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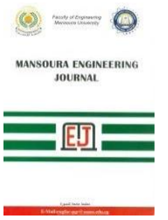

PROPERTIES OF REACTIVE POWDER CONCRETE AND IT'S UTILIZING AS A REPAIR AND STRENGTHEN MATERIALS

خواص خرسانة المساحيق الفعالة وإستخدامها كمادة إصلاح وتقوية

Mariam Farouk Ghazy, *Mohamed Helmy Taman* and Rana Mohamed El Ahwal

KEYWORDS:
Reactive powder concrete, concrete properties, repair materials, wrapping, slant shear strength.

الملخص العربي:

هذا البحث يهدف الى دراسة جزئين. الجزء الاول هو لدراسة خواص خرسانة المساحيق الفعالة والمنتجة باستخدام طريقتين مختلفتين من المعالجة، تحديدا المعالجة فى المياة العادية في درجة حرارة 20^{o} م و المعالجة فى المياة الساخنة فى درجة حرارة 60^{o} م. وفى الجزء الثانى من الدراسة، تم ايضا تقييم استخدام خرسانة المساحيق الفعالة كمادة تقوية واصلاح (كنظام مركب). المتغيرات المختلفة و التى تشتمل على نسبة المياة الى الاسمنت ونوع الالياف المستخدمة تم اخذها فى الاعتبار. بناء على نتائج الاختبار من الدراسة الاولية فى الجزء الاول من انتاج خلطات مساحيق الخرسانة الفعالة تم اختيار الخلطات التى تتميز بانسيابية ومقاومة ضغط عالية لاستخدامها فى التقوية والاصلاح و التى تم معالجتها فى المياة العادية فى درجة حرارة 20^{o} م. تم تقييم خرسانة المساحيق الفعالة كمادة اصلاح عن طريق مقاومة الضغط،الانحناء،والتماسك(بطريقة الانفلاق والقص). اظهرت نتائج الجزء الاول انة يمكن الحصول على خرسانة المساحيق الفعالة ذات مقاومة ضغط حتى 110 و 140 ميجا باسكال فى معالجة المياة العادية وفى معالجة المياة الساخنة على الترتيب. كما اظهرت نتائج الجزء الثانى من الدراسة ان خرسانة المساحيق الفعالة مادة اصلاح واعادة تاهيل ممتازة فى مقاومة الضغط والانحناء وكذلك مقاومة التماسك بالمقارنة بالخرسانة العادية المعاد تأهيلها. نسب الزيادة فى مقاومة الضغط للاسطوانات المحاطة بمقدار10مم و25مم بخرسانة المساحيق الفعالة فى حدود من 25% الى 114% ومن 42%الى 142 % على التوالى، بالمقارنة بالخرسانة العادية المعاد تأهيلها.

Abstract— **This investigation aimed to study two phases. (Phase I) was to study the properties of reactive powder concrete (RPC) produced by two different curing regimes, namely, water curing at 20 ^{o}C and hot water curing at 60 ^{o}C. Moreover, the effect of using the RPC as a repair and strengthening materials (combined system) was also evaluated (Phase II). Different parameters include water to binder ratio and fiber types were considered. Based on the test results of the primary study (Phase I) of the RPC mixes, mixes of adequate flow and high compressive strength (with water curing 20 ^{o}C) were selected and used for both strengthening and repairing processes. The RPC as repair materials were evaluated by the compressive, flexural and bond (splitting and slant shear) strengths. The test results of Phase I showed that the RPC with compressive strength up to 110 and 140 MPa can be obtained in water curing at 20 ^{o}C and hot water curing at 60 ^{o}C, respectively. The test results of Phase II showed that the RPC displays excellent repair and retrofit potential on compression, flexure strengthening and possesses high bond strength as compared to substrate normal concrete (NC). The ratio of the increase of compressive strength of cylindrical specimens with 10 and 25 mm of wrapping with RPC are in the range of 25% to 114% and 42% to 142%, respectively as compared to substrate NC.**

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Mariam Farouk Ghazy ,Associate Professor, Faculty of Engineering, Structural Engineering Department, Tanta University, Email: dr.mariamghazi@yahoo.com

Mohamed Helmy Taman ,Associate Professor, Faculty of Engineering, Structural Engineering Department, Tanta University, Email: taman010@yahoo.com

Rana Mohamed El Ahwal ,M.Sc. Student, Faculty of Engineering, Structural Engineering Department, Tanta University, Email: ranabassuonii@gmail.com.

