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Surface treatments and adhesion bonding between concrete and a CFRP composite

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Abstract—Applications of fibre reinforced plastics to repair worn-out civil structures rely on comprehensive understanding of strengthening mechanisms, especially adhesion bonding between composites and concrete. A special testing procedure was developed to investigate adhesion bonding between concrete and a carbon fibre reinforced plastic (CFRP), mainly under normal loading conditions. As concrete surface treatments were expected to influence bond strength, different abrasive procedures were investigated; in addition, the application of a silane primer on the concrete surface was studied, using an epoxy resin or a vinyl ester resin as adhesive. An approach based on fracture mechanics was applied to evaluate debonding fracture energy. Microscopic examinations were conducted to identify fracture mechanisms. Crack propagation was found to be dependent on surface treatments as well as the type of adhesive. Applying the silane primer as coupling agent, bonding strength was clearly improved for poorly treated surfaces. The vinyl ester resin as adhesive was found to be inefficient for achieving high bonding strength between the CFRP and the concrete.

Keywords: Adhesion bonding; composite; concrete; surface treatment; silane primer.

1. INTRODUCTION

Observations of stepwise deterioration of civil structures worldwide, e.g. due to degradation of constituent materials over service time, overloading, environmental attack, earthquakes and accidental damage, has currently led to the development of technologies for repair and strengthening of these structures. The use of advanced composite materials for structural rehabilitation has shown great promise in this respect, because of their excellent non-corrosive, non-magnetic, non-conductive and generally chemically resistant performance, coupled with high strength- and stiffness-to weight ratios. Clearly, if correctly applied in this new area, composites can result in significant life-cycle benefits related to both overall cost and durability [1–3]. All these aspects can lead to increased safety and durability as well as savings in space, labor fabrication, equipment and maintenance costs.

With regard to strengthening of concrete structures by using composites externally, applications studied mainly include bonding of composite plates to reinforced concrete and prestressed concrete beams for improving their flexural stiffness and strength [4–8]. Also, wrapping of reinforced concrete beams or columns with fibre reinforced composite jackets was carried out in order to provide flexural and shear strength enhancement for better resistance to seismic loads [3, 9–14].

Applications of fibre reinforced plastics to repair worn-out civil structures rely on a comprehensive understanding of the strengthening mechanisms. Especially, when the composite reinforcement sheets are bonded to surfaces of concrete members, the adhesive material must have sufficient toughness to dissipate energy from cracking, and sufficient strength and stiffness to transfer stress between the concrete and the composite reinforcement. The debonding of the composite from the concrete structure can be caused by either interfacial crack propagation, plate peel-off due to shear cracks, or failure of the concrete in shear [15]. The evaluation of interfacial bond strength or fracture energy [16–17] is thus of primary importance to this patching technique.

In this study, an approach based on fracture mechanics was developed to evaluate debonding fracture energy of adhesion between concrete and a carbon fibre reinforced epoxy composite. Different abrasive procedures on concrete surfaces were investigated, and the application of a silane primer on the concrete surface was studied, using both an epoxy resin and a vinyl ester resin as possible adhesives. Following fracture tests, microscopic examinations were conducted to identify fracture mechanisms.

2. MATERIALS AND ADHESION BONDING

2.1. Concrete and surface treatments

Generally speaking, concrete can be referred to as a composite material consisting of two phases: hardened cement paste and hard stone aggregates. The concrete used in the present study was produced from cement, sand, stone aggregate (0.5–1.5 cm in size) and water, following a standard mixing procedure. A steel mould was used for hardening the concrete so as to achieve a rectangular bar geometry, and an oil release agent was applied to easily remove the hardened concrete bars from the steel moulds. The condensation of the concrete prior to hardening of the cement was improved by a vibrator. The hardening time was 28 days at ambient pressure in an environmental room with 100% humidity. In the following investigations, two different kinds of concrete surfaces were identified. The first was the original surface after releasing from the mould; it contained a low aggregate content due to buoyancy effects. The second one was a 'refreshed' concrete surface which normally shows a high aggregate content (HAC); it was produced by removing a surface layer of about 6–8 mm from the concrete panels by the use of a diamond saw. To study the efficiency of adhesive bonding, different procedures were applied for pre-treatment of the concrete surfaces, i.e. abrasion, brushing, sand blasting and application of a silane primer.

