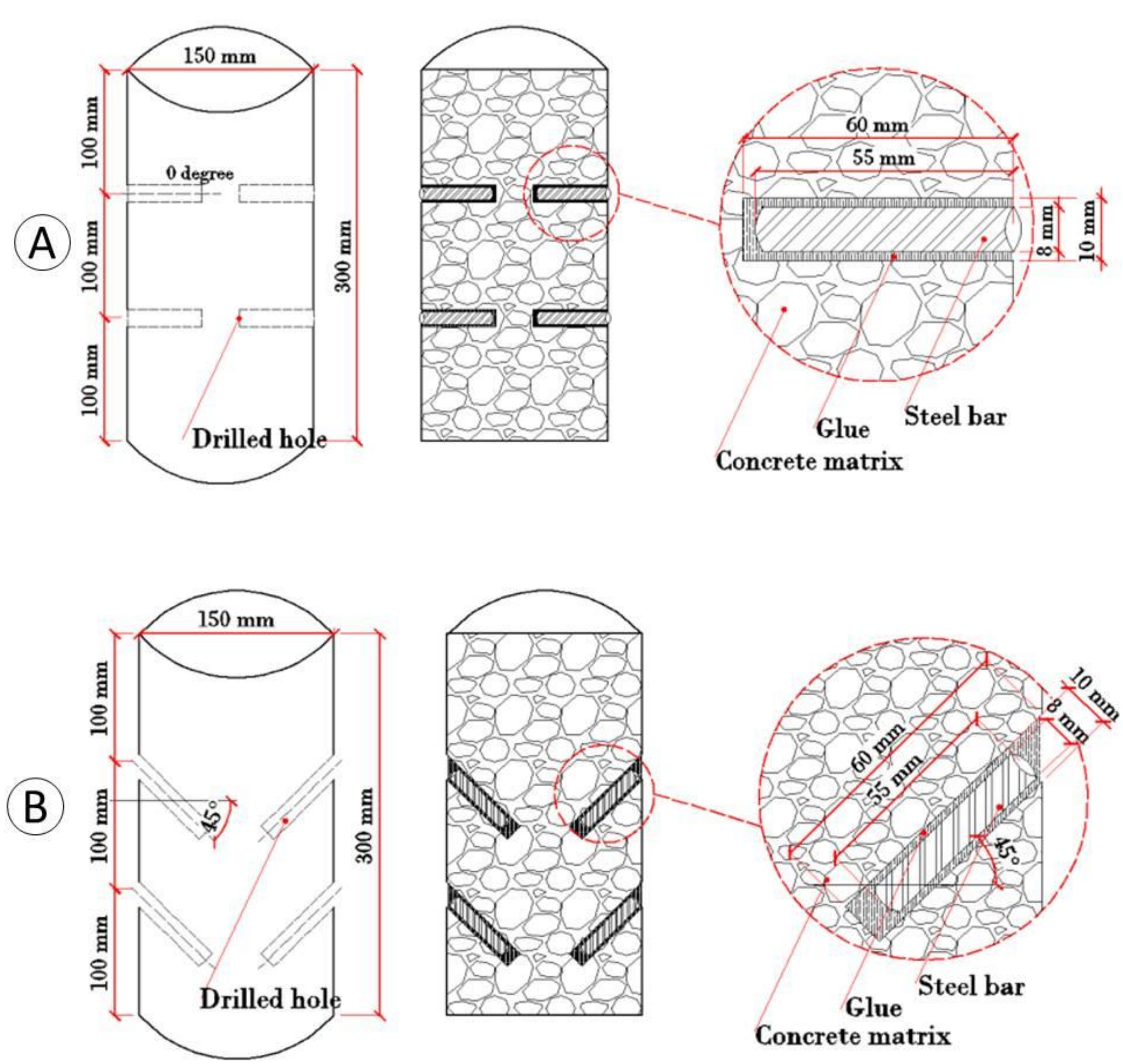
To determine the holes' diameter, considering the fact that the planted rebar should be completely located inside the glue in order to create enough bond strength between the glue and the rebar, this value is considered two mm greater than the rebar diameter. It should be mentioned that the length of the concrete specimen is equal to 300 mm, and low-strength concrete is utilized in the test. Therefore, in order to prevent damage and rupture of the concrete specimens during drilling and considering that one of the studied matters is the impact of bar diameter on the enhancement of concrete strength, the holes with a diameter of 10 mm are drilled on the specimens in which the bars with a diameter of 8 mm are planted. Two holes are drilled on each side of the specimen; hence, considering two sides for each sample, the number of holes for all the specimens is four. Fig. 4 displays the process of rebar planting inside the concrete.