I. INTRODUCTION

REACTIVE powder concrete (RPC), otherwise well-known as ultra-high-performance concrete (UHPC) and its derivatives in the mid-90s of 21st Century. The roots of this material go back to France and Canada [1]. It is developed through micro structural enhancement techniques for cementations materials. Many structures, especially those made of reinforced concrete, suffer from severe degradation after their construction due to many environmental causes (deicing salts, freezing and thawing, aggressive environment like earthquake and a drastic increase of live loads). The needs to new concrete or repair materials in the field of retrofitting and strengthening of concrete structures are gained. Selecting repair materials for concrete structures requires an understanding of material behavior in the uncured and cured states in the anticipated service and exposure conditions. One of the greatest challenges facing the successful performance of repair materials is their dimensional behavior relative to the substrate [2]. The composition of RPC is coarse aggregate-free which differs from that of ordinary concrete. Instead, fine powders such as quartz sand and crushed quartz, with particle sizes ranging from 45 to 600 μm are used. In fact, it is rather a mortar than an original concrete mixture because there is no coarse aggregate [3]. The factors affecting the RPC properties were studied earlier [3, 4]. Basically, production process, water to cement ratio, silica fume content, quartz powder, superplasticiser dosage, curing regime, fiber content influences the properties of RPC. The RPC with a water-to-binder ratio of 0.2, superplasticiser dosage of 2.5%, 150-600 μm quartz sand cured at 27 ^{o}C in water condition provides the best results in terms of mechanical and composite properties as well as for practical and economical reasons, although heat treatment of the RPC can result in a significant increase in compressive strength [3].The compressive strength increases rapidly with curing temperature between 23 and 150 °C due to the acceleration of the hydration process due to the pozzolanic reaction of quartz, which can be activated at these temperatures, causing the formation of very dense calcium silicate hydrates (CSH) compounds with very low numbers of water molecules [4]. The combination of ultra-fine ingredients in RPC to an extremely brittle matrix generally not accepted for structural use. Steel fiber provided much needed ductility and cracking. The brittleness of ultra-fine RPC can be overcome by short steel fibers with aspect ratio L/D= 60 [5]. The RPC compressive strength of 200 MPa made with the cementitious materials consisting of 40% of Portland cement, 25% of ultrafine slag, 25% of ultrafine fly ash and 10% of silica fume, 4% volume fraction of steel fiber [6]. Performance and enhancement of novel, economical repair procedures are required to prolong the service life of concrete structures. Many researchers studied the RPC as repair materials [7-14]. The most recent issues and findings using UHPC as a repair material were discussed and reviewed [7]. A preliminary study of RPC as a new repair material was considered [2, 8]. The test results showed that the RPC displays excellent repair and retrofit potentials on compressive and flexure strengthening and possesses high bond strength, dynamic modulus and bond durability as compared with other concretes. RPC with a flow value of 200% and a compressive strength of 75 MPa was considered. Slant shear; rebar pull-out and tensile strength tests were implemented on cylindrical specimens. It was found that the highly flowable RPC provides much higher rebar pull-out forces and tensile strengths in cylindrical specimens compared to epoxy resin specimens [9]. The reinforcing effect of the RPC with two wrapping thicknesses of 10 and 15 mm on the cylindrical concrete specimen was studied [10]. The results revealed that the increase in the compressive strength were 9.5 and 38% for retrofitted cylindrical specimens with 10 and 15 mm thicknesses, respectively. This paper presents the production and the ability of using RPC as a repair material for strengthening normal concrete (NC). For this purpose, two series tests were performed to evaluate the compressive, flexural, splitting and slant shear strengths of their bond to existing concrete. Based on the experimental primary study, mixes proportions with an adequate flow and high compressive strengths are selected and used throughout this study.

II. EXPERIMENTAL PROGRAM AND METHODS

The experimental program has two phases. The first phase (Phase I) included 11 trial mixes to investigate the possibility of producing and optimizing the RPC mix using materials available in local market in Egypt. To find out the optimal composite materials and conditions for producing RPC using local materials, the effects of several parameters on mechanical properties are investigated. These parameters include: curing regime (water curing temperature (20 ^{o}C) and hot water curing temperature (60 ^{o}C) at first 7 days followed by water curing temperature (20 ^{o}C) up to 28 days), water-to-cement ratio (W/C) (0.21, 0.22, 0.23, 0.25), fly ash content (10% replacement by weight of silica fume) and type of fibers (1% steel and 1% polypropylene).The second phase (Phase II) concerned to the utilizing of RPC as a repair materials. Phase II included two types of concrete NC and RPC. NC with compressive strength 25 MPa proposed as substrate layer that it is need to be repaired. As well as, RPC to be utilized as repair materials which is produced and evaluated in preliminary study (Phase I). Appropriate mixes of RPC were selected to evaluate its performance in repairing of substrate layer and one mix of traditional NC. The following sections summarize the details of the experimental program.

