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Experimental and theoretical investigation on the bond strength between high-strength and lightweight concrete

Ahmed S. Eisa[1], Louay A. Aboul-Nour[1], Asmaa Mohamad[1]*

[1]University of Zagazig, Department of Civil Engineering. 44519, Zagazig, Egypt.
e-mail: ahmedeisa@zu.edu.eg, louayabdelrazek@yahoo.com, asmaa.ghamry21@eng.zu.edu.eg

BSTRACT

The appropriate bond strength between the layers with different concrete strengths is considered the most important concern for the layered elements. An experimental study has been approved to produce structural lightweight concrete with a compressive strength not decreasing by 18 MPa and a unit weight not increasing by 2000 kg/m^3 and high-strength concrete with a compressive strength not decreasing by 60 MPa and then investigate the bond strength between new high-strength concrete and old lightweight concrete with different treatment cases and different compressive concrete strengths. Mix with 0% perlite meets the requirements of the targeted high-strength concrete, and mixes with 30%, 40%, and 50% perlite meet the requirements of the targeted structural lightweight concrete, and they can be used for testing bond strength with different treatment methods. The new concrete jackets have a concrete strength of 62.5 MPa, and the old concrete cube's strength is varied between 18.4, 21.8, and 38.08 MPa. A total of eleven bond strength test specimens were cast with different parameters. The specimen interface was arranged by different systems: roughness, agent material, and nails. The roughness techniques used were hand-wire brushing, grinding, or hand chiseling. Theoretical results were compared with the experimental data. It was concluded that using a new high-strength concrete with two times the strength of the old lightweight concrete and treating it with nails is the best technique to achieve an economic and acceptable value of bond strength. The nails achieved a good bond between the fresh and hardened concrete owing to the developed shear friction. The hand-chiseling roughness method gives the best bond strength results. The high difference in concrete strengths between the fresh high-strength jackets and the hardened lightweight cube isn't mandatory to enhance the interface bond strength between them.

Keywords: Bond strength; lightweight concrete; nails; agent material; high-strength concrete.

1. INTRODUCTION

In concrete structures, shear force can be passed through an interface surface among two different materials. The interface surface may be between concrete and steel, or between concrete and concrete with different casting times, between two crack faces in homogeneous concrete. This shear force is generally simulated as a shear friction theory. This approach, first started in the 1960s by BIRKELAND and BIRKELAND [1], states that the concrete-to-concrete interface shear strength results from the influence of numerous resisting mechanisms, called the friction between two concretes, the cohesion between particles, and the shear force resulted by the reinforcement passing through the interface. Nowadays, the shear friction phenomenon is commonly accepted and has been approved by most design codes, including the PCI, AASHTO LRFD, ACI 318-14, and ACI 318R-14 [2]. Natural adhesion occurs at the interface between two materials, and it is classified as specific and mechanical. Mechanical adhesion happens when agent glue material fills the holes of the interface to confirm a good bond. The development of the shear strength in layered elements with varied concrete strengths is affected by varied issues such as the interface reinforcement, the compressive concrete strength, the interface roughness cases, and the interface normal stresses created by the applied loads [3]. The overlay, contact, and substrate layers represent the interface surface between concrete layers [4]. The bond strength value is affected by utilizing RFT, adhesion, and friction [3]. There are several factors affecting the concrete-to-concrete bonding strength, like curing technique, utilization of agent bonding materials, mechanical characteristics of concrete, age of chemical agent bonding materials, substrate surface state, and compaction technique [4]. The interfacial bond strength of concrete-to-concrete layered sections is affected by numerous factors according to the interface such as surface treatment, moisture condition, crossing reinforcement, and bonding agent, while other factors depend

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on the concrete substrate/overlay such as compressive strength, modulus of elasticity, curing, age, shrinkage, type, fresh properties, structure, mixture, and contact state [5]. Treatment and curing methods of the interface surface affected greatly the interface bond strength and cohesion [6]. The interface layer among substrate and overlay is simulated using Abaqus software as a 100-µm-thick concrete layer that is connected to each layer [4]. Bonding strength can be estimated by different testing methods, such as pull-off tests that estimate it under tensile stresses, direct shear tests that estimate it under shear stresses, and slant shear tests that estimate it under compression and shear stresses. Many researchers investigated the testing type effect on the value of bond strength [7, 8]. The type of bond strength test must be selected carefully according to the stresses subjected to structure, while results for some tests increased up to eight times more than other types [9]. A test of direct shear is utilized for studying the shear stress between concretes [10]. The bond strength between ultra-high-performance and ordinary concrete was studied using direct shear, slant shear, and a third-point loading test [4]. The effects of changing the concrete strength with high-performance and ordinary concrete have been studied [11]. The interface shear bond strength for ordinary with lightweight concrete has been estimated, and the results show the parameters that affected the bond strength with different concrete strengths in production and design [3]. Bond strength is developed by increasing the concrete's strength [12]. Suitable surface treatment, such as using agent materials and dowels, enhanced the bond strength in cases of good cleanliness and interface roughness between the hardened and fresh layers [9]. The unsuitable treatment surface condition leads to an insufficient bond strength value, which causes early stress [13]. Cement-based slurries and epoxies are commonly used as bonding agent materials [14]. Factors affecting the efficiency and choice of bonding agent materials are their shrinkage, thermal expansion, viscosity, chemical, and physical properties. The components of the concrete layers also effect on the performance of the concrete bonded with epoxy adhesives5. The efficiency of epoxies depends on their application method, chemical structure, environmental factors, and concrete state surface [15, 16]. Bonding agent adhesive materials generally increase bond strength, impermeability, and interfacial adhesion [17, 18]. The amount of bonding agent material applied to the interface affects the bond strength. The optimum quantity depends on the stress state and properties of concrete, while insufficient quantity has a negative influence on the bond strength, and excessive quantity decreases the bond strength owing to early failure produced by creep and high deformation [16, 19]. Using dowels to treat the surface between ordinary and high-strength concrete can improve the bond strength value [20]. Using nails increased the interface shear strength by 4.6%, while agent material influenced it slightly9. Dowel action is defined as the moment resistance of the shear connectors. The interface bond strength depends on the number of shear connectors, compressive strength of the concrete, roughness, and reinforcement ratio5. Shear connectors enhanced the bond strength by about three times compared to reference samples [21]. The interface bond strength can be enhanced by roughening the surface and using dowels [22, 23]. The resulted bond strength between ultrahigh-performance and ordinary concrete is greatly influenced by the saturation of the substrate, more than roughing it from pull-off, splitting tensile, and slant shear result tests [24–27]. The interface bond strength between two concretes differs with the location, and decreasing bond strength owing to the pouring delay can be enhanced by roughing the hardened surface before casting the fresh one. Utilizing a lightweight concrete layer as a bulk core section in the layered precast beam decreases its own weight by more than 30% [28]. The flexural interface connection has been simulated numerically depending on adhesion and roughness between the concrete layers using three varied roughness cases: rough, minimum rough, and smooth [29, 30]. The bond strength value can be enhanced by interface roughness [31]. Good compaction between new and old concretes may compensate for the roughness [26]. The roughness of the substrate is affected by the type of agent material used and the direct tensile strength test type (pull-off or slant shear test) [32]. In the tension test, new concrete strength affects the bond strength more than roughening [33]. Brushing, acid etching, grooving, leaching of cement paste, and dragging jute have been considered as surface treatment methods [5]. Wire brushing, chipping, and sand blasting can be used for roughening the interface for the bond strength test [34]. In recent years, structural lightweight aggregate concrete with various lightweight aggregate types has been studied and advanced widely in order to be suitable for the large-scale construction of high-rise buildings and large-span structures. Lightweight concrete can be obtained in three ways: Firstly, by neglecting the fine aggregate; Secondly, by adding chemical mixtures to attain air bubbles in concrete; Lastly, by replacing the normal aggregate with lightweight aggregate to produce Lightweight Aggregate Concrete (LWAC), which can be used in many fields owing to its suitable strength and variety of density [35]. Perlite is considered an available natural material that can be utilized as an excellent lightweight aggregate in LWAC [36]. In the mid-20th century, a characteristic concrete strength (fc) of 25 MPa was determined for high-strength concrete. In 1980, 50 MPa of concrete was considered high-strength. Generally, compressive concrete strength greater than 60 MPa is determined for high-strength concrete (HSC). Then, its compressive concrete strength is developed to be about 120 MPa and is commercially available. High-strength concrete with high values of compressive strength, low values of permeability, and a high unit weight can be created by replacing cement with a binder mixture like silica fume [37–39]. An experimental program has been performed in the research to study the bond strength between high-strength and lightweight concrete.

