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Influence of the roughness of aggregate surface on the interface bond strength

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Abstract

An experimental investigation on the bond strength of the interface between mortar and aggregate is reported. Composite compact specimens were used for applying Mode I and Mode II loading effects. The influence of the type of mortar and type of aggregate and its roughness on the bond strength of the interface has been studied. It has been observed that the bond strength of the interface in tension is significantly low, though the mortars exhibited higher strength. The highest tensile bond strength values have been observed with rough concrete surface with M-13 mortar. The bond strength of the interface in Mode I load depends on the type of aggregate surface and its roughness, and the type of mortar. The bond strength of the interface between mortar M-13 cast against rough concrete in direct tension seems to be about one third of the strength of the mortar. However, it is about 1/20th to 1/10th with the mortar M-12 in sandwiched composite specimens. The bond strength of the interface in shear (Mode II) significantly increases as the roughness and the phase angle of the aggregate surface increase. The strength of mortar on the interface bond strength has been very significant. The sandwiched composite specimens show relatively low bond strength in Mode I loading. The behavior of the interface in both Mode I and Mode II loading effects has been brittle, indicating catastrophic failure.

Keywords: Aggregate; Bond strength; Interface; Mortar; Surface roughness

1. Introduction

Concrete is a three-phase heterogeneous material with cement paste, aggregate and interface between cement paste and aggregate. Load transfer mechanism in concrete depends on the degree of interaction of various phases, strength of cement paste, characteristics of aggregate and cohesive forces at the interface. The contribution of coarse aggregate in transferring the stresses in high-strength concrete (HSC) is very important. The microcrack formation and its growth at the interface are significantly influenced by the bond strength and fracture toughness. Since the mortar–aggregate interface in HSC is stronger, cracks transmit into the aggregate. Moreover, the properties of interface regions, i.e., fiber–paste, aggregate–paste, aggregate–mortar, are central to the performance of high-performance concrete. The development of bond strength is intimately related to the nature of these interface zones. In composite materials, the elastic mismatch between the mortar matrix and aggregate results in stress concentration at the interface, which influences the strength and overall performance of concrete. The pore structure of Portland cement paste has been studied extensively for the past several years [1–9]. The paste near the interface exhibits somewhat porous microstructure than the bulk paste, which extends up to about 20 to 50 μm [2]. However, it changes with continuous hydration of cement. The paste in mortar and concrete is more porous than plain paste with similar microstructure [7]. More discontinuous and impermeable pore structure results with silica fume [3,4,9].

The surface effects produced by the aggregate face create zones of matrix with a higher water–cement ratio in the interface [10]. The formation of interface is due to the water-filled spaces around the aggregates and the wall effect [9]. Silica fume affects the pattern of crystallization and degree of orientation of CH crystals at the aggregate surface, resulting in very thin interface during the first few days of hydration [3,11]. The tensile strength of mortar seems to be higher at about 8% silica fume [12]. The interfacial bond

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strength increases due to the pozzolanic action of fly ash at the age of 90 days for all replacements [13]. However, at the age of 28 days, the interfacial bond strength was improved at 15% replacement. The structure of interfacial zone significantly influences the strength of mortar [6,14]. The enhancing effect of silica fume coating on the transition zone microstructure lies in the elimination of water film on aggregate surfaces in noncoated aggregate–cement systems in addition to pozzolanic reaction. The strength of mortar with pretreated quartz aggregate was higher when compared to the strength of mortar with normal quartz aggregates [15]. The nature of the interfacial zone depends on the microstructure characteristics of the aggregate, in which any of the three mechanisms, physical interaction, physical–chemical interaction and mechanical interlock, may be dominant [8]. The van der Waal's forces of attraction are the primary binding forces at the interface [16]. The surface roughness of the aggregate shows significant influence on the fracture toughness of the interface [17]. Any interaction between cement paste and rock surface at the interface lowers the cracking resistance. The interface exhibits significantly lower toughness than that in cement paste and aggregate and the load levels seem to be low [18]. For a given type of loading conditions the critical interface fracture energy release rate, G_i, increases with rougher aggregate surfaces for both Mode I and mixed mode tractions. In addition, for a given aggregate roughness, G_i increases with increase in the shear loading [19]. The resistance against crack propagation of interface between aggregate surfaces and matrix seems to be only one sixth of the cement–matrix resistance [20]. The interfacial fracture energy markedly increases as the loading phase increases, i.e., the shear effect increases [21]. This has been attributed to the shielding effects at the interfaces with increased shear loading. For high-phase angels, interface crack kinking into the mortar or aggregate may take place. In this paper, an attempt has been made to study the bond strength of the interface between mortar–rock (rough) and mortar–hardened HSC (rough, smooth and casting face) using both sandwiched and direct rock–mortar composite compact specimens on the Mode I and Mode II loading effects.

