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EXPERIMENTAL INVESTIGATION ON STEEL-CONCRETE BOND STRENGTH IN SELF-COMPACTING CONCRETE

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ABSTRACT
The objective of this research was to evaluate the potentials of self-compacting concrete (SCC) mixes to develop bond strength. The investigated mixes incorporated relatively high contents of dolomite powder replacing Portland cement. Either silica fume or fly ash was used along with the dolomite powder in some mixes. Seven mixes were proportioned and cast without vibration in long beams with 10 mm and 16 mm steel dowels fixed vertically along the flowing path. The beams were then broken into discrete test specimens. A push-put configuration was adopted for conducting the bond test. The variation of the ultimate bond strength along the flowing path for the different mixes was evaluated. The steel-concrete bond adequacy was evaluated based on normalized bond strength. The results showed that the bond strength was reduced due to Portland cement replacement with dolomite powder. The addition of either silica fume or fly ash positively hindered further degradation as the dolomite powder content increased. However, all SCC mixes containing up to 30% dolomite powder still yielded bond strengths that were adequate for design purpose. The test results demonstrated inconsistent normalized bond strength in the case of the larger diameter compared to the smaller one.

يهدف البحث إلى دراسة مقاومة التماسك بين أسياخ صلب التسليح والخرسانة ذاتية الدمك. تم إجراء اختبار تعيين مقاومة التماسك لعدد (٧) خلطات خرسانية تحتوى على نسب إحلال مختلفة للأسمنت البورتلاندى باستخدام بودرة حجر الدولوميت مع أى من غبار السيليكا أو الرماد المتطاير. تم تعيين مقاومة التماسك لأسياخ قطر ١٠، ١٦ مم باستخدام اختبار الدفع. تم تعيين مقاومة التماسك لأسياخ الصلب الموزعة طوليا على طول مسار صب الخرسانية ذاتية الدمك. تم صب الخرسانة بكمرات معدة بحيث يمكن تقسيمها لاحقا لعينات اختبار التماسك لدراسة تغيير مقاومة التماسك على طول مسار الصب. أوضحت النتائج نقصا متطردا لمقاومة التماسك مع زيادة نسبة الاحلال ببودرة الدولوميت وتحسنها عند استخدام أى من غبار السليكاأو الرماد المتطاير بالخلطات. هذا وتظل مقاومة التماسك كافية لأغراض التصميم الإنشائى بالخلطات التى تصل بها نسبة الإحلال ببودرة الدولوميت إلى ٣٠% من وزن الأسمنت.

***Keywords*:** Self-compacting concrete; bond; push-out; dolomite powder; silica fume; fly ash.

1. INTRODUCTION

Self-compacting concrete (SCC) refers to a normal or high strength concrete that is flowable enough to be placed without need for compaction due to the ability of filling the forms under gravity. Despite the high flowability of SCC, the mixes are sufficiently stable to resist segregation. Japanese researchers began developing the material in the 1980s to ensure high quality in concrete construction [1]. The availability of this type of concrete provided unique merits including faster construction rates since the concrete places so quickly, reduced labor since no vibration is needed, the quality of compaction is no longer relevant, good finished surface quality and design flexibility in detailing congested steel reinforcement with regard to the limited size of coarse aggregates and the passing ability of SCC [2]. Compared to conventional vibrated concrete (VC), SCC mixes typically use higher contents of fine materials and less coarse aggregate content. The maximum nominal size of the coarse aggregate is typically no more than 19 mm. Also, the use of a high range water reducer is necessary to make the mix flowable at a reasonable water/cement ratio. Viscosity agents are sometimes used to make the mix robust and less sensitive to accidental variations in the proportions and/or quality of the used materials. Increasing the content of fine materials is typically achieved by the increased content of sand and other by-product materials that have specific potentials for being implemented in concrete manufacturing. Silica fume, fly ash, granulated blast furnace slag and limestone powders have been successfully implemented in both VC and SCC mixes. Pozzolanic activity, cementitious properties, smooth surface texture and fineness are appealing features that can be provided by these materials to improve the workability, strength and durability [3-5]. In addition, the consumption of by-product materials has a positive impact on the environment and can also reduce the energy consumption in cement factories.

The authors have conducted extensive experimental testing to explore the potentials of low-cost SCC incorporating relatively high contents of dolomite powder. Early research was devoted to explore the productions aspects, the rheological properties and short term strength for single, binary and ternary systems of silica fume, fly ash and dolomite powders replacing Portland cement [6, 7]. Later, SCC mixes selected on compressive strength criterion were used to study the flexure and shear strength of reinforced concrete beams [8]. Also, these mixes were used to prepare reinforced concrete beams that were subjected to severe corrosive environment [9]. The results obtained that far were very encouraging for implementing binary systems of dolomite powder and either silica fume or fly ash to replace Portland cement in SCC mixes.