A. Materials

Locally available materials were used in this study. Portland cement (C) CEM I 42.5N was used for the production of RPC and NC mixes. The cement met the requirements of EN 197-1 and with fineness 3500 cm3/g. Silica fume (SF) and fly ash (FA) have been used as mineral admixtures addition to the RPC mixes of this study. SF was used as 25% addition of cement by weight. The RPC microstructure becomes less porous through the pozzolanic reaction of SF and hydration product CSH, giving a higher compressive strength. Class F (ASTM C 618-08a) (FA) was used as a mineral admixture with 10% as replacement of SF by weight. Natural siliceous sand (S) with a specific gravity of 2.7 and a grain size distribution ranging from 150 µm to 600 µm was used in all mixes. The sand particles finer than 150 µm were excluded to avoid the interference with the coarse cement particles (100 µm) as recommended by [15]. Sand used was 150 % as addition of cement by weight. Locally produced quartz powder (Q) with a SiO2 content of 98%, Blaine fineness of 3100 cm2/g, a specific gravity of 2.85 and unit weight of 1.46 t/m3 was used. Q was used as 40% addition of cement by weight. Crushed lime stone with maximum particle size of 12 mm and specific gravity of 2.55 was used as coarse aggregate (CA) for NC mixes only. Table 1 presents the chemical composition of C, SF, FA and Q materials. Tap water was used in all concrete mixtures and in the curing of specimens. To enhance workability and reduce W/C a high range water reducer admixture (superplasticizer) having density 1.08 kg/liter was used it is manufactured to conform to ASTM C494 type F and G. 5% as addition of cement by weight was used of the admixture for all RPC mixes. As well as, two types of fibers namely steel fibers (Sf) and polypropylene fibers (Pf) were used with volume fraction at 1% by volume. Table 2 indicates the mechanical properties of the used fibers.

TABLE 1
THE CHEMICAL ANALYSIS OF C, SF, FA AND Q MATERIALS (%)

Component	**Cement (C)**	**Silica fume (SF)**	**Fly ash (FA)**	**Quartz (Q)**
SiO2	4.08	96.00	58.64	99
Fe2O3	4.99	0.09	7.85	0.012
Al2O3	63.01	0.80	25.77	0.13
CaO	0.89	0.65	4.95	0.02
MgO	-	0.09	1.00	0.0
P2O5	0.51	0.01	0.05	0.0
Na2O	0.22	0.44	0.90	-
K2O	0.03	0.02	0.21	0.001
Cl	2.92	0.01	0.01	-
SO3	-	0.02	0.09	0.033
MnO2	2.31	Nil	0.01	-
L.O.I		1.84	0.46	0.03
Total		99.96	99.95	99.5

B. Proportions and Specimens Preparations

Table 3 presents the mix proportions of concrete mixes. NC was mixed in a classical procedure where crushed lime stone and sand were mixed first for 2 minutes then cement was added and the dry components were mixed for about 3 minutes to obtain a homogeneous dry mix, then water was added during the mixing process which continued for another 3 minutes or until obtaining a homogeneous mixture. The different RPC matrices are designed and their compositions are listed in Table 3. After selection of all needed constituent materials and amounts to be used; all materials are weighted properly. Then mixing with drum mixer with capacity of 100 liter started and continued to ensure that all particles are surrounded with cement paste and silica fume and all the materials and fibers should be distributed homogeneously in the concrete mass. For each type of the proposed mix proportions of RPC, mixing procedure was conducted according to the following steps:

1) Adding superplasticizer to the mixing water,
2) Placing cement, and mixing for 2 minutes,
3) Silica fumes with (if any) fly ashes were added to the mix and mixing for 5 minutes,
4) After waiting of 1 minute for rest period, sand and quartz powder were added to the mixture and the mixing continued for another 5 minutes.
5) Finally, adding fibers if they exist, and continue of mixing at least for 3 minutes as the RPC changes to a glossy homogeneous.

TABLE 2
MECHANICAL PROPERTIES OF FIBERS USED

Fiber type	**Length (mm)**	**Diameter (mm)**	**Aspect ratio**	**Density kg/m3**	**Tensile strength (MPa)**	**Modulus of elasticity (GPa)**
Steel (Sf)	15	0.5	30	7850	400	200
Polypropylene (Pf)	19	0.04	475	900	550	40

TABLE 3
CONCRETE MIX PROPORTIONS BY WEIGHT (KG/M3)

Mix no	Mix ID**	C	SF	FA	S	CA	Q	W	SP	Sf	Pf
1	NC	350	-	-	600	1200	-	175	-	-	-
2	0W50	850	-	-	935	-	340	425	-	-	-
3	SFW21	850	212.5	-	935	-	340	178.5	42.5	-	-
4	SFW22	850	212.5	-	935	-	340	187	42.5	-	-
5	SFW25	850	212.5	-	935	-	340	212.5	42.5	-	-
6	SF+FW21	850	127.5	85	935	-	340	178.5	42.5	-	-
7	SF+FW22	850	127.5	85	935	-	340	187	42.5	-	-
8	SF+FW23	850	127.5	85	935	-	340	195.5	42.5	-	-
9	SF+FW25	850	127.5	85	935	-	340	212.5	42.5	-	-
10	SFW25Sf	850	212.5	-	935	-	340	212.5	42.5	78	-
11	SFW22Sf	850	212.5	-	935	-	340	187	42.5	78	-
12	SFW22Pf	850	212.5	-	935	-	340	187	42.5	-	9

**Where: SFW21 refers to silica fume with water / cement=0.21
SFW22Sf refers to silica fume with water /cement=0.22 and steel fiber fibers
SFW22Pf refers to silica fume with water / cement =0.22 and polypropylene fibers
SF+FW21 refers to silica fume + fly ash with water / cement =0.21