2. RESEARCH SIGNIFICANCE

- Producing a structural lightweight concrete mixture with a 28-days cube compressive strength not decreasing by 18 MPa and unit weight not increasing by 2000 kg/m^3, and high-strength concrete having a compressive strength not decreasing by 60 MPa, then studying their mechanical properties (flexural strength, compressive strength, and splitting-tensile strength).
- Studying the bond strength between the new high-strength concrete jackets with 62.5 MPa concrete strength and the old lightweight concrete cube with different concrete strengths of 18.4, 21.8, and 38.08 MPa and different treatment methods of roughness using hand wire brushing or grinding or chiseling, agent material, and nails
- Compared the experimental data with theoretical investigations by the European Standard, Eurocode 2, ACI-318, and the Egyptian Code, ECP 203.

3. DETAILS OF THE EXPERIMENTAL TEST

3.1. Used materials

The mix design given in Table 1 was prepared with different variables to obtain a structurally lightweight concrete mixture and high-strength concrete. Gravel with a maximum nominal size of 14 mm besides Expanded Perlite Aggregate (EPA), with replacement ratios of 0%, 10%, 20%, 30%, 40%, 50%, and 60%, was utilized as natural coarse aggregate. Ordinary Portland Cement with a grade of 52.5 N, besides silica fume (15% by cement), was used as binder material. Sand was utilized as a natural fine aggregate. superplasticizer (SP) was used with a ratio of 4% binder content. The 0.45 water/binder (W/b) ratio was saved as a constant value in all concrete mixtures.

3.2. Preparation of specimens

In this experimental work, the 7 mixes with different perlite replacement ratios of 0%, 10%, 20%, 30%, 40%, 50%, and 60% were carried out according to the absolute volume method to produce structural lightweight concrete mix and high strength concrete mix and investigate their mechanical properties (flexural strength, compressive strength, indirect-tensile strength, and unit weight). At first, all drying materials were weighted and mixed for five minutes, then liquid materials were added carefully and mixed for two minutes. All mixing procedures were prepared at about 25 °C.

Wooden material has been used for casting the bond test specimens. A lightweight concrete cube with dimensions of 100*100*100 mm and concrete strengths of 18.4, 21.8, and 38.08 MPa has been prepared to refer to the old concrete from this test. After one day (24 hours), the cubes have been demolded and cleaned, and then the two high-strength jackets having dimensions of 100*100*70 mm and 62.5 MPa concrete strength are cast on the two opposite sides of the cube to represent the new concrete from this test. For specimens treated with a roughness case, the cubes have been roughened carefully with hand wire brushing, grinding, and hand chiseling before casting the two jackets. For specimens treated with agent material case, an agent bond material (Addibond-65) has been utilized as an adhesive for concrete-to-concrete, and old cubes have been treated with the agent material slurry before casting the two new jackets according to the instructions of the producer

Table 1: Concrete mix design for specimens (kg/m^3).

MIX. NO.	1	2	3	4	5	6	7
Epa%	0	10	20	30	40	50	60
Cement	520	520	520	520	520	520	520
Silica Fume	78	78	78	78	78	78	78
Admixture	24	24	24	24	24	24	24
Water	240	240	240	240	240	240	240
Sand	473.7	319.6	241.15	193.6	161.7	138.8	121.67
Gravel	947.6	575.28	385.84	271	194.08	138.8	97.33
Perlite	0	63.92	96.46	116.17	129.4	138.8	146

company. The properties of the used agent material are given in Table 2. For specimens treated with a nail case, steel bars with an 8-mm diameter and grade of 240 MPa have been embedded with 30 mm length in the two opposite sides of the cubes before casting the two new jackets. The specimens have been cured and covered for 28 days before being tested. Dimensions for bond strength test samples are demonstrated in Figure 1. Modeling with the casting of tested samples is given in Figure 2 and Figure 3. Roughness techniques are shown in Figure 4. Tools used for the surface preparation process are shown in Figure 5.