In the authors' previous works, dolomite powder (DP) rather limestone powder was used to replace Portland cement for two reasons. The first was the availability of the fine DP in local plants for ready-mix asphaltic concrete and the second was the restrictions of the Egyptian Code of Practice (ECP 203) [10] that did not allow the use of Portland limestone cements (PLC) in reinforced and prestressed concrete. While the code did not give an explanation for this restriction, a survey on the subject showed that the consulted international specifications were concerned about some durability considerations. For instant, the French Cement Standards in 1979 allowed the use of PLC containing up to 20% limestone as a lower cost cement for ordinary buildings not subject to sever exposure [11]. The British standard BS 5328-1 [12] restricted the use of PLC in reinforced concrete subjected to sever chloride exposure or freezing and thawing conditions, while its use was allowed in class 1 sulfate conditions (SO_4 concentration in the soil is less than 400 mg/l). BS 8500 [13] reported that the BS 5328-1 durability restrictions were due to lack of information and stated, based on recent available data, that the performance of concrete made with PLC containing up to 20 percent limestone is equivalent to some other permitted cement types. However, BS 8500 in 2002 [13] still restricted the use of PLC in concrete exposed to sulfate bearing environment classified as DS-1 (SO_4 concentration in the soil is less than 500 mg/l). Later, a revision of BS 8500 in 2006 [13] adopted the changed guidance in BRE SD1 [14] and permitted using PLC in DS-2 sulfate conditions (SO_4 concentration in the soil 500-1500 mg/l). Currently, BS EN 197-1 allows CEM II Portland-composite cement to contain up to 35% limestone replacement levels. However, only CEM II/A-L and CEM II/A-LL containing 6-20% limestone are allowed for use in DS-2 sulfate conditions according to BS 8500 in 2006 [13]. Recently in 2009, the Canadian Standards Association (CSA) standard (CSA A23.1) [15] permitted the use of PLC containing up to 15% limestone in all classes of concrete except sulfate-exposure classes. Hotton et al. [16] and Thomas et al. [17] reported that PLCs were the largest single type of cement currently used in the European countries in a variety of works including pavement works and precast concrete. They reported that the benefits of PLCs included: reduced greenhouse gas emissions due to reduced CO_2 as the clinker factor in the cement is reduced, improved workability and pumpability, similar physical performance to current cements when the cements are properly optimized and similar durability to chloride ingress and alkali silica reaction.

The current work was devoted to study the bond strength between steel bars and concrete utilizing test specimens prepared using the SCC mixes tested in previous research work by the authors. Steel-concrete bond is a fundamental property to ensure the integrity of reinforced concrete structural elements because efficient bond ensures reliable force transfer between reinforcement and the surrounding concrete. In case of a deformed steel bar, the following mechanisms contribute to force transfer: (1) Chemical adhesion between the bar and the concrete, (2) Frictional forces arising from the roughness of the interface and (3) Mechanical anchorage or bearing of the ribs against the concrete surface. It has been demonstrated that the bond strength is governed by the mechanical properties of the concrete, the volume of the concrete around the bars in terms of the concrete cover and bar spacing parameters; the presence of confinement in the form of transverse reinforcement, which can delay and control crack propagation; and the diameter and geometry of the bar (deformation height, spacing and face angle) [18, 19].

There were only limited researches on bond strength in SCC providing conclusions that were not comparable. In the bond tests carried out using pull-out specimens, De Almeida et al. [20] obtained similar bond strengths with SCC and VC, Chan et al. [21] and Daoud et al. [22] obtained 5% higher strengths with SCC, while Zhu et al. [23] reported strengths that were up to 25% higher with SCC, with lower bond stresses as the bar size increased. Turk et al. [24] studied the effect of using different types and contents of fly ash and silica fume on the bond strength using splice specimens in different SCC and VC mixes. The results showed that SCC demonstrated higher bond strengths compared to VC due to superior filling and covering capability. Moreover, the beam specimens produced from SCC containing 5% replacement of silica fume had the greatest stiffness as a result of the pore structure improvement due to the pozzolanic activity of silica fume.

2. BOND TEST SPECIMENS

A variety of test specimen configurations have been used to study bond between reinforcing bars and concrete. The details of the specimen affect both the measured bond strength as well as the nature of the bond response. According to the ACI 408R-03 report [18], the four most common configurations are the pull-out specimen, beam end specimen, beam anchorage specimen and splice specimen. Pull-out specimens are widely used because of ease of fabrication. However, they are considered to be less realistic because the stress fields within the specimen simulate few cases in actual construction. As the bar is placed in tension, the concrete is placed in compression. Further, compressive struts form between the support points for the concrete and the surface of the reinforcing bar, placing the bar surface in compression. On the other hand, beam anchorage and splice specimens represent larger scale specimens designed to directly measure development and splice strengths in full-size members. The anchorage specimen simulates a member with a flexural crack and a known bonded length. The splice specimen, normally fabricated with the splice in a constant moment region, is easier to fabricate and produces similar bond strengths to those obtained from the anchorage specimen.