In order to label the specimens, a two-part notation system is considered. The first letter "L" and the number after it: in all specimens, Letter "L" is the abbreviation of the word "Length", after which the number shows the planted length of rebar in mm. The second letter "A" and the number after it: in all specimens, Letter "A" is the abbreviation of the word "Angle", after which the number shows the rebar planting angle in degree. For instance, L35A0 represents a cylindrical specimen, in which rebar with a diameter of 8 mm, a length of 35 mm, and a rebar planting angle of 0-degree are exerted. Characteristics of all the specimens and the bars planted inside them are presented in Table 6. Moreover, the rebars arrangement for each specimen is plotted in Fig. 5 precisely.

Table 6. Characteristics of the concrete specimens

Specimen	$f'_c\ (MPa)$	$D_b\ (mm)$	$L_b\ (mm)$	$\theta\ (degree)$
L35-A0	15.51	8	35	0
L35-A45	15.51	8	35	45
L55-A0	15.51	8	55	0
L55-A45	15.51	8	55	45

Fig. 4. Displays the process of rebar planting inside the concrete, a) Drilling the holes, b) cleaning the holes before casting glue, and c) casting the glue.



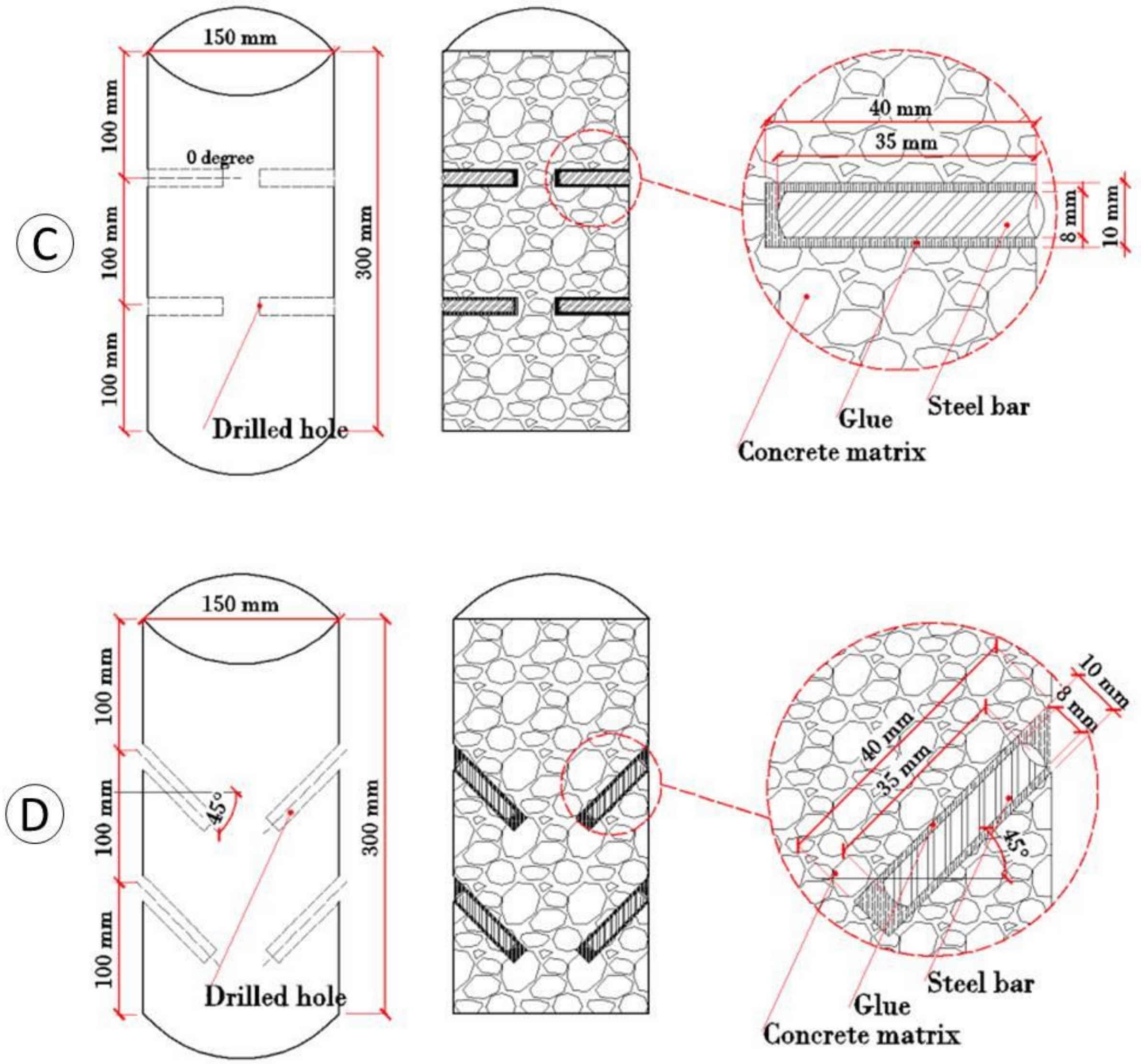


Fig. 5. rebar planting arrangement for a) specimen L55-A0, b) specimen L55-A45, c) specimen L35-A0, and d) specimen L35-A45.

3.2. Set up and instrumentation

A hydraulic jack with a nominal capacity of 1000 kN is used in the compressive strength test. Furthermore, to measure the axial strain of the specimens, two LVDTs are mounted at the top of specimen. Moreover, as shown in Fig. 6 a strain gauge is installed on the middle of the planted rebar for each specimen to measure axial strain and tensile stress as well. Fig. 7 shows the setup test configuration.