3.3. Test procedures

A total of 42 cubes, 63 cylinders, and 21 prisms were cast in this research. A total of 7 mixtures were prepared to determine unit weight (ρ), cube (F_{cu}), and cylinder compressive strength (F_{cy}) measured at 28 and 7 days, splitting-tensile strength (F_{sp}) measured at 28 days, and flexural strength (F_r) measured at 28 days. Cylinder compression tests were done as stated by ASTM C39. Cube compression tests were done as stated by ASTM C109. Indirect or splitting tensile tests were performed on cylinders according to ASTM C496. Flexural testing was conducted on prism specimens subjected to a 3-point bending test according to ASTM C 1018. Every mixture consists of 6 cubes with 100*100*100 mm dimensions, 9 cylinders with 100mm diameter and 200mm height dimensions, and 3 prisms with 100*100 mm cross-section and 500mm total length. The test results for each mixture were the average of three specimen results. For the bond strength (F_b) test, a total of 33 lightweight cubes with concrete strengths of 18.4, 21.8, and 38.08 MPa were prepared to refer to the old concrete, and 66

Table 2: Properties of agent bond material of addibond-65 [40].

PROPERTY	BENDING STRENGTH (MPa)	COMPRESSIVE STRENGTH (MPa)	TENSILE STRENGTH (MPa)	% WATER ABSORPTION	ABRASION RESISTANCE LOSS%	%AT CHANGE7 DAYS KEROSENE	CHEMICAL RESISTANCE 5% H_2SO_4
Value	28	168	12	9.65	4.2	4.8	8

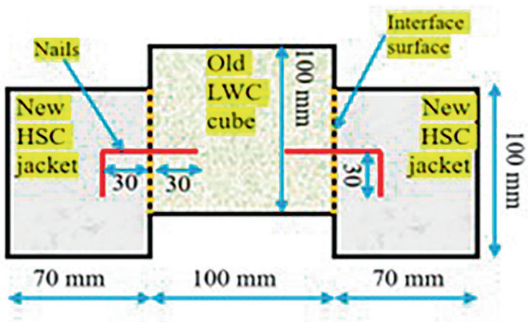

Figure 1: Dimensions for bond strength test specimens.

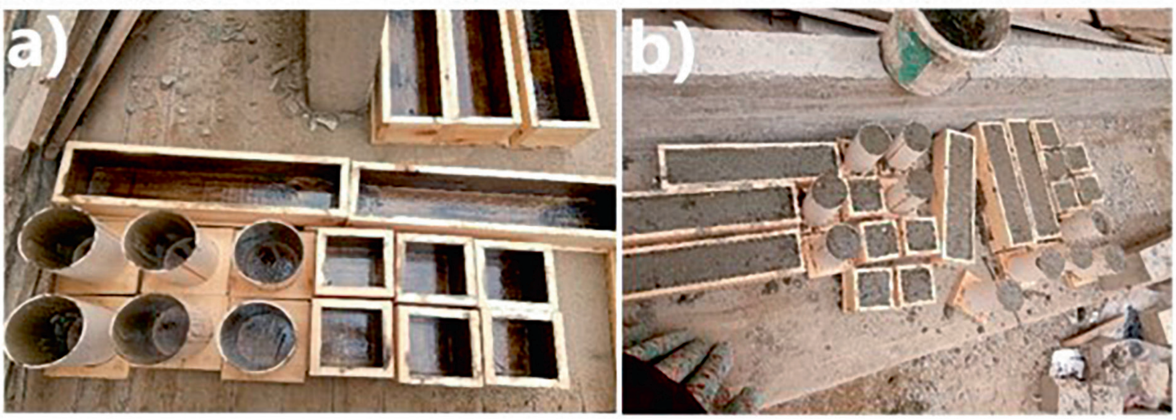

Figure 2: Molding and casting for cube, cylinder, and prismatic specimens (a) wooden molds, and (b) casting specimens.

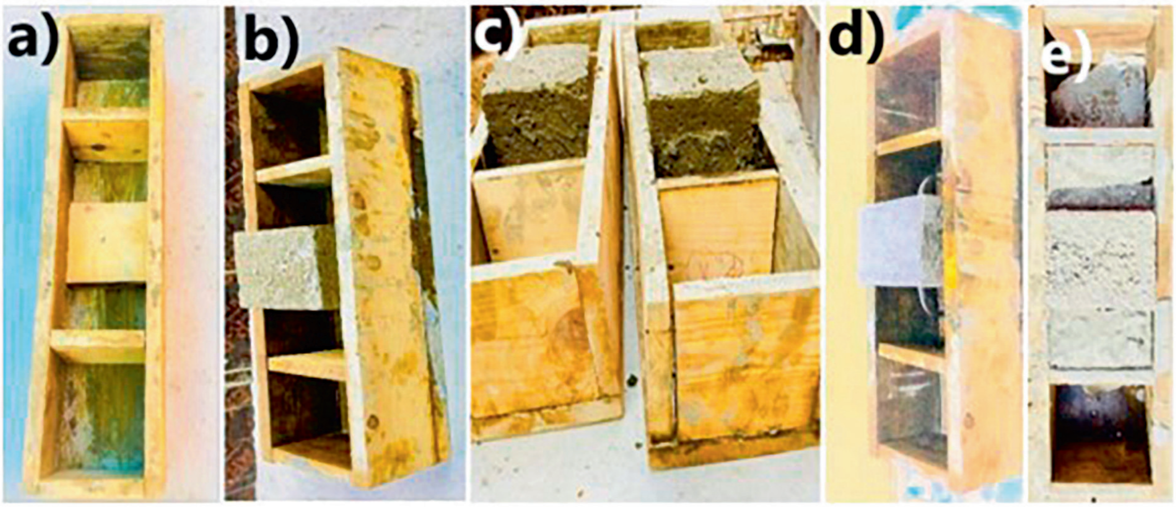

Figure 3: Molding and casting for bond strength test specimens (a) wooden molds, (b) casting specimens with old concrete, (c) casting specimens with agent material, (d) casting specimens with nails, and (e) casting specimens with new concrete.

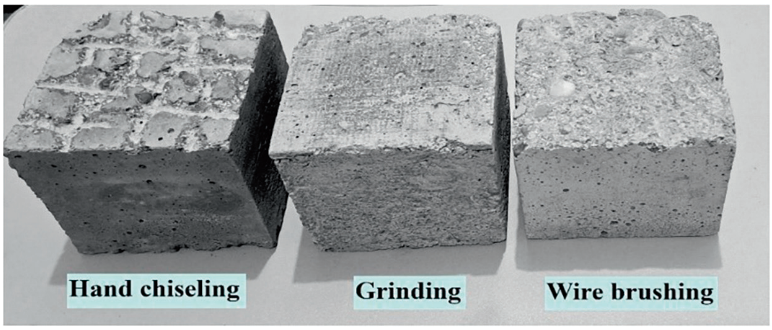

Figure 4: Surface preparation for specimens with different roughness techniques.