3. RESEARCH SIGNIFICANCE

This research was a part of an extensive program to explore the potentials of low-cost self-compacting concrete. Earlier, the production aspects, rheology and short-term compressive strength were investigated for SCC mixes incorporating different systems of by-product fillers. Also, the shear strength in RC beams and the performance of RC beams in an aggressive environment were investigated for selected mixes that demonstrated relatively superior strength performance. The current work was devoted to explore the bond strength between steel bars and SCC. The main parameters were the diameter of the steel bars, composition of the filler material and variation of compressive strength along the flow path of SCC. The research presents correlations between the experimental bond strength and compressive strength to asses the capability of the different mixes to develop adequate levels of bond strength. Actually, the bond strength is strongly influenced by the adhesion characteristics and the mechanical prosperities of the surrounding concrete. The current research results are expected to provide some necessary answers concerning the bond strength as an essential prosperity for the integrity of structural elements with regard to the variable composition of SCC among the other mentioned test parameters.

4. MATERIALS

Cement and fillers: cement type CEM I 32.5 N meeting the requirements of BS EN 197-1:2000 [25] was used. The specific gravity of cement was 3.13 and the initial setting time was 90 min. at 27.5 percent water for standard consistency. Locally produced densified silica fume was delivered in 20 kg sacks. According to the manufacturer, the light-gray powder had a specific gravity of 2.2, specific surface area of 17 m^2/gm, loss on ignition of 1.5, and SiO_2 content of 93 percent. Imported class F fly ash meeting the requirements of ASTM C618 [26] was used. According to the manufacturer, the average sum of SiO_2, Al_2O_3 and Fe_2O_3 is 85 percent by weight with a specific gravity of 2.1, and loss on ignition of 1.25 percent. The particle size distribution curve, Fig. (1), shows that 90 percent by weight of ash passes through the 45 μm sieve. The dolomite powder was obtained as a by-product from a local plant for ready-mix asphaltic concrete. The production processes include drying the crushed dolomite used as a coarse aggregate by heating at a degree of 120 ^{o}C and sieving the aggregates to separate the different sizes. A small fraction of the powder that passes through sieve No. 50 (300 μm) is used in the mix, while most of the powder is a by-product. This powder had a light brownish color, specific gravity of 2.72. Sieving six random samples of the powder showed that the average passing percentage through the 45 μm sieve was 63 percent. The chemical analysis results of the fine materials are reported in Table (1). Fig. (1) shows the grading of the used fine materials.

Table 1. Chemical analysis of fine materials (% by mass)

Material	cement	silica fume	fly ash	Dolomite Powder
SiO_2	24.3	93.2	49.0	0.83
Fe_2O_3	3.67	1.58	4.10	0.52
Al_2O_3	4.10	0.51	32.3	0.77
CaO	58.3	0.20	5.33	28.5
MgO	2.35	0.57	1.56	19.3
K_2O	0.98	0.53	0.54	nd
Na_2O	0.35	0.45	0.28	nd
SO_3	3.40	0.22	0.16	nd
CO_2	Nd	nd	0.80	46.8
L.O.I	2.10	2.62	1.25	43.2

nd: not detected

Aggregates: natural siliceous sand having a fineness modulus of 2.54 and a specific gravity of 2.65 was used. Crushed dolomite with a maximum nominal size of 16 mm was used as coarse aggregate. The aggregate had a specific gravity of 2.65 and a crushing modulus of 23 percent. About half of the particles were flaky and elongated. The grading of the used aggregates is shown in Fig. (1).

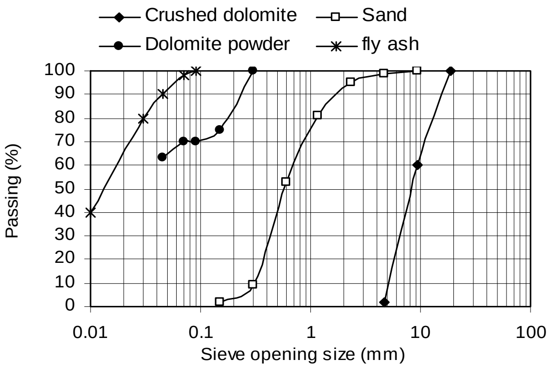

Figure 1. Particle size distribution for concrete materials

Admixtures: a traditional sulfonated naphthalene formaldehyde condensate HRWR admixture conforming to ASTM C494 (types A and F) [27] was used. The admixture is a brown liquid with a specific gravity of 1.18.