After complete mixing, the flow value of the RPC was measured and recorded by using mini flow table (ASTM C 1240), and the fresh homogeneous concrete is poured into steel molds. Finally, all the specimens were mechanically compacted using vibrating table for 30 seconds. After preparing the specimens; cubes were covered with plastic sheets for about 24 hours to prevent moisture loss and left in ambient temperature at 23 ^{o}C and 55% RH. One day later, the RPC specimens were removed from the steel molds. Half of the RPC specimens were cured in water at temperature (20 ^{o}C) for an additional 27 days, while the remaining RPC specimens were cured in hot water tank at 60 ^{o}C for 7 days, then but in water at temperature 20 ^{o}C until the time of the test. Before the tests, the specimens were air dried for 10 to 15 minutes and any loose sand grains from the faces that may be in contact with the bearing plat of the testing machine was removed.

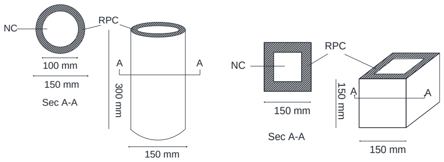
C. Test Specimens Fabrication

1. Phase I

The RPC mixes was tested by using Digital Hydraulic Testing Compression-Flexure Machine of capacity 300 kN. Prismatic specimens with dimension 40×40×160 mm were cast and used to obtain compressive strength at 7 and 28 days and flexural strength at 28 days, according to EN 196-1 for different curing conditions. Cylindrical specimens with dimension (50 mm diameter ×100 mm height) were used for splitting tensile strength according to Brazilian Standard NBR 7222, at 28 days.

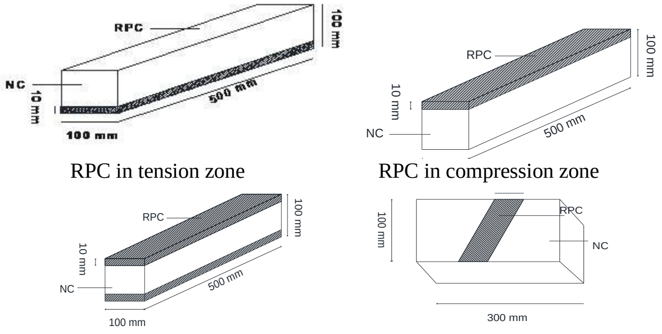
2. Phase II

Substrate specimens (NC) were cured for 28 days using normal water curing at 20 ^{o}C. Then the specimens were removed from water and placed in the ambient temperature at 23 ^{o}C and 55% RH for another 60 days. After 90 days of curing in water and air, they were processed to put the repair material. The change in the W/C ratio of the fresh RPC due to the water absorption of substrate specimens' halves might result in a decrease in workability. Hence, all cut specimens were cured in water for an additional 24 h [9]. Finally, the tests of the repaired specimens were done after 28 days of normal water curing at 20 ^{o}C. Cylindrical specimens with dimensions of (150 mm in diameter and 300 mm in height) without (NC) or with bonding RPC repair material of 10 and 25 mm thickness were used for compression test. Moreover, cubical specimens with dimensions 150×150×150 mm without (NC) or with bonding RPC repair material of 25 mm thickness were cast as shown in Fig. 1.



Cylinder Cube

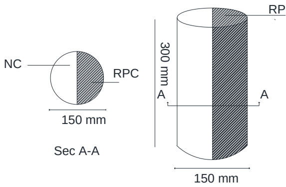
a- Compression



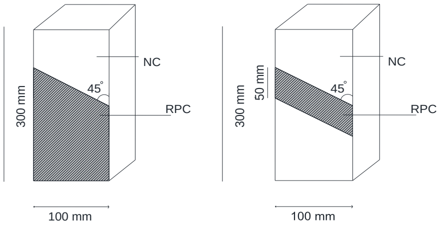
RPC in tension zone RPC in compression zone