2. Experimental program

2.1. Materials

An ordinary Portland cement conforming to IS 8112-1989 was used for the program. Silica fume was used as cement replacement material at 10% by weight of cement. The specific surface of the silica fume varies between 18 and 20 g/m^2. The specific gravity is 2.05. The SiO_2 in the silica fume is 93.6%. Natural river sand passing through a 2.36-mm sieve and with a specific gravity of 2.68 was used. The bulk density is 1580 kg/m^3. Potable water was used along with high-range water-reducing agent for improving the flow of mortars. All the mortars show good cohesiveness and uniformity. The interfacial transition zone between the matrix and the aggregate was studied for three types of mortars. The mortars with different mix proportions are designated as M-13, M-12 and M-14, with cement–sand ratios of 1:3, 1:2 and 1:4, respectively. The water–cementitious materials ratio was 0.4 throughout. Table 1 shows the mechanical properties of the mortars. The compressive strength of mortar was determined on 50-mm cube specimens and the tensile strength was determined on 100-mm split cylindrical specimens. The modulus of elasticity was calculated using ultrasonic pulse velocity technique.

Table 1
Mechanical properties of mortars for interfacial bond strength

Mix designation	Cement–sand ratio	Compressive strength (MPa)	Split tensile strength (MPa)	Ultrasonic pulse velocity (km/s)	Modulus of elasticity (MPa)
M-13	1:3	46.00	2.38	4.00	25.54
M-12	1:2	43.10	2.31	3.96	25.00
M-14	1:4	30.07	1.33	3.95	24.82

2.2. Geometry and preparation of test specimens

Two types of test specimens were prepared. In the first type, fresh mortar M-13 was cast against rough concrete surface. In the second type (sandwich specimens), a thin layer of aggregate with different surface characteristics was embedded at the required position in the mortar matrix. Rock and hardened concrete slices were embedded in mortars M-13 and M-12 for Mode I loading. For Mode II loading type, three mortars, M-13, M-12 and M-14, were used with different aggregate surfaces. By selecting different sizes of the composite specimens, the size of interface was varied. The length to depth ratio was 2.0. The thickness of the specimen was 80 mm. Double-edge notches were made in the composite specimens using a diamond saw cut at the age of 28 days. The specimens were in the form of double-edge notched compact tension specimens. The actual failure surface area of the interface was used to calculate the strength of interface in tension and shear. The bond strength is calculated as the failure load divided by the actual interface area. Rough rock surfaces were formed using chiseling. In the case of concrete, rough failure surfaces were used in one case and with smooth and casting surfaces in the other cases. Smooth surface was formed using the diamond saw cut. Direct shear loading was applied in two-way shear in Mode II failure. The tensile test geometry consisted of steel angles welded with steel flats to provide sufficient contact area with the test specimen near the grips. Nuts and bolts were used to fasten the specimen. G-clamps were also used to avoid the slipping of the specimens from the end grips. A thick layer of rubber padding was provided between the specimen and the loading platens to avoid concentration of the stress.

3. Test results and discussion

3.1. Interfacial bond strength in tension (Mode I)

Table 2 shows the experimental observations on the tensile bond strength of the interface between mortar M-13 and rough concrete surface. The surface area of the rough concrete surface with mortar M-13 was measured on the failure surface along the interface. The surface area of the interface varies between 3000 and 6720 mm^2. The tensile bond strength at the interface with rough concrete surface under Mode I failure varies between 0.54 and 1.01 MPa, which is about one fourth to one half of the tensile strength of the mortar M-13, whose strength is 2.38 MPa. The tensile bond strength of the interface on an average is 0.82 MPa, which is about one third of the tensile strength of mortar itself, whereas the modulus of rupture of the granite rock is 9 MPa, which seems to be very high, about 10 times that of the interface tensile bond strength. Some traces of aggregate flakes have been noticed with the mortar matrix indicating a strong mortar interface with aggregate. However, the crack propagation is predominant in the interface. The influence of the size of the interface seems to be negligible.