Steel dowels: high tensile ribbed steel bars of 10 mm and 16 mm diameter were cut into 180 mm and 240 mm long dowels, respectively. The geometry of the bars and measured dimensions are shown in Table (2) and Fig. (2).

Table 2. Dimensions of the steel bar profile

diameter (mm)	Dimensions (mm)					
	d_1	d_2	t	r_s	r_t	r_h
10	9.9	10.4	2.0	4.2	2.2	0.75
16	15.9	17.3	1.7	6.9	3.1	1.25

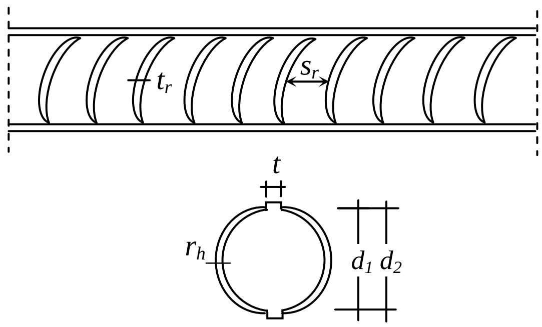

Figure 2. Geometry of the steel bars

4.1 Concrete mix proportions

Based on the results reported in an initial phase of research [6], seven mixes were selected to produce SCC based on compressive strength criterion. The selected mixes incorporated dolomite powder (DP) replacing up to 30% of cement weight along with either silica fume (SF) or fly ash (FA) that replaced 10% of cement by weight. The constituents of the selected SCC mixes are given in Table (3). In these mixes, the fine-to-coarse aggregate ratio was 1.13, the total content of powders (cement and fillers) was 500 kg/m^3, the HRWR dosage was fixed at 10 kg/m^3 (2% by weight of powders). The water content was determined by trail and error procedure to obtain consistent mixes with the required fresh rheological properties. Table (4) shows the mechanical properties at 28 days, and the measured rheological properties.

Table 3. Concrete mix materials and proportions

Mix	Mix Constituents*, kg/m^3						
	C	FA	CA	w	DP	SF	FA
M1	500	945	840	160	-	--	--
M2	450	935	830	165	50	--	--
M3	400	925	820	170	100	--	--
M4	350	915	810	170	100	50	--
M5	300	900	800	175	150	50	--
M6	350	915	810	170	100	--	50
M7	300	900	800	175	150	--	50

* superplasticizer dosage in all mixes = 10 kg / m^3

Table 4. Rheological and hardened properties

Mix	mechanical properties			Rheological properties	
	f_{cu} (MPa)	f_r (MPa)	$f_r / f_{cu}^{0.5}$	slump flow (mm)	V-funnel t_o (sec.)
M1	34.0	3.8	0.65	700	6.0
M2	33.0	4.0	0.69	665	6.4
M3	29.5	3.8	0.70	655	5.5
M4	35.0	4.1	0.69	600	5.5
M5	31.5	3.9	0.69	580	5.2
M6	30.5	4.0	0.72	650	5.0
M7	28.5	3.9	0.73	640	5.1