Figure 5: Tools used for surface preparation process: (a) hand wire brushing, (b) grinding, and (c) hand chiseling.

high-strength jackets with concrete strengths of 62.5 MPa were prepared to refer to the new concrete. Three samples treated for roughness with hand wire brushing are denoted as B18.4, B21.8, and B38.08. One sample treated for roughness with grinding is denoted as G18.4. One sample treated for roughness with hand chiseling is denoted as C18.4. Three samples treated with agent material are denoted as M18.4, M21.8, and M38.08. Three samples treated with nails are denoted as N18.4, N21.8, and N38.08. Specimens, with variables given in Table 3. The specimens have been tested after 28 days in a compression test machine under static loading to measure the direct shear stress between the new lightweight cube and the old high-strength jackets. Three specimens have been tested and loaded to failure for each case, and the average result of them has been taken by MPa. Test samples are shown in Figure 6.

Table 3: Specimen's variables abbreviations used in the test.

MIX. NO.	CONCRETE STRENGTH (MPa)	TREATMENT SURFACE CASE				
		ROUGHNESS			AGENT MATERIAL (M)	NAILS (N)
		BRUSHING (B)	GRINDING (G)	CHISELING (C)		
Bond Strength (F_b) (MPa)	18.4	B18.4	G18.4	C18.4	M18.4	N18.4
	21.8	B21.8	–	–	M21.8	N21.8
	38.08	B38.08	–	–	M38.08	N38.08

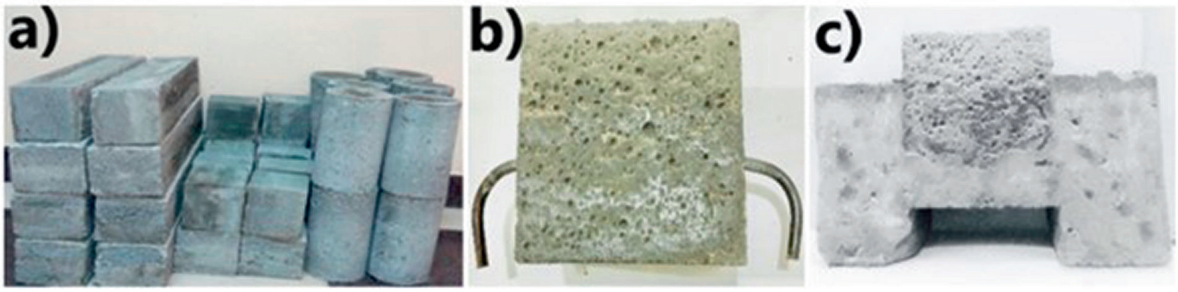

Figure 6: Test samples: (a) cubes, cylinders, and prisms, (b) specimen with nails, and (c) bond strength specimen.

4. RESULTS AND DISCUSSION

Results of flexural, splitting, and compression tests are given in Table 4, Table 5 and Figure 7 show the overall average bond strength test results for different treatment cases.

4.1. Mode of failure for specimens

Mode of failure of cubes, cylinders, and prisms shown in Figure 8. All specimens prepared by roughening the interface separated at the interface with a brittle shear collapse between new and old concretes without any damage to particles. Specimens treated with agent bond material collapsed with a crack that passed through the interface surface between the agent bond material and the new concrete with a few particles damaged, which indicated that the bond between the new concrete and the agent bond material is considered weaker than the bond between the hardened old concrete and the agent bond material. Specimens treated with nails collapsed with a crack that passed through the old concrete cube without slight particle damage, which indicated that the nails achieved a good bond between the fresh and hardened concrete owing to the developed shear friction, as shown in Figure 9.

4.2. Effect of changing perlite replacement ratio on the mechanical properties of lightweight concrete and high-strength concrete

As expected, increasing the perlite replacement ratio decreased all mechanical properties of the designed mixtures, as shown in Figure 10. A mix without perlite (0%) was used as a control mix to compare the results. Unit weight is considered a significant property in the case of lightweight concrete, which greatly affected the hardened concrete strength. Unit weight has decreased by 9.4%, 15.57%, 22.82%, 41.17%, 45.9%, and 46.95% for perlite replacement ratios of 10%, 20%, 30%, 40%, 50%, and 60%, respectively, compared to the perlite replacement ratio of 0%, and this may be due to the perlite's lower specific gravity and its porous structure related to natural aggregate value. Such reductions in unit weight values can have great benefits for the performance of structures. They can also reduce cross-section and reinforcement for the structure elements, so the overall cost can be decreased. Using perlite as a lightweight aggregate to replace natural aggregate produced a reduction in the density of concrete [41–43]. The hardened concrete compressive strength is considered the most significant mechanical property, so it should be determined carefully for all mixtures. Cube compressive strength at 28 days has decreased by 12%, 32.16%, 39.072%, 65.12%, 70.56%, and 80.48% for perlite replacement ratios of 10%, 20%, 30%, 40%, 50%, and 60%, respectively, compared to the 0% perlite replacement ratio. The 7-days compressive strength results were roughly equal to 80% of the 28-days concrete compressive strength; this

Table 4: Results of compression, splitting, and flexural tests.

MIX. NO.	%EPA	P (KG/M³)	F_c (MPA)				F_{sp} (MPA)	F_r (MPA)
			CUBE (F_{cu})		CYLINDER (F_{cy})			
			7-DAYS	28-DAYS	7-DAYS	28-DAYS		
1	0%	2594	48.6	62.5	47.87	58.3	4.53	5.73
2	10%	2350	40.2	55	39	48.8	3.85	4.84
3	20%	2190	36.7	42.4	28.7	36	2.88	4.24
4	30%	2002	29.3	38.08	27.3	33.4	2.24	3.8
5	40%	1526	16.65	21.8	15.93	20.65	1.28	2.19
6	50%	1403	13.13	18.4	10.6	14.37	0.94	1.512
7	60%	1376	8.50	12.2	7.25	11.35	0.793	1.24

Table 5: Average overall bond strength test results.