The tensile bond strengths at the interface with sandwiched composite specimens with different aggregate surfaces are shown in Table 3. The bond strengths were 0.34 and 0.56 MPa in the interface with mortar M-13 and rough rock surface, whereas the strengths were 0.23 and 0.46 with casting and smooth surfaces of concrete with mortar M-13. The interface bond strength seems to be significantly less in sandwiched composite specimens, which is about half of that with M-13 cast against rough concrete. The casting surface exhibited lowest bond strength with M-13. This is because of the weak bond developed with casting surface, in which physical interaction was dominant. However, the smooth concrete surface showed better bond strength with M-13. The surface was perfectly smooth, which was obtained by diamond saw cut. The aggregates exposed in the concrete after cutting showed very smooth surface. If only physical interaction had taken place, the strength should not have been high. Some mechanism should be dominating. The rock surface might have interacted with the hydration products of the matrix resulting in very strong bond. In the case of the interface between rough rock aggregate and mortar M-12, the tensile bond strengths are 0.12 and 0.23, which seem to be very small, about 1/20th and 1/10th of the strength (2.31 MPa) of the mortar M-12. The bond strength of the interface under Mode I loading conditions significantly varies with the type of mortar. The strength of mortar seems to be the dominating factor on the type of interface with any type of aggregate surface. In this case, the mortar made with cement–sand ratio of 1:3 at w/c ratio of 0.40 shows highest strength with 10% silica fume, whereas the mortar M-13 is followed by M-12 in decreasing order. It can be inferred from the above observations that the tensile bond strength of the interface between M-13 and the rough concrete surface show significantly higher values than those with rough granite aggregate. The sandwiched composite specimens show significantly lower bond strength.

Table 2
Experimental observations on the bond strength of interface against rough concrete surface under Mode I loading conditions

Type of mortar	Type of aggregate surface	Aggregate surface area (mm^2)	Failure load (kN)	Tensile strength (MPa)
M-13	Rough concrete	5550	4.60	0.83
M-13	Rough concrete	6720	6.80	1.01
M-13	Rough concrete	5600	4.50	0.80
M-13	Rough concrete	3000	2.70	0.90
M-13	Rough concrete	3680	2.0	0.54

Table 3
Experimental observations on the bond strength of the interface in Mode I loading conditions in sandwiched composite specimens

Type of mortar	Type of aggregate surface	Aggregate surface area (mm^2)	Failure load (kN)	Tensile strength (MPa)
M-13	Smooth concrete	5,360	2.45	0.46
M-13	Concrete (CS)	11,371	2.50	0.22
M-13	Rough rock	5,040	2.80	0.56
M-13	Rough rock	13,284	4.50	0.34
M-12	Rough rock	6,880	1.60	0.23
M-12	Rough rock	11,680	1.40	0.12

CS = casting surface.

The failure surfaces of the concrete made with larger size coarse aggregate show significant traces of pulling out of the aggregate from the matrix. The fracture surfaces of the concrete were observed with significant tortuosity and porosity. The strong mortar–cement matrix penetrates in the pores/troughs resulting in significant mechanical interlock. In addition, the bond strength in mortar M-13 increases due to the pozzolanic reaction of silica fume, which improves the physical interaction at the interface. Therefore, the phenomena of physical interaction and mechanical interlock dominate with rough concrete surface, resulting in higher tensile bond strength of the interface. The type of rock surface significantly influences the interfacial properties of composite materials [17]. The nature of the interfacial zone depends on the microstructure characteristics of the aggregate [8]. Three types of mechanisms are possible at the interface: physical interaction, physical–chemical interaction and mechanical interlock. The van der Waal's forces of attraction are the primary binding forces at the interface [16]. G_i increases with rougher aggregate surfaces for both Mode I and mixed-mode tractions [19]. In the case of rough granite, the physical interaction with cement–mortar matrix has been dominant. The bond strength seems to be weaker than that with rough concrete rough surface. It seems that the fracture energies of the interface with concrete with smooth and casting surface exhibit somewhat lower values than that with rough granite aggregate. The interactions between cement paste and rock surface lowers the toughness and cracking resistance of the interface [18]. With the incorporation of silica fume, the interfacial fracture energy increases considerably. The roughness of the aggregate surface significantly increases the fracture energy of the interface. The nature of the interfacial zone depends on the microstructure characteristics of the aggregate [8]. In the case of porous surface, the hydration products penetrate into the pores yielding to an increase in the mechanical interlock.