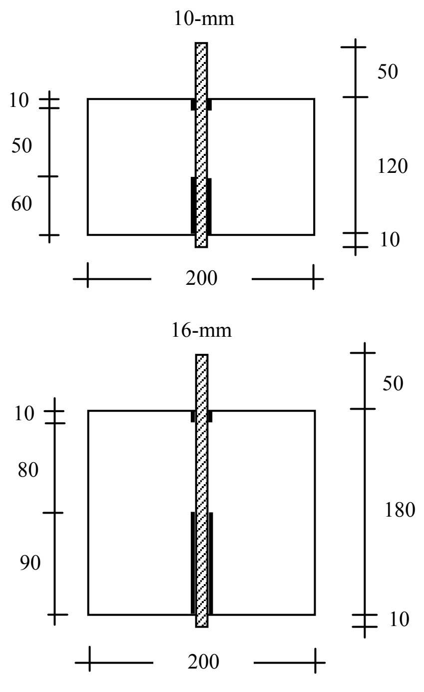

Figure 3. Configuration of push-out bond test specimens

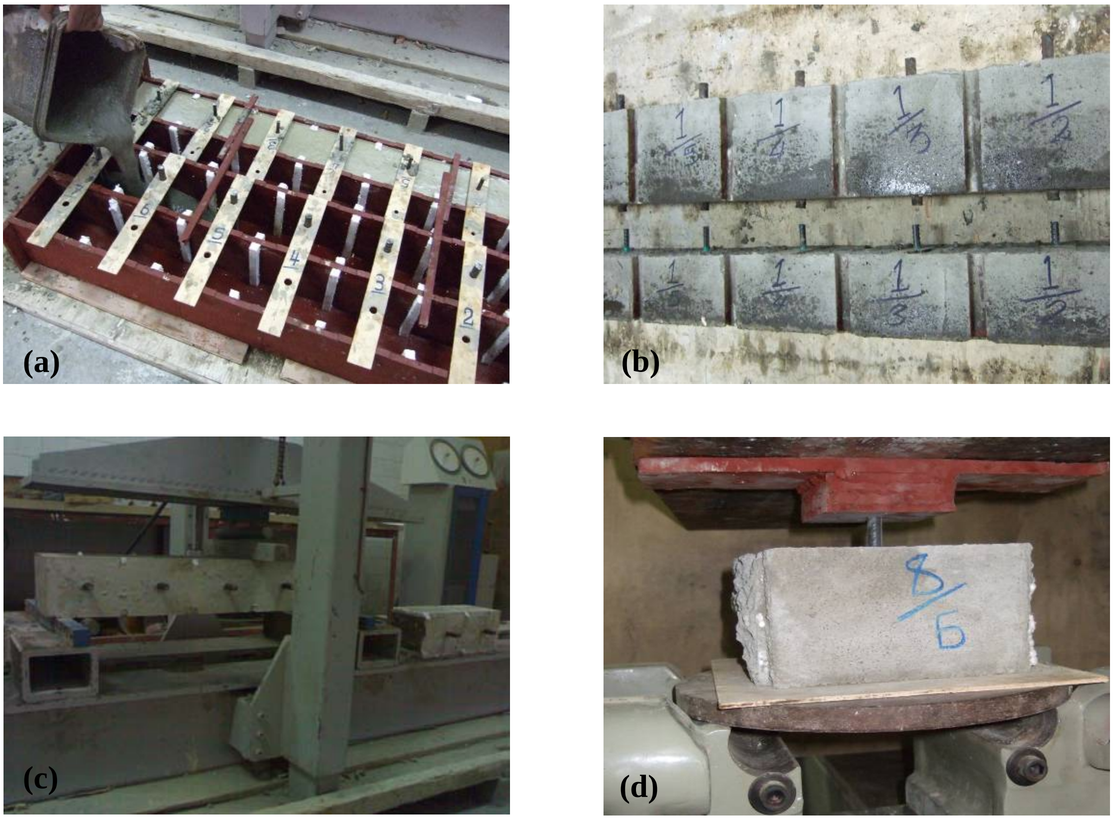

Figure 4. Preparation and testing of push-out test specimens

4.2 Configuration of push-out specimens

Push-out test specimens were used in the current work. Generally, the weak points of push-out test specimens, similar to pull-out test specimens, were the friction between the specimen and the bearing plate, and the arch-effect in the region close to the bearing plate. For these reasons, the bonded length was moved away from the bearing plate by providing a broken- bond zone next to the bearing plate as can be seen in Fig. (3). The procedure adopted by Foroughi et al. [28] to introduce a broken-bond zone and to avoid an unplanned force transfer between the bar and the concrete in this area was followed by encasing the bar with a plastic tube and sealing with a highly elastic silicone material. Also, 10 mm broken-bond zone was provided at the loading end so that the bonded length was five times the bar diameter in both the 10 mm and 16 mm bar specimens.

4.3 Casting forms:

Casting forms were needed to manufacture concrete beams by casting the SCC mixes at one end and allowing concrete to flow to the other end without any compaction or vibration. The forms were designed to make it possible to split each beam into seven bond specimens with a steel dowel inserted at the center of each specimen. Specially designed wooden forms were manufactured for this purpose. The wooden forms had net internal dimensions of 120 mm depth, 150 mm width and 1400mm length for the 10 mm steel bar diameter specimens. The corresponding dimensions for the 16 mm steel bar diameter specimens were 180 mm, 150 mm and 1400 mm. A separate plate was laid along the bottom of the form. The bottom plate was provided with seven holes at 200 mm center-to-center spacing to accommodate the lower end of the steel dowel. Vertical 25x25 mm polyurethane strips were cut and adhered along the depth of the two sides of the form at 200 mm center-to-center spacing. The soft polyurethane strips were intended to provide notches along the beam specimens to facilitate its splitting into discrete test specimens. After sampling the forms, a thin layer of grease was applied to the internal faces to prevent water absorption and ensure easy stripping of the forms. Upper horizontal plywood strips provided with holes were used to confine the upper portion of the steel dowel and thus the dowels were held in a vertical position during casting. Fig. (4-a) shows the wooden forms with the steel dowels inserted and confined.