2.1.1. Abrasion. Two different abrasive papers having a fine particle size (gp size#400) and a coarse one (gp size#80) respectively, were used to grind the concrete surface. After these treatments, the differences in appearance were clearly visible, with a very smooth surface for the fine paper and a rather rough surface for the coarse paper.

2.1.2. Brushing. A regular metal brush was applied to roughen the surfaces by hand or by the use of a hand drill. Machine brushing was applied only in the 0° and 90° directions, whereas hand brushing occurred randomly. The difference in appearance between the differently treated surfaces was not very obvious, except that square tracings on the machine brushed surfaces could be observed.

2.1.3. Sand blasting. The main goal of sand blasting was to remove loose particles and to produce a rough surface area on the concrete. It could also be used for removing contaminated layers. The size of the sand particles was about 1.6 mm in diameter, and the blasting-pressure amounted to 70 kPa with an incidence angle of 70°–90° to the concrete surface.

2.1.4. Application of primer. Because many adhesives often possess poor wetting characteristics, due to their high viscosity during the bonding operation, primers are normally used to pretreat high surface energy substrates prior to adhesive bonding. This can improve the performance of the bonded component. Furthermore, primers offer improvements in such aspects as thermal stability and environmental resistance, establishing strong and moisture-resistant interfacial bonds and protecting surface regions of the substrate from hydration and corrosion [18]. The primer used in this study was based on A-187 γ-glycidoxypropyltrimethoxysilane (γ-GPS), supplied by Union Carbide, USA.

A 1% aqueous solution of this primer was painted on to the mechanically treated and water-jet cleaned concrete surface over a period of about 10 min. After that, the silane solution was allowed to hydrolyse at a temperature of 60°C for a minimum of 1 h. Then the surface was ready for bonding, preferably within 1 h.

2.2. CFRP laminates

The composite used in this study was made of T300 carbon fibre epoxy prepreg (BASF 5218, USA). Unidirectional laminates (320 mm × 320 mm × 1.45 mm), consisting of 10 layers, were processed in an autoclave according to the manufacturer's specification. After curing, the laminate plates were cut into 20 mm × 250 mm strips, using a diamond saw. The fibre volume fraction of consolidated composites amounted to 65%, with a Young's modulus of 133 GPa in the fibre direction.

2.3. Adhesion bonding

Two types of adhesive resins were used in this study. The first one was a Ciba-Geigy Araldite adhesive, which is a two-part epoxy resin providing high bond strength, achieved after 2–3 days of curing. The second one was a vinyl ester resin supplied by Polymer Chemicals Australia Pty. Ltd., which is widely used as a matrix in infrastructure applications. The catalyst chosen for room temperature curing was a MEK (methyletherketone) peroxide, supplied as a liquid; it was thoroughly mixed into the resin to ensure uniform curing. Its content amounted to 1.5 wt% of the resin used, and full bond strength was attained after 1 day.

Prior to the bonding process, a water-jet was used to remove dust and smaller dirt particles which might have prevented good adhesion. Grease and oil left on the surface was wiped off using acetone as a cleaning agent, followed by air drying. The surfaces of composite strips to be bonded were also roughened by using the coarse abrasive paper mentioned before (gp size#80), followed by acetone cleaning and subsequent drying. Now the adhesive was uniformly applied to both the treated concrete and the