MIX. NO.	CONCRETE STRENGTH (MPA)	TREATMENT SURFACE CASE									
		ROUGHNESS						AGENT MATERIAL (M)		NAILS (N)	
		BRUSHING (B)	F_b	GRINDING (G)	F_b	CHISELING (C)	F_b				
Bond Strength (F_b) (MPa)	18.4	B18.4	0.75	G18.4	0.52	C18.4	1.08	M18.4	1.263	N18.4	1.378
	21.8	B21.8	0.84	–	–	–	–	M21.8	1.67	N21.8	1.73
	38.08	B38.08	0.89	–	–	–	–	M38.08	2.0	N38.08	2.13

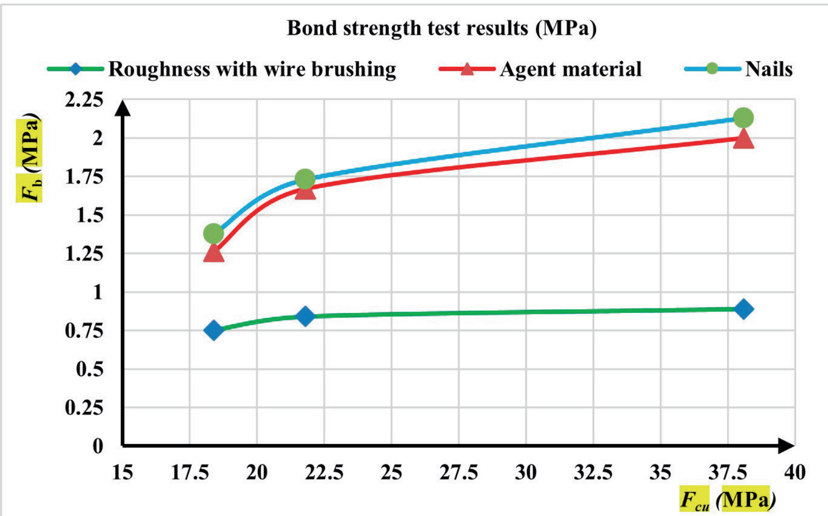

Figure 7: Average bond strength test results for different treatment cases.

may be because of the large amount of cement plus silica fume and super-plasticizer used in these samples. The cube compressive strength increased by about 10% compared to the cylinder compressive strength owing to its smaller aspect ratio and the proportionally greater lateral attachment provided by the machine platens. Such reductions in compressive strength may be owing to the weak perlite structure of the mixtures. As is known, compressive strength is considered a function of unit weight, so the obtained results show a regular decrease in compressive strength with the unit weight, as given in Figure 11. Compressive strength was reduced with a high EP content in the matrix [44–47]. The splitting or indirect tensile strength is considered one of the greatest essential mechanical properties of the hardened concrete, which seriously effects on the ductility and safety of the hardened concrete. Splitting tensile strength has decreased by 15.01%, 36.42%, 50.55%, 71.74%, 79.25%, and 82.5% for perlite replacement ratios of 10%, 20%, 30%, 40%, 50%, and 60%, respectively, compared to

Figure 8: Failure mode for; (a) cubes for compression test, (b) cylinders for compression test, (c) cylinders for splitting tensile test, and (d) prisms for flexural test.

Figure 9: Failure for bond strength test specimens in case of; (a) roughness, (b) agent material, and (c) nails.

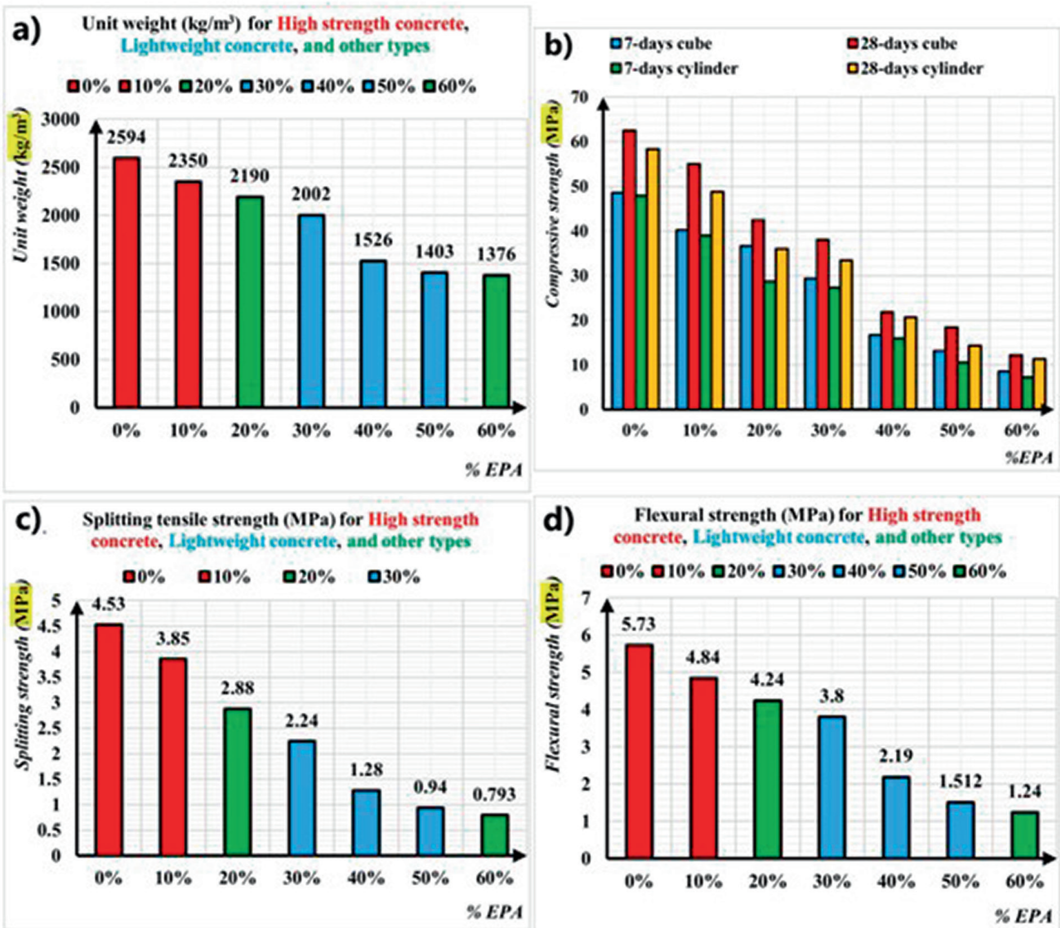

Figure 10: Effect of changing perlite replacement ratio on (a) unit weight, (b) compressive strength, (c) indirect-tensile strength, and (d) flexural strength.