Fig. 6. Prepared strain gauge for installation on the planting rebar.

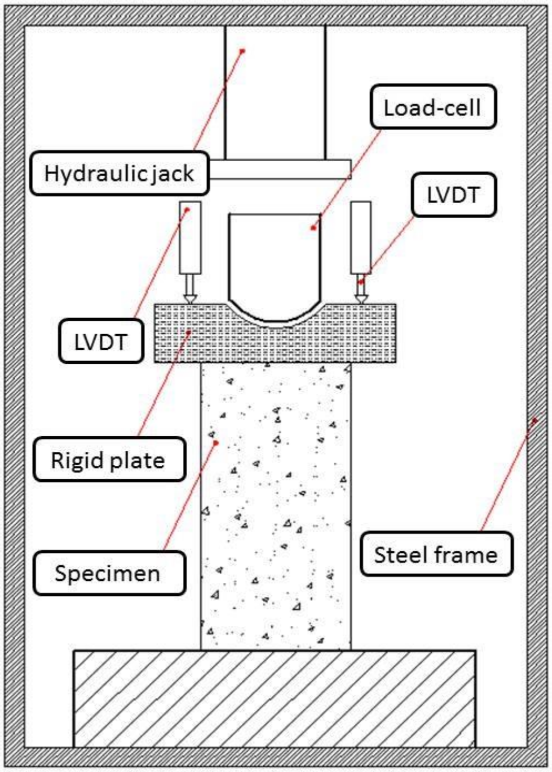


Fig. 7. Test setup and instrumentation.

4. Results and discussion

By performing the uniaxial compression test on the cylindrical concrete specimens, Load-displacement diagrams are plotted which is shown in Figs. 8. The results of the aforementioned test are summarized in Table 6. It should be noted that each test has been repeated three times to ensure accuracy; therefore, the average value, standard deviation, and COV are also presented in Table 7. During the test, all the concrete specimens reach the maximum compressive stress and cracking strain; then, when the stress reaches about 85% of the rupture stress, the planted bars inside the concrete are removed. The amount of each rebar slipping during applying the compressive load is also presented in Table 7. Moreover, the rebar's strain is obtained by using the strain gauge during the test, by multiplying the modulus of elasticity and rebar's strain obtained at the moment of slipping; the maximum tensile stress developed in the rebar before slippage is recorded, as presented in Table 6. Hence, the obtained parameters P_{max} , f'_c, ε_{cr_a}, ε_{uc_a}, ε_{uc_l}, f_s, ε_{us} , and S_{max} presented in Table 7 are peak load, ultimate compressive strength of concrete, axial strain of concrete at cracking, ultimate axial strain of concrete, ultimate lateral strain of concrete, tensile stress of planted rebar, ultimate strain of planted rebar, and maximum slippage of planted rebar, respectively.