3.2. Bond strength in shear (Mode II)

The experimental observations on the bond strength of the interface in Mode II loading conditions are shown in Table 4. The bond strength of the interface in shear has been significantly high with M-13 mortar. Mortar M-14 shows relatively lower values of bond strength in shear with the same granite rock. Mortar M-12 exhibits strength values somewhere in between M-13 and M-14. The shearing bond strength of the interface between different aggregate surfaces and M-13 mortar varies between 2.12 and 2.79 MPa. It seems that the influence of type of mortar is more pronounced on the strength of the interface than that of the type of aggregate surface. The bond shear strengths of the interface with M-13 mortar against smooth concrete surface are 2.13 and 2.61 MPa. These values are 2.24 and 2.79 with rough granite aggregate with M-13 mortar. This shows that the type of mortar significantly influences the type of bond formed in the interface. The interface bond shear shows almost the same range of strength values with smooth concrete and rough granite aggregate. However, the bond strength seems to be very high in rough rock surface when the aggregate surface was inclined at about 10° with the line of action of the load. The bond strength of the interface between mortar M-13 and rough rock surface varies between 1.47 and 2.0 MPa, which are lesser than those with M-13 mortar. The higher values correspond to the higher phase angles. Using M-14 mortar, the bond shear strength seems to be much lesser. The highest bond shear strength was 1.66 MPa with rough granite aggregate with a phase angle of 10° using M-14 mortar. The lowest value was 0.79 MPa at 0° angle. It has been generally observed that the bond strength increases as the roughness of the aggregate increases.

From the observations on the smooth concrete surface, it can be shown that the chemical reaction between the aggregate in the concrete and mortar due to pozzolanic reaction of the silica fume has taken place. The shear strength increases as the roughness of the aggregate increases. Further, it has been observed that the shear strength also increases as the inclination of the interface increases leading to higher shielding effect of the aggregate. Higher values of the shear strength have been observed with the combination of the rougher surfaces and higher phase angles. Trende and Buyukozturk [19] reported that for a given type of loading conditions G_i increases with rougher aggregate surfaces for both Mode I and mixed mode fractions. In addition, for a given aggregate roughness, G_i increases with increase in the shear loading.

Table 4
Experimental observations on the bond strength of the interface under Mode II loading conditions in sandwiched composite specimens

Type of mortar	Type of surface	Inclination of the surface (degrees)	Contact area (mm^2)	Shear force at failure (kN)	Bond shear strength (MPa)
M-13	Smooth concrete	0	9,348	20.00	2.12
M-13	Smooth concrete	0	17,630	46.00	2.61
M-13	Rough rock	0	15,088	33.80	2.24
M-13	Rough rock	10	14,350	40.00	2.79
M-12	Rough rock	10	11,066	22.00	2.00
M-12	Rough rock	0	9,520	14.00	1.47
M-12	Rough rock	20	8,107	14.50	1.80
M-14	Rough rock	10	7,392	12.10	1.66
M-14	Rough rock	0	10,560	8.30	0.79
M-14	Rough rock	0	12,320	14.50	1.18

4. Conclusions

The following conclusions can be drawn from the experimental observations on the bond strength of the interface in Mode I and Mode II loading effects.

1. The bond strength of the interface between mortar M-13 cast against rough concrete in direct tension seems to be about one third of the strength of mortar. However, it is about 1/20th to 1/10th of the mortar M-12 in sandwiched composite specimens.

2. The bond strength in sandwiched composite specimens has been significantly low. The interface seems to be very weak when compared with the mortar or aggregate. The addition of silica fume increases the bond strength of the interface due to its pozzolanic effect. The mortar M-13 shows better bond strength with any type of aggregate surface.

3. The bond shear strength at the interface has been very high with M-13 mortar.

4. The shear strength increases as the roughness of the aggregate increases. Further, it has been observed that the shear strength also increases as the inclination of the interface increases leading to higher shielding effect of the aggregate. Higher values of the shear strength have been observed with the combination of the rougher surfaces and higher phase angles.

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