RPC in tension and Compression zones RPC in diagonal layer

b- Flexural



c. Splitting



RPC in diagonal one-half RPC in diagonal layer

d- Slant shear

Fig. 1. Specimen Configuration for Different Tests

Three point loading of flexural test was performed on beam specimens with dimensions of 100×100×500 mm without (NC) or with RPC bonding repair material of 10 mm thickness in tension zone or in compressive zone [2,8] or with both as shown in Fig. 1. Moreover, beam specimens with dimensions of 100×100×300 mm were used for diagonal bonding layer. RPC slurry layer with a thickness of 50 mm was placed on the area between the two saw-cut halves [13]. The bond strength between the repair RPC material and concrete substrate NC plays an important role in determining the efficiency of a repair material used in repairing concrete structures. Slant shear test and splitting prism test were performed to quantify the bond strength in compression and shear, and in tension, respectively [11, 12]. Cylindrical specimens with (100 mm diameter and 3 c00 mm height) were poured to measure the splitting tensile strength of NC. Splitting tensile strength of repair RPC materials was also implemented with the same assumption that half of the represents the substrate concrete (NC) while the other half should be cast with RPC repair material to be connected into concrete in one system (one-half NC and one-half RPC repair material) as shown in **Fig. 1**. The splitting tensile strength was calculated by dividing the maximum load with the bond plane area [12]. Slant shear test is economical and can be easily reproduced. The prismatic specimens have dimensions of 100×100×300 mm were used [12] for evaluating the slant shear strength at an inclined angle of 45^o [2,8,14]. Two different techniques of slant shear test namely, RPC slurry diagonal layer with 50 mm thickness was placed on the area between the two saw-cut halves of NC and diagonal (one-half NC and one-half RPC repair materials. As well as, two different surface textures were used for slant shear test of diagonal one-half specimens applied on NC, namely, as saw-cut (AC) and drill holes (DH) every ≈25 mm each hole having 10 mm diameter and 5 mm depth [12]. The prismatic specimens with a diagonal layer of RPC are shown in Fig. 1. The slant shear strengths for repair materials can be obtained by conducting a series of compression tests. The slant shear strength was calculated by dividing the maximum load with the bonded area [12]. Hydraulic Testing Machine with total capacity of 2000 kN was used for testing specimens. At least three of samples were tested and the mean value of the specimens was considered as the strength of the experiments. Therefore the methods of rehabilitation or strengthening of these zones should be reliable, effective and economical.

III. RESULTS AND DISCUSSIONS

A. Phase I

The experimental test results of Phase I of the RPC specimens are summarized in Table 4.

1. Flow of Fresh Mixes

The test results of flow are in the range from 85% to 180% as given in Table 4. Fig. 2 represents the main effect plot of the flow test results (using Minitab 16 software package). An optimal setting was evaluated from this plot. The factors affect the flow of RPC mixes are arranged in a descending order as W/C, FT and FA, respectively.

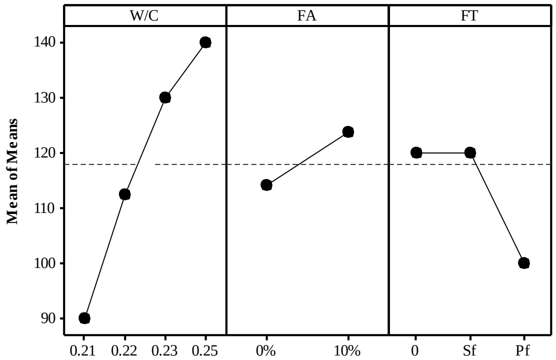


Fig. 2. Mean Effect Plot for Flow

2. Compressive Strength

The strength of concrete is very much dependent upon the hydration reaction in which water plays a critical role, particularly the amount of water used. Therefore, an optimal W/C ratio is important in achieving high strength. It can be seen from Table 4 and Fig. 3 that compressive strength for hot water curing specimens consistently higher than compressive strength for ambient water curing specimens at different ages regardless of the RPC mix proportions. The increases at 7 and 28 days (60 ^{o}C) for the proposed mixes ranged from 12 to 36% and from 8 to 28%, respectively compared to (20 ^{o}C). The hydration of cement produces many compounds; including CSH and calcium hydroxide (CH). When silica fume and fly ash is added to fresh concrete, it chemically reacts with the CH to produce additional C-S-H which improves the bond between the cement and the surface of the aggregate. The type of curing has a significant role for formative the increasing in the compressive strength for concrete commonly and for RPC especially. This is because W/C ratio at RPC is lower than W/C ratio of NC. The water curing of RPC in its early age is important. In addition, it leads to a better and stronger formation of silicate hydrates [16]. As known the W/C ratio has a great effect in concrete compressive strength, that the lower the W/C ratio of a concrete mix, the higher the compressive strength of the concrete will be, in which the concrete is workable enough for achieving adequate compaction. Conversely, concrete with higher W/C ratio gives lower compressive strength. This is because these more fluid mixes are more susceptible for entraining air bubbles owing to the folding action of the mixing process. As a result, more voids are left in the matrix which increase the porosity and thus considerably reduce the compressive strength. The decrease in compressive strength are 8.1 and 12.9% for mixes SFW22 and SFW25 compared to mix SFW21, respectively at 28 days for ambient water curing. It can be seen from Fig. 4 (the mean effect plot) that the strongest influence was exerted by WC (curing condition Rank 1), W/C ratio (Rank 2), fiber type (Rank 3), and fly ash ratio (Rank 4). Therefore, mixes SFW25, SFW25Sf, SFW22Sf and SFW22Pf are appropriate when both adequate flow and high compressive strength are required. Selected RPC specimens were produced and measured for compressive strength, flexural strength and bond strength test (splitting and slant shear) to evaluate the feasibility of using RPC as a repair and strengthening materials in concrete structures.