In all the specimens after rebar planting with various lengths and angles, the compressive strength increases. Table 8 demonstrates the amount of this enhancement for each specimen. As it is obvious in Table 8, rebar planting with different lengths and diameters can enhance the ultimate compressive strength of low-strength concrete specimens by an average of 17 to 29 percent. The control specimen's ultimate compressive stress is 15.52 MPa, consequently by planting horizontal rebar the ultimate compressive stress reaches at 18.17 MPa and 19.11 MPa for specimens L35-A0 and L55-A0 respectively.

Considering the fact that the angle of planted rebar could be an effective parameter, in the next phase the test process repeated by the angle of 45-degree, the ultimate compressive stress reaches at 19.05 MPa and 20.08 MPa for specimens L35-A45 and L55-A45, respectively. As demonstrated in Fig. 8 load-deflection diagram shows a relatively close behavior in all specimens. Planting steel rebar generally could increase ultimate compressive strength, axial strain, and lateral strain. Fig. 9 shows the ultimate lateral strain for specimens. Furthermore, Fig. 10 displays the amount of tensile stress developed in planted rebar.

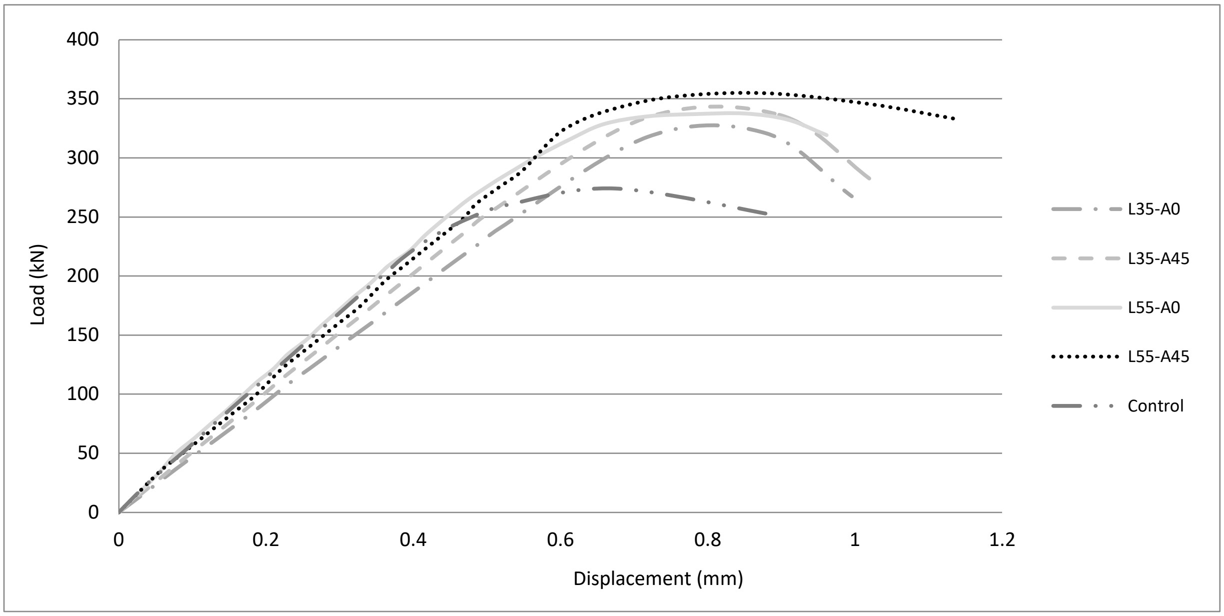


Fig. 8. Load-deflection diagram for specimens

Table 7. Summary of test results

Specimen		P_{max} (kN)	Concrete				Planted steel rebar		
			$f'_c\ (MPa)$	ε_{cr_a} (%)	ε_{uc_a} (%)	ε_{uc_l} (%)	$f_s\ (MPa)$	ε_{us} (%)	$S_{max}\ (mm)$
Control	Ave	274.09	15.52	0.15	0.305	0.03	-	-	-
	SD	11.84	0.67	0.01	0.01	0.001	-	-	-
	COV	4.32	4.32	6.67	3.28	3.33	-	-	-
L35-A0	Ave	320.92	18.17	0.287	0.328	0.061	80.76	0.038	2.33
	SD	4.51	0.255	0.008	0.006	0.001	1.201	0.001	0.471
	COV	1.41	1.4	2.79	1.83	1.64	1.45	2.44	20.21
L35-A45	Ave	336.43	19.05	0.299	0.341	0.064	86.37	0.041	1.67
	SD	4.85	0.27	0.009	0.006	0.001	1.3	0.001	0.23
	COV	1.44	1.42	3.01	1.76	1.56	1.5	2.33	7.9
L55-A0	Ave	337.53	19.11	0.287	0.321	0.042	90.55	0.043	2.87
	SD	2.76	0.16	0.003	0.002	0.004	1.79	0.001	0.182
	COV	0.82	0.84	1.05	0.62	4.76	1.93	2.17	5.99
L55-A45	Ave	354.72	20.08	0.293	0.379	0.046	96.73	0.046	3.23
	SD	3.93	0.22	0.01	0.02	0.001	0.949	0.001	0.555
	COV	1.11	1.1	3.41	5.28	2.17	0.98	2.08	18.44

Table 8. Compressive strength enhancement in specimens.

Specimen	compressive strength (MPa)		Enhancement (%)
	Initial	planted	
L35-A0	15.51	18.16	17.08
L35-A45	15.51	19.04	22.75
L55-A0	15.51	19.11	23.21
L55-A45	15.51	20.08	29.46

4.1. The effect of rebar's length