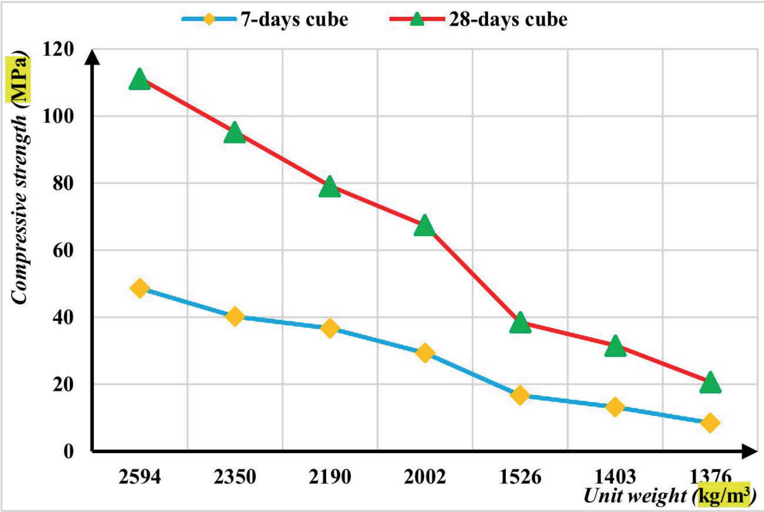

Figure 11: Relationship between unit weight and cube compressive strength.

the perlite replacement ratio of 0%. It can be concluded that tensile strength roughly equals 13% of the 28-days compressive strength. The indirect-tensile strength decreased with an increase in EP ratios [35, 48, 49]. Flexural strength has decreased by 15.53%, 26%, 33.68%, 61.78%, 73.61%, and 78.36% for perlite replacement ratios of 10%, 20%, 30%, 40%, 50%, and 60%, respectively, compared to the perlite replacement ratio of 0%. The addition of perlite brings down the concrete's flexural strength [50]. It can be seen that mix with 0% perlite meets the requirements of the targeted high-strength concrete and mixes with 30%, 40%, and 50% perlite meet the requirements of the targeted structural lightweight concrete, and they can be used for testing bond strength in this study with different treatment methods.

4.3. Effect of changing surface preparation with different roughness cases on the bond strength

As given in Table 5, the reference sample B roughened by hand-wire brushing has a moderately low bond strength value of 0.75 MPa without any particle damage at failure. The sample G roughened by grinding gave the lowest bond strength value of 0.52 MPa, while the sample C roughened by hand chiseling technique gave the highest bond strength value of 1.08 MPa, compared to the reference specimen B. Using grinding for roughening the surface (G) decreased the bond strength by 30.67% compared to the (B). This may be due to the obvious smooth texture resulting from grinding. In contrast, using hand-chiseling for roughening the surface (C) improved the bond strength by 44% compared to (B) sample due to the rough surface resultant of this roughness technique. This means that the hand chiseling roughness method gives the best bond strength results. Increasing the concrete roughness of the overlay surface increased the interface bond strength owing to the developed value of the shear friction at the interface and the mechanical interlocking among the two concrete surfaces. The benefits of increasing roughness on the tensile and shear bond strength mainly depend on the applied stress and the roughness level. ELBAKRY *et al*. [1] concluded that using hand-chiseling for surface roughness is significantly more effective than using grinding. The effect of changing the roughness technique on the interface bond strength results is illustrated in Figure 12.

4.4. Effect of varying concrete strength with the same treatment method on the bond strength

Table 6 and Figure 13 show the effect of varying concrete strength with the same treatment method on the interface bond strength between the new high-strength jackets and the old lightweight cube. Increasing the concrete strength enhanced the structural behavior and bond strength of specimens, owing to changing the mode of failure from adhesive to cohesive. Increasing the lightweight concrete strength for cubes leads to increasing the bond strength by 12%, 18.67% for 21.8 MPa, and 38.08 MPa, respectively, compared to 18.4 MPa in the case of using brushing roughness as a treatment method. In the case of using agent material as a treatment method, the bond strength increased by 32.22% and 58.35% for 21.8 MPa and 38.08 MPa, respectively, compared to 18.4 MPa. Increasing the compressive strength in the case of using bonding agent material enhanced the bond strength value owing to changing the mode of failure from rupture to adhesive, which helps to reduce the fast and brittle failure. Also, in the case of using nails as a treatment method, the bond strength increased by 25.54% and 54.57% for 21.8 MPa and 38.08 MPa, respectively, compared to 18.4 MPa. The rate of bond strength increased

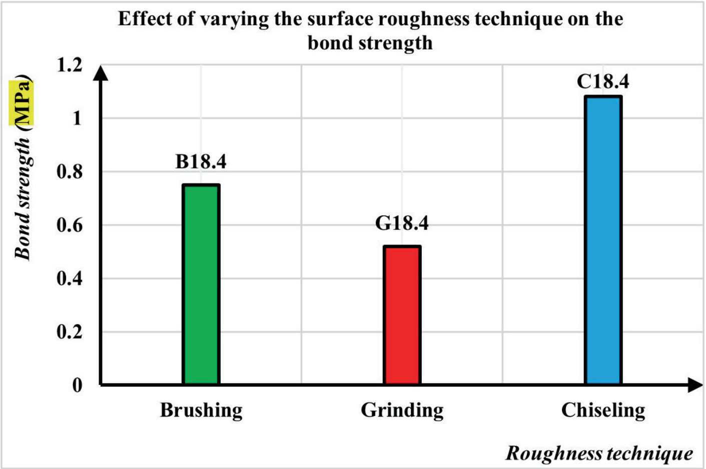

Figure 12: Effect of changing the surface roughness technique on the bond strength.

Table 6: Effect of varying concrete strength with the same treatment method on the bond strength.

MIX. NO.	TREATMENT SURFACE CASE								
	ROUGHNESS BY BRUSHING		$\%F_b$	AGENT MATERIAL		$\%F_b$	NAILS		$\%F_b$
Bond Strength (F_b) (MPa)	B18.4	0.750	–	M18.4	1.263	–	N18.4	1.378	–
	B21.8	0.84	+12%	M21.8	1.67	+32.22%	N21.8	1.73	+25.54%
	B38.08	0.890	+18.67%	M38.08	2.0	+58.35%	N38.08	2.13	+54.57%