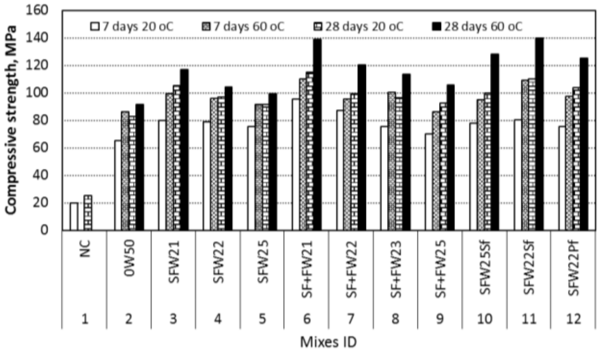


Fig. 3. Compressive Strength for Concrete Mixes with Different Curing Conditions

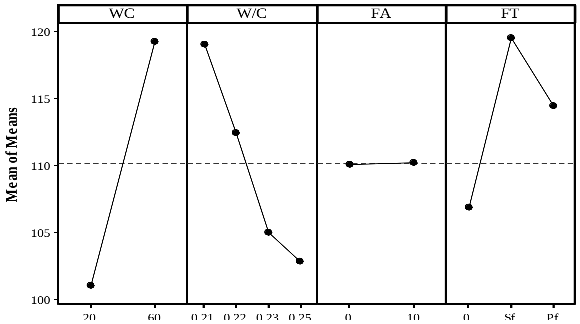


Fig. 4. Mean Effect Plot for Compressive Strength

3. Flexural Strength

The test results presented in Table 4 and plotted in Fig. 5 show that the variables affect the flexural strength at the same curing condition arranged in a descending order as FT, W/C, and FA, respectively. Flexural strength for hot water curing specimens consistently higher than flexural strength for ambient water curing specimens at different ages regardless of the RPC mixes proportions. The highest value of flexural strength was recorded at 28 days as 20.8 MPa for mix 11 (SFW22Sf) at hot water curing as shown in Fig. 5.

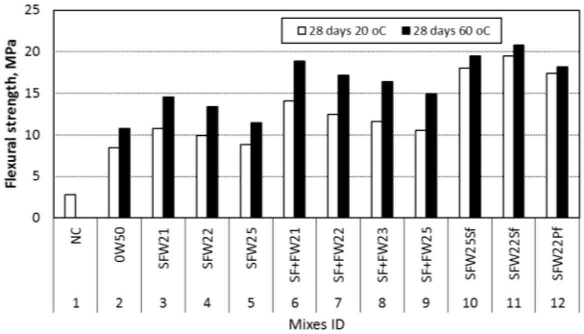


Fig. 5. Flexural Strength for Mixes with Different Curing Conditions

TABLE 4
TEST RESULTS FOR EXPERIMENTAL STUDY PHASE I

Mix No.	Mix code	Flow %	Compressive strength, MPa				Flexural strength, MPa		Splitting tensile strength, MPa	
			7 days		28 days		28 days		28 days	
			20 oC	60 oC*	20 oC	60 oC*	20 oC	60 oC*	20 oC	60 oC*
1	NC	-	20	-	25	-	3	-	2.3	-
2	0W50	180	65	86.19		91.65	8.45	10.79	5.59	6.63
3	SFW21	85	80	99.19	105.2	117	10.79	14.56	7.93	9.49
4	SFW22	120	79	95.68	96.7	104.4	9.88	13.39	7.54	8.45
5	SFW25	140	75.4	91.52	91.65	99.19	8.84	11.44	6.76	7.8
6	SF+FW21	95	95.42	109.9	115	139	14.04	18.85	7.93	10.14
7	SF+FW22	120	87.1	95.55	99.19	120.4	12.48	17.16	7.54	9.23
8	SF+FW23	130	75.4	100.1	96.6	113.4	11.57	16.38	7.15	8.32
9	SF+FW25	150	70	86.06	92.3	105.7	10.53	14.95	6.89	7.54
10	SFW25Sf	130	78	95	100	128	18	19.5	13	16
11	SFW22Sf	110	80.08	109	110	140	19.5	20.8	13.26	18.59
12	SFW22Pf	100	75.4	97.5	103.8	125	17.42	18.2	12.74	15.99

* Water curing at 60 ^{o}C for first 7 days and followed by water curing at 20 ^{o}C up to 28 days

4. Splitting Tensile Strength

Splitting tensile strength for hot water curing specimens reliably higher than splitting tensile strength for ambient water curing specimens at different ages regardless of the RPC mix proportions as the same trend for compressive and flexural strengths. Fig. 6 shows the test results of splitting tensile strength. The highest value of splitting tensile strength at 28 days reached 18.59 MPa recorded for mix 11 (SFW22Sf) with hot water curing. The results revealed that addition of 1% steel fibers by volume resulted in 105% 120% higher than comparable mix 5 and 4 (SFW25 and SFW22) at the same curing conditions (60 ^{o}C), respectively

