Advanced Materials Research Vol. 626 (2013) pp 265-269
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doi:10.4028/www.scientific.net/AMR.626.265

The role of silica fume in the adhesion of concrete restoration systems

Bassam A. Tayeh[1,2, a] B. H. Abu Bakar[1,b] M. A. Megat Johari[1,c] A.M. Zeyad[1,3 d]

[1]School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia

[2]Engineering Division, Islamic University of Gaza, Gaza, Palestine

[3]Department of Civil Engineering, University of Science and Technology, Sana'a, Yemen

[a]btayeh@iugaza.edu, [b]cebad@eng.usm.my, [c]cemamj@eng.usm.my, [d]zeyad_eng@yahoo.com

Keywords: Adhesion; Concrete restoration systems; Interfacial transition zone; Reactive powder concrete; Silica fume; Substrate.

Abstract. The weak interfacial transition zone between new and old concrete is always paid much attention and controls many properties of repaired concrete, The present work reports a study on the influence of the silica fume on the adhesion of reactive powder concrete (RPC), as a concrete restoration material, with the ordinary concrete (OC) substrate. The results showed that, the silica fume presence in the interfacial transition zone significantly enhances the adhesion strength between RPC and OC substrate. Furthermore, the silica fume particles consume calcium hydroxide, which is in attendance in the interfacial transition zone, and make the zone more dense, uniform and tough.

Introduction:

A Large number of existing concrete structures worldwide are in urgent need of effective and durable repair. However, it has been estimated that up to half of all concrete repairs fail [1]. This inadequate performance is often ascribed to lack of reliable and perfect bond. The improvement of the durability of the repaired concretes has drawn great attention from researchers. It has been indicated by the previous researches that the interfacial transition zone between new and old concrete is the weakest section in the repaired concrete [2]. The performance of a repaired concrete structure, and consequently its service life, depends on the quality of the interfacial transition zone of the composite system formed by the repair material and the existing concrete substrate, for the better resistance of concrete structures against penetration of harmful substances [3]

Reactive powder concrete (RPC) is one of the breakthroughs in concrete technology providing an important improvement in strength, workability, ductility and durability when compared with normal concrete. The properties of RPC can be improved by reducing the amount of water, removing all of the coarse aggregate , using highly refined silica fume and introducing steel fibers [4]. Extremely low porosity of RPC gives low permeability and high durability, and makes it potentially suitable for being used in a new technique for restoration of the reinforced concrete structures [5].

Silica fume is one of the main components of reactive powder concrete (RPC), and the main objective of this paper was to study the influence of silica fume on the adhesion between RPC, as a concrete restoration material, and the ordinary concrete (OC) substrate. The microstructure of the transition zone was studied using both Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM/EDX) to assess the behavior of the interfacial transition zone.

Experimental programme

RPC and OC substrate properties

The mix design of RPC used as a repair material contains Type-I ordinary Portland cement (OPC), densified silica fume (SF) (Table 1 shows the chemical compositions of cement and silica fume), well graded sieved and dried mining sand, very high strength micro-steel fiber and polycarboxylate ether based (PCE) superplasticizer. The steel fiber used has a fiber length and diameter of 10mm and 0.2mm, respectively, and has an ultimate tensile strength of 2500 MPa. The RPC used has achieved an average 28 days cube compressive strength of $f_{cu} = 170\,\text{MPa}$. The mix design of the RPC is presented in Table 2.

The mixing design of OC used in this study ensures average compressive strength 45MPa at 28 days. The OC used contains Type-I ordinary Portland cement, river sand with fineness modulus of 2.4, coarse aggregate (granite) with a maximum size of 12.5mm, a water-to-cement ratio of 0.5 and a slump value between 150-180 mm. The mix proportion of the OC substrate is presented in Table 2. The control specimen used consists of 100mm x 100mm x 300mm tall prism for uniaxial compression strength test with an average compression strength 38MPa at 28 days.

Table 1 Chemical compositions of cement and silica fume

Compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	K_2O	SO_3	TiO_2	MnO	Na_2O	Cl^-
OPC [%]	19.01	4.68	3.2	66.89	0.81	0.08	1.17	3.66	0.22	0.19	0.09	-
SF [%]	92.26	0.89	1.97	0.49	0.96	-	1.31	0.33	-	-	0.42	0.09

Table 2 Mix proportions for RPC and OC substrate

Concrete Type [kg/m³]	OPC [Type1]	Coarse Aggregate [max. 12.5mm]	River Sand [F.M. =2.4]	Mining Sand [<1180μm]	Silica Fume [23.7 m²/g]	Steel Fiber [L_f = 10mm, d_f =0.2mm]	Super-plasticizer	Water	W/B
RPC	768	-	-	1140	192	157	40	144	0.15
OC substrate	400	930	873	-	-	-	4	200	0.5