Comparing load-displacement diagrams of specimens L35-A0 and L55-A0 as well as considering the values of enhancement ratio in Table 7, it is clear that increasing the length of the planted rebar from 35 mm to 55 mm leads to improve the ultimate compressive strength from 18.16 MPa to 19.11 MPa. Fig. 8 compares the load-displacement diagrams of L35-A0 and L55-A0. As shown in this figure, increasing the length of the planted rebar inside the concrete climbed the peak load. Moreover, the slope of the linear part of the diagram, which indicates the stiffness of the specimen, augments with the increase of the rebar length. Another point of view is the effect of rebar's length on the lateral strain and maximum tensile stress developed on the rebar cross-section area. As the length of planted rebar increase the ultimate lateral strain decrease and the tensile strength in the rebar's cross-section area increase. Fig. 9 compares the lateral strain between specimens. Obviously planting rebar increase the lateral strain in all specimens, particularly specimens with the smaller length of the planted rebar reach a relatively higher lateral strain before rupture. Fig. 10 shows the tensile stress in planted steel rebar which obtained 80.76 MPa, 86.37 MPa, 90.55 MPa, and 96.73 MPa for specimens L35-A0, L35-A45, L55-A0, and L55-A45, respectively.

4.2. The effect of rebar's angle

In order to assess the effect of the planting angle on the compressive strength of low-strength concrete, the load-displacement diagrams of specimens L35-A45 and L55-A45, as well as specimens L35-A0 and L55-A0 are compared. As Fig. 8 displays the average load-displacement diagrams, a comparison between these diagrams indicates that an identical rebar's length with an angle of 45-degree witnessed a higher increase in peak load than horizontally planted rebars (i.e., with an angle of 0-degree). However, the stiffness values of the mentioned specimens are almost equal. Moreover, the angle of planted rebar has a marginal effect on the increase of lateral strain of specimen as shown in Fig. 11. To illustrate, specimens L55-A45 and L35-A45 experienced about 9% and 5% improvement in lateral strain compare to specimens L55-A0 and L35-A0, respectively. The tensile stress level in planted rebar's cross-section area slightly climbed by the specimens with the planting angle of 45-degree, as shown in Fig. 12.

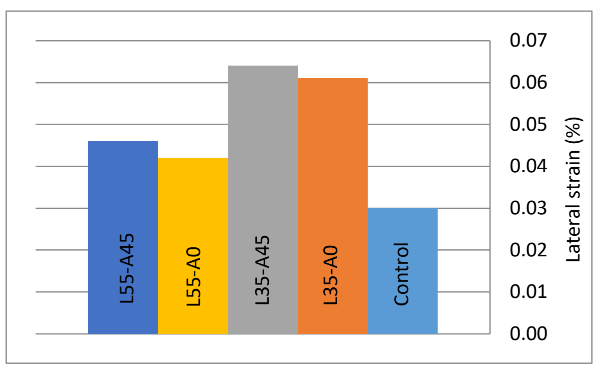


Fig. 9. Lateral concrete strain diagram for specimens.