Two 40-liter batches were used to cast two beams of 120 mm and 180 mm depth along with one 100 mm cube to determine the compressive strength, f_{cu}, and one 100x100x500 mm prism to determine the tensile strength in terms of the fracture modulus, f_r. Each concrete mix was used to fill the forms and molds three times, so that each reported test result was the average of three test results. After mixing, the concrete was poured in a wide vessel and successively hand-poured in the forms and molds, Fig. (4-a). The forms were stripped 24 hours after casting. Fig. (4-b) shows the beam specimens after stripping and sequentially numbering the bond test specimens. After that, each beam was carefully poisoned in a hydraulic flexure machine to split it at the notched sections and obtain the bond test specimens, Fig. (4-c). All specimens were cured under continuously wet cloth that was moistened twice a day until testing at 28-day age.

4.4 Testing procedure

A total number of 147 bond test specimens, 21 cubes and 21 prisms were tested. Fig. (4-d) shows the test set up and loading configuration of the push-out test. The bond test specimen was tested under a compression force driving down the steel dowel. A 500 kN universal testing machine was used to apply the compression force at a loading rate of 50 kN/min. The machine provided an automatic control of the loading range to ensure precise load measurements. A 20 mm thick bearing plate provided with a central hole was used to support the test specimen. The plate was supported on the edges of a rigid base allowing the penetration of the dowel. A packing plywood plate was used to ensure even contact between the bottom surface of the concrete specimen and the bearing plate. To prevent buckling of the 50 mm long upper free part of the dowel under the applied load and to ensure eccentric loading, a special steel punched head was fixed in the upper platen of the testing machine. The punched head confined 30 mm of the free loaded part and thus a bar length of 20 mm was available for the dowel to penetrate through the concrete block. The 20 mm maximum penetration value was more than sufficient to achieve the ultimate bond strength knowing that the rip spacing was 4.2 mm in case of the 10-mm dowels and 6.9 mm in case of the 16 mm dowels. The test was ended once the ultimate load was recorded.

5. ANALYSIS OF TEST RESULTS

While the configuration of the push-out test specimen adopted in this work is not a standard one, some measures were considered to make the obtained results more realistic. The bonded length was shifted away from the bearing plate to avoid confinement effect due to the lateral compression stress induced in the concrete. Also, a relatively limited bond length of five times the steel bar size was adopted. These factors were expected to yield favorable bond failures due to the slip of the bar rather than due to splitting of concrete. However, splitting failures could still occur if the tensile strength is exhausted given that no radial steel reinforcement was provided to resist splitting.

The test results were evaluated based on normalized bond strength obtained by dividing the average bond strength of a given mix to the square root of the corresponding compressive strength. The bond strength was calculated by relating the ultimate load by the bonded area $(\pi.d.l)$. Given that the bonded length (l) was five times the bar diameter (d), the ultimate bond strength can be expressed as:

$$f_b = P_u / 5 \, \pi \, d^2 \qquad (1)$$

Due to the variation of the concrete compressive strength, the bond strength was expressed in terms of normalized bond strength f_{bn}, where:

$$f_{bn} = f_b / f_{cy}^{0.5} \qquad (2)$$

To examine the adequacy of the obtained levels of bond strength, two approaches were adopted. The first was to checkout the design bond strength requirements in the ACI 318-08 code [29] and the second was to compare the obtained results with the results available in the literature for similar SCC mixes and bar diameters. For this purpose, the bond strength was related to the square root of the cylinder compressive strength. The cylinder compressive strength f_{cy} was taken equal to 80% of the corresponding cube compressive strength according to data collected by Domone [30]. The average bond strength along the flowing path, the total average and the normalized bond strength are reported in Tables (5, 6).

Table 5. Bond strength [10-mm bar specimens] (MPa)

Spec. No.	Mix No. 1	2	3	4	5	6	7
1	13.1	9.4	5.3	6.8	5.5	5.6	4.9
2	15.4	9.8	5.5	6.9	6.0	6.0	6.2
3	15.9	12.4	6.9	7.8	6.4	6.8	6.6
4	17.8	10.2	6.6	7.5	7.4	7.2	7.3
5	18.7	10.2	6.0	7.2	8.1	6.6	6.1
6	17.1	9.7	6.0	6.9	6.8	6.4	4.9
7	16.8	9.2	5.0	6.5	6.3	6.3	4.5
Aver.	16.4	10.1	5.9	7.1	6.6	6.4	5.8
f_{bn}	3.1	2.0	1.2	1.3	1.3	1.3	1.2

Table 6. Bond strength [16-mm bar specimens] (MPa)