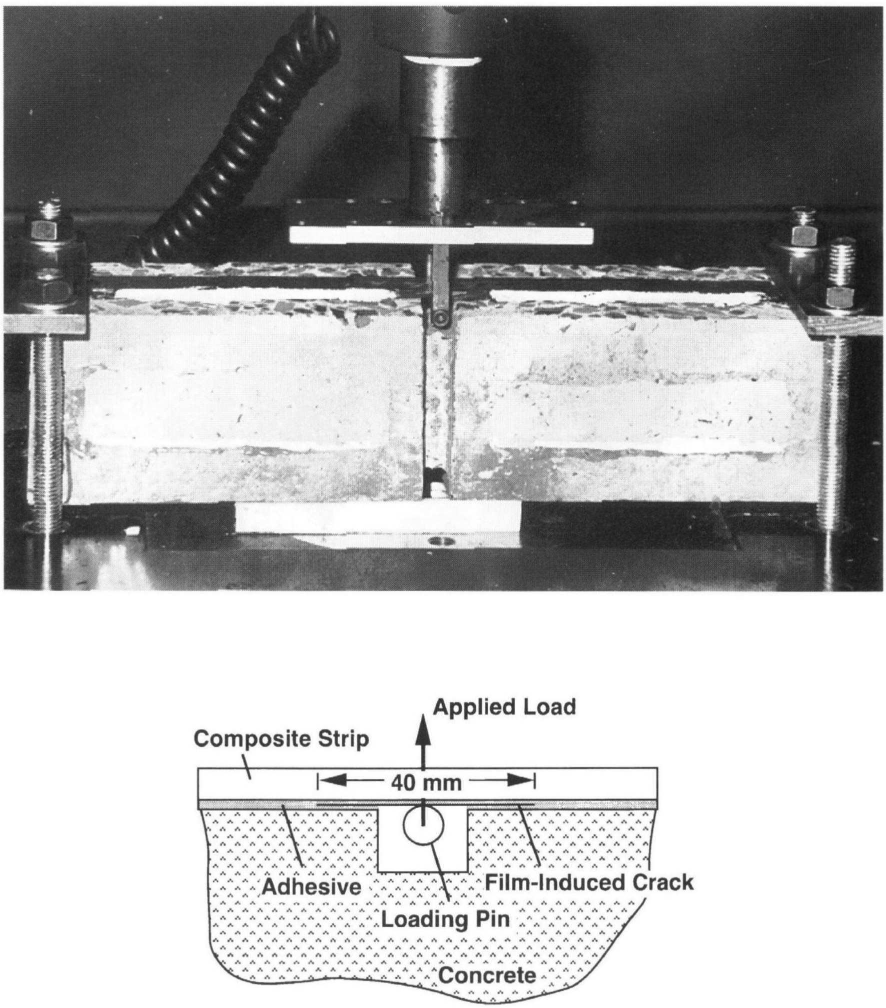


Figure 1. Experimental set-up for adhesion bonding test.

composite surface; then the composite strip was laid over the concrete with a dead weight pressure of 0.33 MPa for 1 day. At the centre location, a Upilex® film of 12.5 μm in thickness was placed between the concrete and the composite strip in order to produce a pre-crack of 40 mm in length, as shown in Fig. 1.

3. EVALUATION OF FRACTURE ENERGY

Adopted from other fracture mechanics tests for adhesion bonding, a fracture testing fixture was specially designed (Fig. 1), to measure the fracture energy of adhesion bonding between the concrete and the composite. The total length of the composite strip was 350 mm, and the concrete bar bonded with the composite strip was clamped at both ends with a span of approximately 400 mm, shown in Fig. 1. An Instron 5567 with a 1 kN load cell was used to apply the load through the loading pin. The cross-head speed was set to 0.2 mm/min with continuous recording of the load–displacement curve. A stereo microscope was used to observe crack growth, so that about every 5 mm, the exact position of both tips of the crack (i.e. one on each side of the sample) could be marked on the load–displacement curve. It was found that the crack growth speed was almost the same for both tips.

Fracture mechanics has been widely applied to evaluate interfacial adhesion of bonded joints [18]. In this study, the global fracture energy, G_c, was evaluated using the 'compliance calibration method' [19]. From load–displacement curves and measurements of crack length for each group of specimens, a master compliance calibration *versus* the total crack length, a, could be determined. Fortunately, in almost all tests the compliance and the crack length could be correlated by a straight line with a slope m (Fig. 2). This allowed us to calculate the global fracture energy using the formula

$$G_c = \frac{F_i^2}{2B}\frac{\partial C}{\partial a} = \frac{F_i^2}{2B}m, \tag{1}$$

where B is the width of the composite strip, and F_i is the load for crack propagation.