Specimens Preparation

Each of the tested specimen comprised of two different materials, which were the OC as a substrate and RPC as a repair material. The fresh OC was sealed and left to set in its moulds for 24 hours after casting. After 24 hours the OC specimens were demoulded, cleaned and cured for another two days in a water curing tank. At the age of three days, the OC substrate specimens were taken out from the water tank for surface preparation. In this study, Five different types of surface preparation were used, (i) as casted without roughening (AC), (ii) sand blasting (SB), (iii) wire brushing (WB), (iv) drill holes (DR) and (v) grooves (GR). Then the OC specimens were further cured in a water tank until the age of 28 days since the OC casting date. At the age of 28 days, the OC substrate specimens were left to dry for two months.

Before casting the RPC, the surfaces of the OC substrate specimens were moistening for 10 minutes and wiped dry with a damped cloth. The OC substrate specimens were then placed into steel-made moulds with the slant side face upward. Mixing of the RPC was carrying out using a pan mixer. The moulds were then filled with RPC. Fig. 1,a. shows the complete composite specimens for the slant shear strength tests. The composite specimens were steam cured for 48 hours at a temperature of 90°C. At age 7 days, slant shear test was performed.

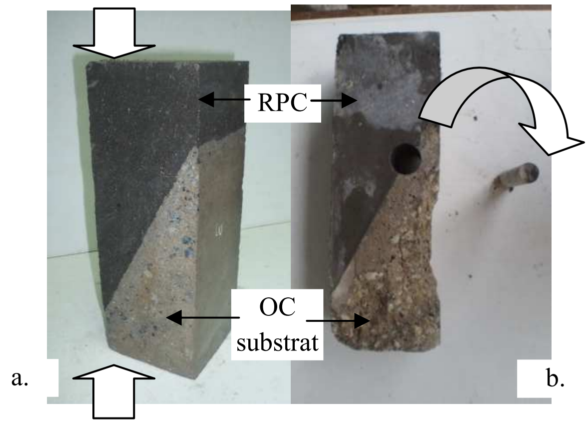


Fig. 1. a. Slant shear test specimens. b. Core sample extracted from the interface between OC substrate and RPC for SEM/EDX test

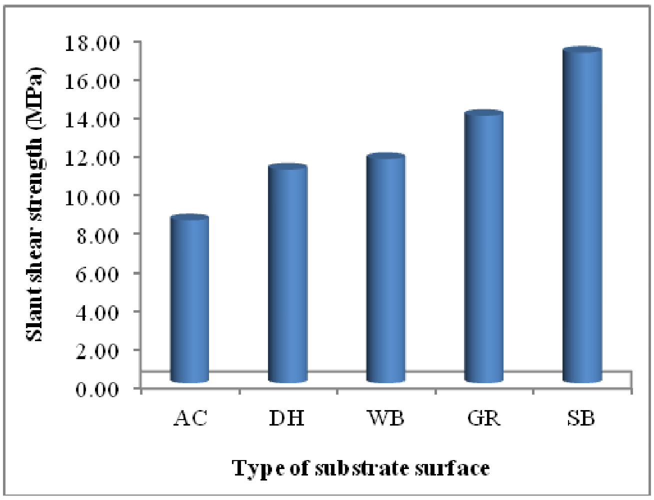


Fig. 2. Slant shear strength for each type of substrate surface

Slant shear test

As mentioned in the specification of ASTM C882 [6], slant shear test was used to investigate the behavior of compressive stress-strain of the composite specimens OC substrate and RPC repair material. The bond strength between OC substrate and RPC repair material also was calculated. The RPC was casted and bonded to the OC substrate specimens on a slant plane inclined angle of 30° from the vertical axis to form a 100mm x 100mm x 300mm composite prisms specimens as shown in Fig. 1,a.

SEM/EDX of the transition zone between the OC substrate and RPC

In order to study the interface between the OC substrate and the RPC, core sample was extracted from the transition zone of the slant shear test sample after performing the slant shear test. Care was taken not to select the sample that exhibited failure at the interface as shown in Fig. 1,b. The sample was then studied using Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM/EDX).

Discussion of Results

The bond strength for the slant shear strength was calculated by dividing the maximum load by the bond area which can be expressed as Eq. 1 :

$$S = \left\{ \frac{P}{A_L} \right\} \tag{1}$$

Where S is the slant shear strength (in MPa); P is the maximum force recorded (in kN) and A_L is the area of the slant surface (in mm^2). The experimental slant shear strength test results were presented in Fig. 2. As shown in Fig. 2, the type of substrate surface preparation affected the compressive stress-strain behavior of the composite specimens, the recorded compressive strength increases in the order of as casted surface, drill holes surface, wire brushed surface, grooved surface and sand blasted surface. Hence, the differently prepared surfaces of the substrates provided a significant improvement in the bond strength of the composites in comparison to no preparation surface (as casted). The different substrate surfaces provided a relative increase of 31.1, 37.5, 64.0 and 102.7 %, for drill holes surface, wire brushed surface, grooved surface and sand blasted surface, respectively. The failure modes for the slant shear specimens can be categorized into four types as following: type A is the interfacial bond failure; type B is the interfacial failure and substrate cracks or small parts broken; type C is the interfacial failure and substrate fracture and type D is the substratum failure.