Spec. No.	Mix No. 1	2	3	4	5	6	7
1	11.3	8.7	5.6	7.6	6.4	6.4	10.0
2	11.1	9.3	5.8	7.7	6.9	6.7	9.3
3	12.9	9.8	6.9	7.9	6.7	7.3	9.3
4	12.4	9.1	6.0	7.8	7.1	7.6	10.4
5	13.1	8.4	6.0	8.0	6.7	8.0	8.7
6	12.0	8.4	5.8	8.0	6.2	7.6	8.4
7	11.8	8.2	5.3	7.6	6.2	6.7	8.4
Aver.	12.1	8.9	5.9	7.8	6.6	7.2	9.2
f_{bn}	2.3	1.7	1.2	1.5	1.3	1.5	1.9

The current ACI 318-08 code [29] did not provide an explicit expression linking the bond strength to the concrete compressive strength. Rather, the bond strength was implicitly applied in the calculation of the development length. The development length concept is based on the average bond stress over the length of embedment of the reinforcement. For some favorable conditions concerning the spacing between developed or spliced bars, clear cover and confinement, the following equation is used to calculate the development or splice length (l) associated with relatively higher bond strengths for 19 mm and smaller steel bars:

$$l = f_y \, d \,/\, 2.1 \, f_{cy}^{\;0.5} \qquad (3)$$

Setting the ultimate force in the push-out bond test equal to $f_y\,A_b$, then the bond strength (f_b) can be expressed as:

$$f_b = f_y \, A_b \,/\, \pi \, d \, l \qquad (4)$$

where f_y is the yield stress of steel and A_b is the area of the steel bar. Equation (4) yields:

$$l = f_y \, d \,/\, 4 \, f_b \qquad (5)$$

The analogy between equations (3) and (5) yields:

$$f_b = 0.53 \, f_{cy}^{\;0.5} \qquad (6)$$

Equation (6) shows that the normalized bond strength for design purposes is taken 0.53 in favorable design conditions that require the development of satisfactory bond strength levels. The normalized bond strength values in Tables (5, 6) ranged from 1.21 to 1.97 for the SCC mixes incorporating dolomite powder. These values are 2.3 to 3.7 times the design value with an average of 2.6 and 2.9 for the 10 mm and 16 mm bars, respectively.

Fig. (5) shows a plot of the normalized bond strength obtained from pull-out tests against the corresponding compressive strength (f_{cy}). The data were collected for different SCC mixes that had comparable compressive strength in the range of 26 to 36 MPa and steel bar diameters of 10, 14 and 16 mm [28, 30, 31]. In this range, the normalized bond strength varied from 1.07 to 2.6. It can be seen that the obtained normalized bond strengths are within this range.

The 10 mm and 16 mm test specimens cast using mixes 1 and 2 failed due to splitting as the tensile stresses reached its ultimate values. The average normalized bond strength was higher in the 10 mm bar diameter specimens compared to the 16 mm diameter specimens. The decrease of the bond strength for a given concrete strength as the steel bar diameter increased has been traditionally reported in