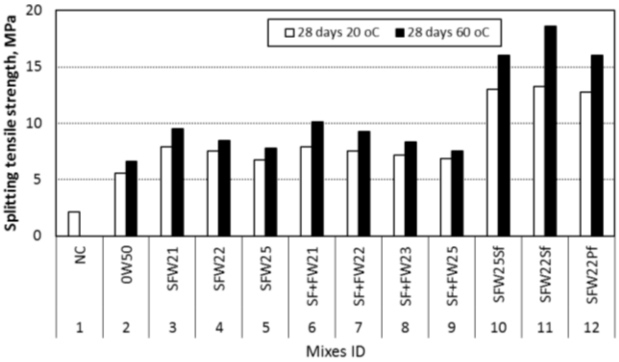


Fig. 6. Splitting Tensile Strength for Mixes with Different Curing Conditions

B. Phase II

Based on the results of Phase I, four RPC mixes were selected, namely, SFW25, SFWSf25. SFWSf22 and SFWPf22 for reproducing RPC repair system RPCW25, RPCWSf25, RPCWSf22, RPCWPf22, respectively. Moreover, mix 1 was used as a control mix as it represents a common conventional mix for NC. These mixes were studied to evaluate the performance of RPC as repair materials.

1. Compressive Strength

The compressive strength of the confined specimens was determined at 28 days after providing the RPC confinement layers (10 and 25 mm). **Table 5** illustrates the results of the combined systems for both square and circle shapes. The results of compressive strength for the combined system show that all the RPC mixes used to repair the substrate concrete exhibit a remarkable increase in the compressive strength of this combined system. The significant effect was recorded for the cylindrical specimens compared with square specimens. From the test results presented in Table 5 and plotted in **Fig. 7**, the highest value of the compressive strength 65 MPa was obtained by using RPC in addition to 1% steel fibers (NC/RPCSf22) at 28 days against to 28 MPa recorded for NC at 90 days. It can be noticed that the compressive strength of NC with its wrapped repair materials increased in the rate of 42.9 and 17.9% when used RPC with W/C ratio at 0.25 and without any fibers (NC/RPC25) for cylinder and square wrapping specimens compared to NC, respectively. As well as, the increases in compressive strengths were 114.3% and 132.14% for 10 and 25 mm cylindrical RPC wrapped systems, respectively compared to NC.

TABLE 5
TEST RESULTS OF RPC AS A REPAIR MATERIAL (PHASE II) (STRENGTH/ FAILURE MODE)

Upper/lower materials	NC	NC/RPC25	NC/RPCSf25	NC/RPCSf22	NC/RPCPf22
Compressive strength, MPa cylinder (10 mm)	28	35 Interface failure	50 Interface failure	60 Interface failure	49 Interface failure
Compressive strength, MPa cylinder (25 mm)	28	40 Interface failure	55 Interface failure	65 Interface failure	52 Interface failure
Compressive strength, MPa cube (25 mm)	28	33 Interface failure	40 Interface failure	45 Interface failure	39 Interface failure
Flexural strength, MPa (compression zone) (Flex. C)	3	3.5 Substratum failure	4 Substratum failure	4.5 Substratum failure	3.5 Substratum failure
Flexural strength, MPa (tension zone) (Flex. T)	3	4 Repair and substratum failure	4.2 Repair and substratum failure	5.4 Repair and substratum failure	3.9 Repair and substratum failure
Flexural strength, MPa (compression and tension zone (Flex. TC)	3	3.9 Lower failure	5.1 Lower failure	6 Lower failure	4 Lower failure
Flexural strength, MPa (diagonal zone) (Flex. D)	3	3 Interface failure	4 Interface failure	4.5 Interface failure	3.5 Interface failure
Splitting tensile strength, MPa (Split.)	2.3	2.5 Interface failure	2.5 Interface failure	3 Interface failure	2.4 Interface failure
Slant shear strength, MPa (As saw-cut) (Slant AC)	9 Interface failure	11 Interface failure substrate cracks	12 Interface failure substrate cracks	17 Interface failure substrate cracks	15.4 Interface failure
Slant shear strength, MPa (Drill holes) (Slant DH)	10.2 Interface failure	13 Interface failure substrate cracks	19 Interface failure substrate cracks	21 Interface failure substrate cracks	18 Interface failure

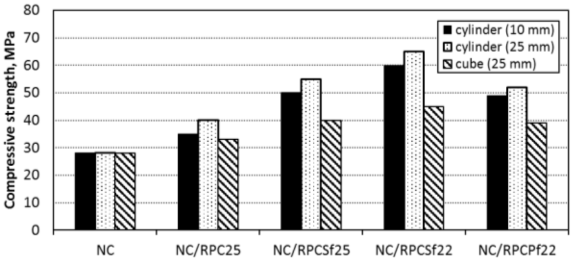


Fig. 7. Compressive Strength for Combined Systems

2. Flexural Strength

Flexural beam specimens with bonding repair material RPC of 10 mm thickness in tension zone (Flex. T), compressive zone (Flex. C) and both (Flex. TC) were investigated. As well as bonding repair with RPC in diagonal (Flex. D) Was used and the test results are shown in **Fig. 8**. The obtained results can be justified as a better bonding developed due to the use of RPC strengthening materials. The higher development was indicated for RPC with steel fiber in all test specimens, and the increases were 50%, 80%, 100%, and 33.33% for (NC/RPCSf22) in Flex. C, Flex. T, Flex. TC and Flex. D more than NC, respectively. The addition of distributed homogenously steel or, polypropylene fibers worked as a reinforcement and would sustain the developed tensile stresses thus increased the flexural strength of specimens.