The ACI Concrete Repair Guide specifies the acceptable bond strength for repair work within the range of 6.9 – 12MPa for slant shear strength at 7 days test age [7]. This guideline is particularly useful for the selection of appropriate repair material. The tested specimens in this study were tested at 7 days and the comparison with ACI requirement showed that most of slant shear strength of this study within or more than the ACI requirement at 7 days.

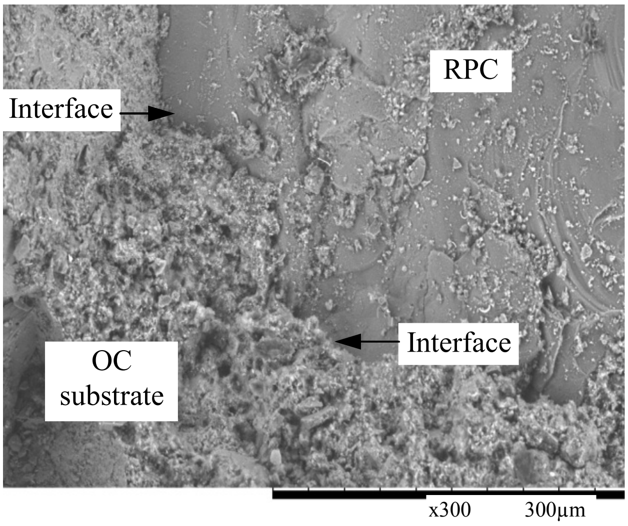
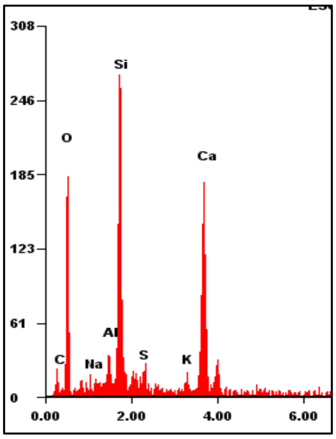


Fig. 3. SEM micrograph of the transition zone between OC substrate and RPC



Element	Wt%	At%
C K	08.45	14.89
O K	38.23	50.57
NaK	00.58	00.54
MgK	00.57	00.50
AlK	02.11	01.66
SiK	23.93	18.04
K K	01.36	00.73
CaK	24.76	13.08

Fig. 4. EDX of the transition zone between OC substrate and RPC

The result of SEM clearly shows the improvement of the microstructure of the interface zone by using silica fume, as shown in Fig.3, the interface zone is more dense, uniform and no cracks can be observed. The significant increase in strength may also from the chemical reaction between the active silicon dioxide of silica fume in the RPC and the $Ca(OH)_2$ in the OC substrate to form (C-S-H) gel as shown in Fig. 4. The physical action of silica fume in concrete is in the refinement of the void system of cement paste and particularly the transition zone. It can be inferred that the microstructure of the interface zone can be improved further with time in consequence of a secondary reaction between the Ca(OH)2 present there and pozzolana, thus leading to even a denser interface zone with a better durability [2]. The noticeable improvement in the microstructure led to a significant increase of the intermolecular force and mechanical interlocking. Consequently, the bond strength increased greatly as shown in Fig 2.

Summary

This paper focused on the influence of silica fume, which is one of the main components of reactive powder concrete (RPC), on the adhesion between RPC as a concrete restoration material and the ordinary concrete (OC) substrate. Each of RPC and OC used could achieve cube compression strength of 170MPa and 45MPa respectively.

The results of SEM/EDX noticeably showed that, the presence of silica fume in the interfacial transition zone significantly enhances the adhesion strength between RPC and OC substrate, the silica fume in RPC reacts with the calcium hydroxide produced by the hydration of cement, forming (C-S-H) gel. The formation of additional C-S-H fills the pores, decreases the calcium hydroxide and increases the adhesion strength in the interfacial transition zone; as a result, the transition zone was compact, dense, uniform and strong, since no cracks can be observed.

Long-term test for bond strength between the RPC and OC substrate should be carried out to investigate the effect of silica fume on the performance of the interfacial transition zone.

Acknowledgment

The authors gratefully acknowledge Universiti Sains Malaysia for providing the financial support for this study through the Research University (1001/PAWAM/8044055).

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