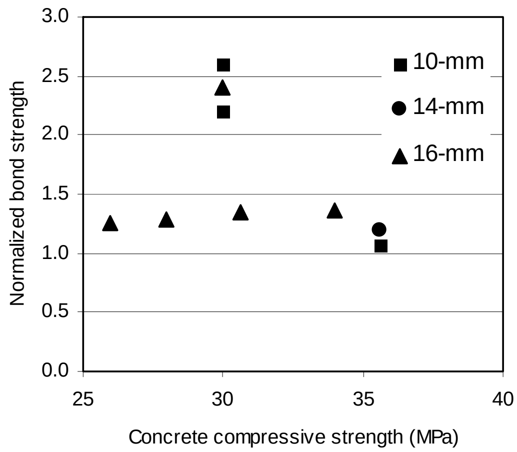

Figure 5. Normalized bond strength and corresponding compressive strength

the literature. The rest of the test specimens failed favorably due to the penetration of the steel par through the concrete without concrete cracking. This behavior can be attributed partially due to the relative improvement of the tensile strength expressed in terms of the normalized values of the fracture modulus as indicated in Table (4). On the other hand, SCC mixes incorporating finely divided minerals were reported to demonstrate improved interfacial transition zones between the paste and the steel bars. Zhu et al. [23] investigated the steel–concrete interfacial transition zone with a nano-indentation technique, and found that the increased bond strength with the SCC mixes compared to vibrated concrete could be attributed to a greater uniformity in the ITZ around the bars. The relative improvement of the tensile strength and uniformity of the ITZ associated with better adhesion can rationally explain the penetration of the steel bar extracting a uniform layer of mortar between the ribs as observed after the test. This failure mode was associated with two distinct observations. First, the reduction of the both the bond and normalized bond strength due to cement replacement in all mixes. Second, the normalized bond strength was higher for the 16 mm bars in mixes 4, 6 and 7 compared to the 10 mm bars, while the normalized bond strength was the same for the two diameters in mixes 3 and 5. The reduction of the bond strength in SCC mixes seemed to increase as the percentage replacement with dolomite powder (DP) increased in mix 3 compared to mix 2. The addition of either silica fume or fly ash seemed to have a positive effect even when the DP ratios increased. The reduction of the bond strength due to the incorporation of the DP can be explained by recalling that load transfer between concrete and steel occurs through the action of three mechanisms: chemical adhesion, friction and mechanical interaction of the lugs of the deformed reinforcement bearing on the surrounding concrete. For deformed reinforcement, mechanical interaction is the dominant mechanism of response according to Zhu et al. [23]. The use of the DP as cement replacement seemed to have a softening effect on the matrix, while keeping an adequate chemical adhesion due to the improvement in the ITS as mentioned before. This behavior hindered the development of the mechanical interaction and the bond strength was dominated by the friction resistance. Another parameter contributing to the reduction of the bond strength is the reduced shrinkage of concrete upon cement replacement and consequently the reduced gripping force exert by the concrete as reported by Sonebi et al. [32]. The observed occasional increase in the bond strength for a bigger diameter was reported by Khan et al. [33]. The increase was attributed to the increase in the friction bond component as the bar diameter increased. Also, the inconsistency of bond strength results in SCC mixes has been reported by Zhu [34] and Domone [30] and it was recommended that each concrete mix with a specified composition of the fillers should be tested to evaluate the bond behavior.

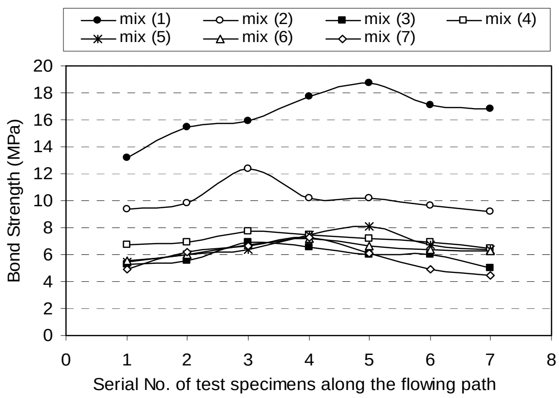

Figure 6. Bond strength along the flowing path (10-mm bar diameter specimens)

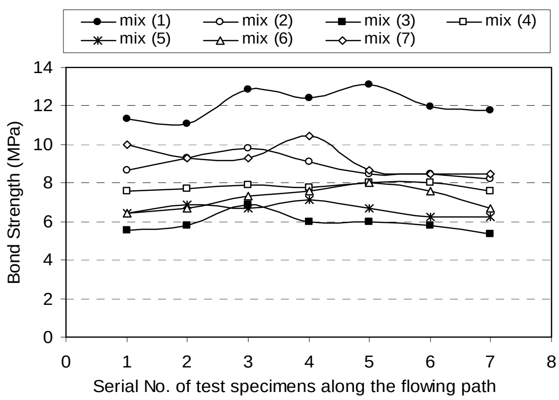

Figure 7. Bond strength along the flowing path (16-mm bar diameter specimens)

Figs. (6, 7) shows a plot of the average bond strength for the test specimens along the flow path for the10 mm and 16 mm bars. The specimens were numbered sequentially beginning with the first specimen at the casting end and ending with the seventh specimen at the end of the flow path. It can be seen that the bond strength tended to be higher about the middle of the flow path compared to the strength evaluated at the casting and end points. This trend needs to be further examined in actual size concrete elements being related to size effect and flow characteristics.

6. CONCLUSIONS

The current work investigated the potentials of the SCC mixes incorporating dolomite powder along with either silica fume or fly ash to develop bond strength. The variability of bond strength along a flowing path was evaluated, based on the available test results, the following conclusions could be drawn:

1. The bond strength was reduced due to Portland cement replacement with dolomite powder. While the chemical adhesion component was improved, the mechanical interaction was hindered and the bond strength was dominated by the friction resistance.
2. The addition of either silica fume or fly ash positively hindered further degradation of bond strength as the dolomite powder content increased.
3. SCC mixes containing up to 30% dolomite powder yielded bond strengths that were adequate for design purpose according to the requirements of the ACI 318-08 code.
4. The test results demonstrated inconsistent normalized bond strength in case of the larger steel bar diameter of 16 mm compared to the 10 mm steel bar diameter.
5. The bond strength tended to increase about the middle of the flowing path. This trend needs to be further examined in actual size concrete elements being related to size effect and flow characteristics.

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