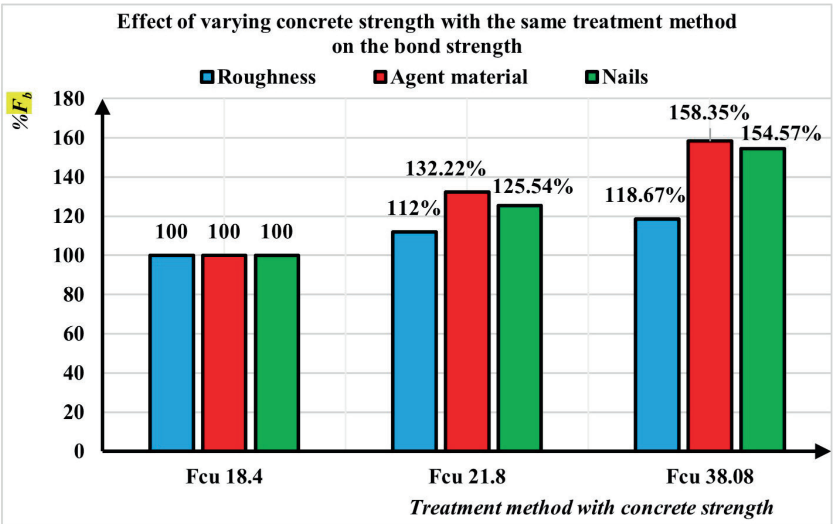

Figure 13: Effect of changing concrete strength with the same treatment method on the bond strength

by about 2.64% and 0.3% for increasing the concrete strength from 18.4 to 21.8 and from 21.8 to 38.08 MPa, respectively, in the case of using brushing roughness as a treatment method. The rate of bond strength increased by about 11.97% and 2.02% for increasing the concrete strength from 18.4 to 21.8 and from 21.8 to 38.08 MPa, respectively, in the case of using agent material as a treatment method. The rate of bond strength increased by about 10.35% and 2.45% for increasing the concrete strength from 18.4 to 21.8, and from 21.8 to 38.08 MPa, respectively, in the case of using nails as a treatment method. This means that the concrete strength between

18.4 MPa and 21.8 MPa is given the most effective value of interface bond strength, while utilizing high concrete strength values of (38.08 MPa) reduces the rate of bonding strength and fails the bond between the hardened and fresh concretes due to its brittle characteristics in all treatment cases. The high difference in concrete strengths between the fresh high-strength jackets and the hardened lightweight cube isn't mandatory to improve the interface bond strength between them. Economically, the new high-strength concrete for jackets must increase by about 2-3 times the hardened lightweight strength for cubes in all treatment cases. Increasing the strength of the fresh concrete enhanced the interface bond strength with the same surface preparation method, whether using epoxy, shear dowels, or both of them [51].

4.5. Effect of changing treatment method with the same concrete compressive strength on the bond strength

Table 7 and Figure 14 show the effect of varying the treatment method with the same concrete strength on the interface bond strength between the high-strength jackets and the lightweight cube. Using agent material and nails as treatment methods improved the bond strength by 68.4% and 83.73%, respectively, compared to the treatment method of brushing roughness with a compressive strength of 18.4 MPa. Using agent material and nails as treatment methods increased the bond strength by 98.8% and 105.95%, respectively, compared to the treatment method of brushing roughness with a 21.8 MPa compressive strength. Using agent material and nails as treatment methods increased the bond strength by 124.72% and 139.32%, respectively, compared to the treatment method of brushing roughness with a compressive strength of 38.08 MPa. It can be noticed that using nails gives the highest bonding strength with about 15.33%, 7.15%, and 14.6% for 18.4, 21.8, and 38.08 MPa, respectively, compared to agent material. So, using nails as a treatment method between high-strength jackets and lightweight cubes with an appropriate concrete strength value achieves good and economic bond strength. Using shear connectors passing through the interface between concrete-to-concrete composites enhanced the load capacity transferred at higher slips. Utilizing shear dowels, epoxy material, or both of them improved the

Table 7: Effect of varying treatment method with the same concrete strength on the bond strength.

MIX. NO.		TREATMENT SURFACE CASE					
		ROUGHNESS BY BRUSHING		AGENT MATERIAL		NAILS	
Bond strength (F_b) (MPa)	F_b	B18.4	0.750	M18.4	1.263	N18.4	1.378
	$\%F_b$		–		+68.4%		+83.73%
	F_b	B21.8	0.84	M21.8	1.67	N21.8	1.73
	$\%F_b$		–		+98.8%		+105.95%
	F_b	B38.08	0.890	M38.08	2.0	N38.08	2.13
	$\%F_b$		–		+124.72%		+139.32%

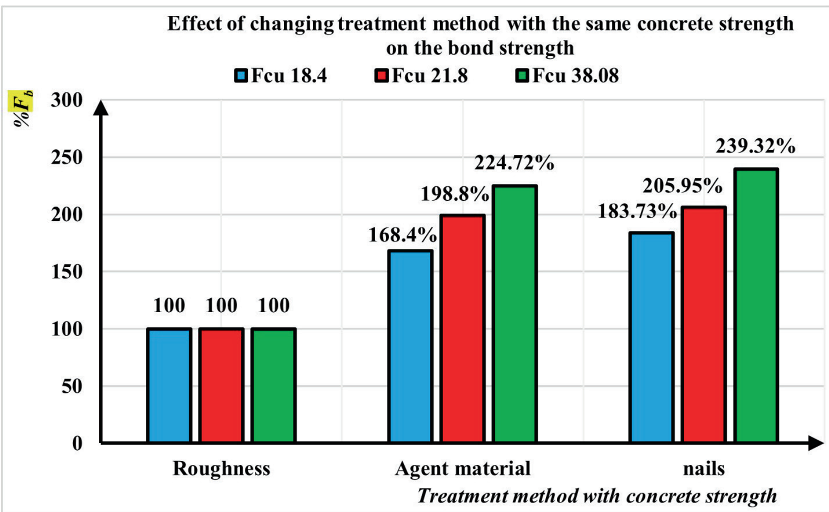

Figure 14: Effect of changing treatment method with the same concrete compressive strength on the bond strength.

Table 8: The interface relative bond strength results.

TREATMENT METHOD	ROUGHNESS BY BRUSHING			AGENT MATERIAL			NAILS		
Relative bond strength %	B18.4	B21.8	B38.08	M18.4	M21.8	M38.08	N18.4	N21.8	N38.08
	100	112	118.67	168.4	222.67	266.67	183.73	230.67	284

interface bond strength compared to the non-treatment case [9, 51]. It is concluded that using shear connectors for bonding old cubes to new jackets gave the best bond strength results compared to agent material and roughness.

4.6. Relative bond strength using different treatment methods

Table 8 illustrates the interface relative bond strength compared to the specimen treated with roughness using an 18.4 MPa concrete strength (B18.4). It can be noted that the sample using 38.08 MPa concrete strength with nails (N 38.08) gives the highest relative ratio bond strength of 284% compared to the reference case. With the same treatment method, using a sample with 21.8 MPa concrete strength (N 21.8) gave an interface relative bond strength of 230.67%, and using a sample with 18.4 MPa concrete strength (N 18.4) gives a relative bond strength of 183.73% from the original case. Therefore, the treatment method using nails has a greater effect on the bond strength than utilizing a concrete with higher strength values, saving costs. From tests, utilizing a new high-strength concrete with a double value of the old lightweight concrete strength and treating it with nails is the best technique to attain an acceptable and economic value of bond strength. AMIN *et al*. [51] concluded similar results.