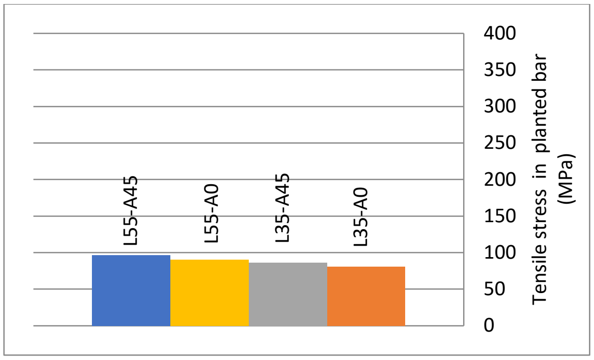


Fig. 10. Tensile stress developed in planted bar.

4.3. Prediction of the peak load vs. planted rebar's length and angle

As discussed in Sections 4.1 and 4.2, planted rebars with the length of 55 mm and the angle of 45 degrees showed the best performance of the enhancement in ultimate compressive strength. In this case, the rebar's length and planting angle control the peak load of the specimens; consequently, the length of the rebar and its angle are the variables (considering constant initial compressive strength of concrete) that affect the maximum compressive load. Eq. (1) and Eq. (2) are derived from a linear regression analysis of the experimental results which predict the effect of the planted rebar length and planting angle, respectively.

$$y = 0.8725x + 298.14 \quad (1)$$

$$y = 0.3633x + 329.23 \quad (2)$$

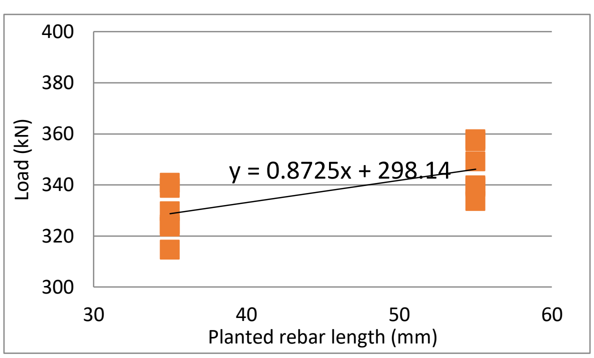


Fig. 11. The linear regression between peak load and planted rebar length.

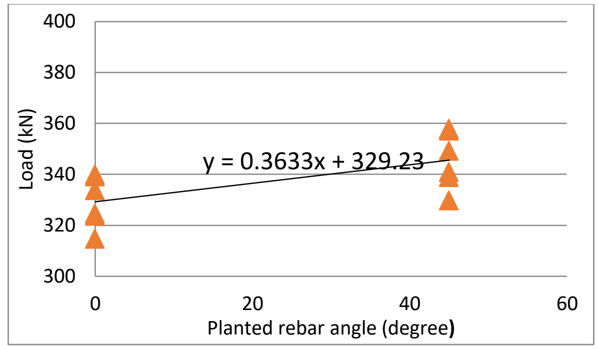


Fig. 12. The linear regression between peak load and planted rebar angle.

5. Conclusions

Based on the experimental test and observations which conducted in the present study the following results are obtained.

- Planting rebar inside low-strength concrete specimens increases the ultimate compressive strength by an average of 17% to 30% of the initial compressive strength.
- The enhancement of compressive strength in the concrete column specimens by rebar planting method depends on two main parameters; rebar length, and planting angle. Results indicated that as the length of planted rebar increase the ultimate compressive strength increase and the planting angle of 45 degrees leads to higher compressive strength.
- Results show that adding steel bars could effectively increase lateral strain in concrete column specimens before rupture.
- Tensile stress developed in planted rebar depends on rebar length and planting angle, results showed that planted rebar with 45 degrees and

length of 55 mm reaches higher ultimate compressive strength.

- In the present study, the proposed method by authors is a new approach, therefore the variables and obtained results are different from previous methods.

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