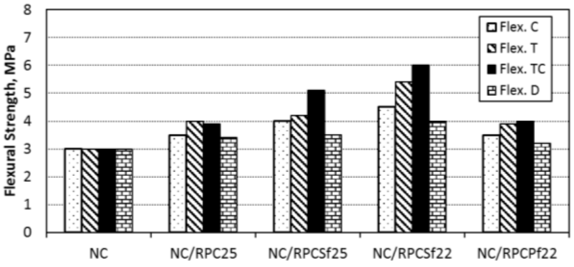


Fig. 8. Flexural Strength for Combined Systems

3. Bond Strength

1) Splitting Test

The test results of the splitting tensile strength indicated that the use of RPC strengthened the tensile strength of the substrate concrete better than the NC as one system as shown in Fig. 9. The enhancements in the splitting tensile strength were 8.7%, 8.7%, 30.4% and 4.3% for NC/RPC25, NC/RPCSf25, NC/RPCSf22 and NC/RPCPf22 compared to NC, respectively.

2) Slant Shear Test

The slant shear test measures the shear bond between the repair material and the substrate at an inclined angle of 45o. The surface preparation of substrate concrete was as saw-cut (Slant AC) or drill holes (Slant DH) before placing the RPC repair material. The test results are presented in Table 2 and shown in **Fig. 9**. The slant shear provided the highest strength regardless the proportions of mixes, for all repair materials and surface preparations. This can be attributed to the high compressive strength that exist in slant shear test which produce higher interlock and friction forces that increase the shear failure load. The results showed that the shear bond strength between the repair material and substratum are arranged in an ascending order as NC, NC/RPC25, NC/RPCPf22, NC/RPCSf25, and NC/RPCSf22, consecutively for different surfaces preparation. The increase was 27.5%, 66.7%, 86.3%, and 105.9%, respectively for (Slant DH) over the control specimens NC. Rough surface (DH) preparation leads to higher slant shear strength. These increases ranged from 13.3% to 58.3% with respect to as saw-cut (AC) surface.

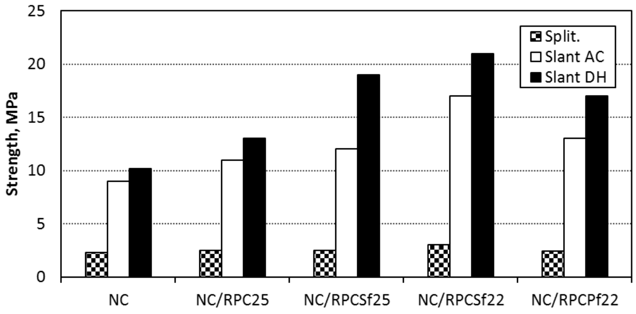


Fig 9. Bond Strength for Combined Systems

C. Modes of Failure

The failure modes were characterized by the location of the failure in the specimens. Interface or bond failure is defined when the plane of failure is along the interface surface. Some of the specimens failed by partial failure of either the substratum concrete or the RPC repair material. Table 5 illustrates the failure types of the tested combined systems. The study demonstrated that the repaired splitting prism specimens failed in bond, while under slant shear test, the bond strength is greater than the strength of concrete substrate, and therefore, failure occurred at the interface included corner breaks in the concrete substrate with no failure within the RPC repair materials.

IV. CONCLUSIONS

From the test results presented in this study on properties of RPC mixes and the bond properties of the interface between NC substrate and RPC as a repair and strengthening materials, the following conclusions are offered:

1. The RPC can be produced with superior properties using local materials. As RPC with 140% flow and compressive strength up to 140 MPa is produced by using local materials available in Egypt.
2. The early age's mechanical properties of RPC are more sensitive to curing conditions. The high temperature curing is essential for RPC to achieve higher early strength. The increase in compressive strength up to 36% when compared with normal curing at 7 days was achieved.
3. Inclusion of fibers in RPC mixes increases the mechanical properties with different curing conditions. A significant increase for using steel compared to polypropylene fibers was observed. Therefore the flowable high strength combined system reinforced with fibers has a considerable improvement in repairing the NC and it gave a higher performance than that of the NC as one system.
4. The RPC exhibitions excellent repair and potentials on compressive and flexural strengthening. The effect of compressive and flexural strengthening with bonding RPC of 10 mm thickness are about 114.3 and 100%, respectively more than those of NC.
5. The measured bond strength decreases with the test method in the order as slant shear, splitting. The bond strength in the slant shear test was very strong, as the interfacial failure occurred after the partial damage of the NC substrate.
6. Rough surface preparation by drill holes for slant shear test led to higher bond strength. The maximum increase recorded up to 58.33% for combined system NC/RPCSf22 with respect to as saw-cut surface.

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