5. THEORETICAL INVESTIGATION

The interface bond strength between the fresh and hardened concrete was calculated using the European Standard, Eurocode 2 [52], the Egyptian Code, ECP 203 [53], and ACI (American Concrete Institute) Committee 318 [54].

ECP 203

The cohesion between the fresh and hardened concrete and the interface normal compressive strength aren't considered in the Egyptian Code, but only the interface shear friction, which developed owing to the use of dowels. The bond strength of the specimen with nails was calculated in Table 9 according to the following ECP 203 equation:

$$Q_u = \mu_f * A_{sf} * (f_y/\gamma_s) \tag{1}$$

Where:

- Q_u = ultimate shear force.
- μ_f = friction coefficient; consider μ_f = 0.8 for rough and 0.5 for smooth surfaces.
- A_{sf} = cross-section area of nails.
- f_y = yield stress for nails.
- γ_s = reduction factor for nails; take γ_s = 1.0.

Eurocode 2

The Eurocode equation depends on the cohesion between the fresh and hardened concrete, the interface compressive stresses, and using nails. The bond strength for specimens was calculated in Table 9 according to the following Eurocode 2 equation:

$$V_{Rdi} = (c * f_{ctd}) + (\mu * \sigma_n) + [\rho * f_{yd} * (\mu * \sin\alpha + \cos\alpha)] \leq (0.5 * \upsilon * f_{cd}) \tag{2}$$

Where:

- V_{Rdi} = interface shear stress.
- c and μ = interface roughness factors; consider c = 0.20, μ = 0.60 for smooth interface and c = 0.40, μ = 0.70 for rough interface.

Table 9: Experimental and theoretical average bond strength.

SPECIMEN	BOND STRENGTH VALUE (MPa)			
	EXPERIMENTAL	ECP 203	EUROCODE 2	ACI-318
B18.4, brushing	0.75	–	0.746	–
G18.4, grinding	0.52	–	0.746	–
C18.4, chiseling	1.08	–	1.62	–
N18.4, nails	1.378	0.67	1.94	1.407

- f_{ctd} = concrete tensile strength; $f_{ctd} = (\alpha_{ct} * f_{ctk},0.05)/\gamma_c$. where α_{ct} is a coefficient of 1.0, $f_{ctk},_{0.05}$ is the concrete axial tensile strength, and γ_c is the concrete partial safety factor of 1.0.
- f_{cd} = concrete compressive strength; $f_{cd} = (\alpha_{cc} * f_{ck}/\gamma_c)$. Where α_{cc} is a coefficient of 1.0, f_{ck} is the cylinder compressive strength at 28 days.
- f_{yd} = yield stress for RFT; $f_{yd} = f_{yk}/\gamma_s$. where f_{yk} is the yield strength for reinforcement and γ_s is the RFT partial safety factor of 1.0.
- σ_n = stress per unit area; +ve for compression, and -ve for tension, $\sigma_n = \mu_s V_{Rdi}$. Where μ_s is the friction coefficient between the testing plate of the machine and the fresh concrete jacket, take $\mu_s = 0.55$.
- $\rho = (A_s \div A_i)$, where A_s is the cross-section area of nails and A_i is the interface joint area.
- α = the angle between the interface surface and the RFT crossing the interface; take $\alpha = 90°$.
- υ = reduction factor for strength; $\upsilon = 0.6\ (1 - f_{ck}/250)$.

ACI-318

According to ACI 318, the interface shear stress, which is subjected to pure shear and traversed by perpendicular steel reinforcement, can be calculated as

$$\nu_n = \rho * f_y * \mu \tag{3}$$

where

ρ = reinforcement ratio for interface nails

f_y = yield strength for nails

μ = friction coefficient at the shear plane, which depends on the type of shear plane and shear friction failure mechanisms. For shear planes at the concrete anchored to the structural steel by reinforcing bars, μ is defined as 0.7λ, where $\lambda = 1.0$ for normal-weight concrete and 0.75 for all lightweight concrete.

5.1. Discussion of theoretical results

The comparison between the estimated Egyptian, ACI-318, and Euro code bond strength values and the measured experimental value is given in Table 9. The Egyptian code equation for bond strength calculations excluded specimens without nails due to unconsidered cohesion. Comparing the experimental bond strength value with the theoretical code value for specimens with nails N18.4 indicated that the theoretical code equation underestimated nail influence on bond strength. A similar result could be concluded when the estimated values were compared with the measured value increase in bond strength. Eurocode bond strength values agreed with experimental values for brushing, but higher values were found for grinding, chiseling, and nails. American code results agree with the experimental bond strength results for specimens treated with nails. The Eurocode results were higher than the Egyptian code and ACI code results.

6. CONCLUSIONS

From the previously presented results, these conclusions can be numbered:

As expected, increasing the perlite replacement ratio decreased all of the mechanical properties of the designed mixtures.

Mix with 0% perlite meets the requirements of the targeted high-strength concrete, and mixes with 30%, 40%, and 50% perlite meet the requirements of the targeted structural lightweight concrete, and they can be used for testing the bond strength with different treatment methods.

The hand-chiseling roughness method gives the best bond strength results.

The high difference in concrete strengths between the fresh high-strength jackets and the hardened lightweight cube isn't mandatory to enhance the interface bond strength between them.

Using a new high-strength concrete with a double value of the old lightweight concrete strength and treating it with nails is the best technique to attain an acceptable and economic bond strength.

Eurocode bond strength values agreed with experimental values for brushing, but higher values were found for grinding, chiseling, and nails. Eurocode results were higher than Egyptian and American code results.

American code results agree with the experimental bond strength results for specimens treated with nails.

All specimens prepared by roughening the interface separated at the interface with a brittle shear collapse between new and old concretes without any damage to particles.

Specimens treated with agent bond material collapsed with a crack that passed through the interface surface between the agent bond material and the new concrete, with a few particles damaged, which indicated that the bond between the new concrete and the agent bond material is considered weaker than the bond between the hardened old concrete and the agent bond material.

Specimens treated with nails collapsed with a crack that passed through the old concrete cube without slight particle damage, which indicated that the nails achieved a good bond between the fresh and hardened concrete owing to the developed shear friction.

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