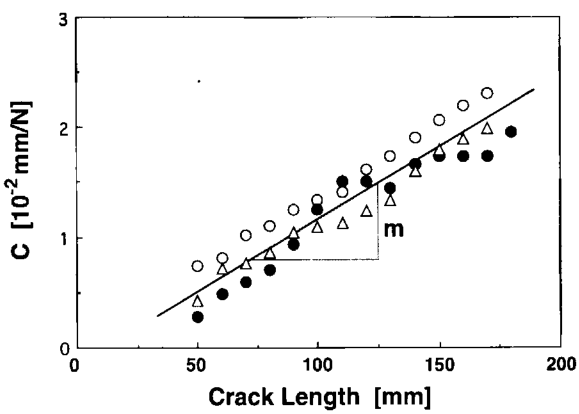


Figure 2. Compliance *versus* total crack length for sand blasted concrete surface (various symbols refer to various specimens).

At least three specimens were tested for each condition. Fracture surfaces of both composite and concrete were examined by using optical microscopy.

4. RESULTS AND DISCUSSION

Figure 3 shows a typical load–displacement curve recorded during the fracture tests. The load increased almost linearly up to a deviation point at which crack initiation started almost simultaneously from the two film-induced-crack tips. The maximum load was normally achieved after 30–40 mm of crack propagation. Evaluation of the fracture energies gave rise to the conclusion that the debonding energy in most of the cases was independent of crack length, as shown in Fig. 4, where the debonding energies are plotted against crack growth for the sand blasted concrete surfaces with the Araldite adhesive and the vinylester resin. Therefore, only average values of frac-

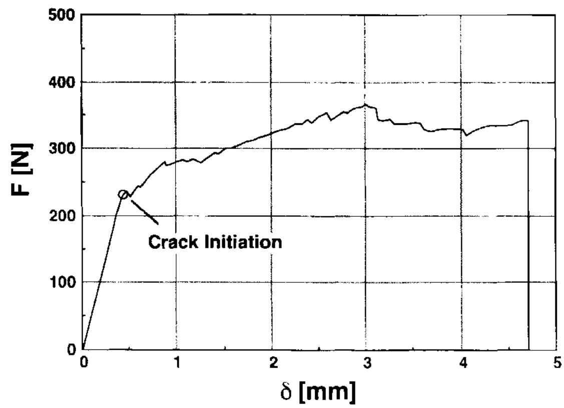


Figure 3. Typical load–displacement curve from debonding tests.

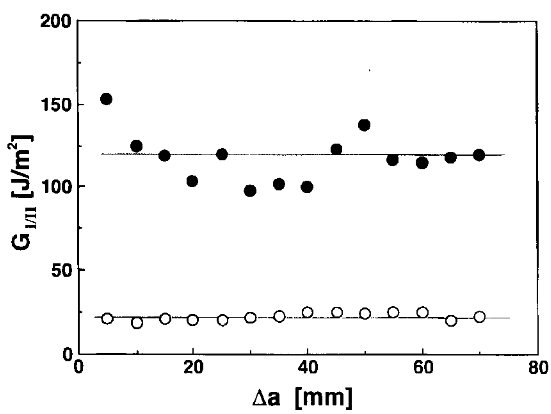


Figure 4. Global debonding energies *versus* crack extension for sand blasted concrete surfaces with Araldite adhesive (●) and vinylester resin (○).

ture energies were considered. Furthermore, five different crack paths were possible, namely, interfacial debonding between the composite and the adhesive, between the adhesive and the concrete, or cohesive failure inside the adhesive, inside the concrete or inside the composite substrate [16, 20]. It should be noted that no effect of different crack propagation paths is taken into account in equation (1) which can only produce the global fracture energy.

4.1. *Effects of mechanical surface treatments*

The adhesive bonding between the composite and the concrete is highly dependent on the methods of concrete surface treatment. Figure 5 shows the critical load for crack initiation and the maximum load obtained for crack propagation. It can be seen that the surface treatment methods have significant effects on both critical load for crack initiation and maximum load for propagation. The highest values (263 N and 330 N, respectively) were obtained for sand blasting on the 'refreshed' concrete surface with a high aggregate content (HAC). Compared to the smooth surface as produced by the abrasive paper (gp size#400), the values of fracture energy of the other treatments were clearly higher (Fig. 6); in all of these cases the Ciba-Geigy Araldite super strength adhesive was used. For example, the fracture energy was increased from 61 J/m^2 for a smooth surface to 137 J/m^2 for a sand blasted concrete surface. The sand blasting apparently results in an enlarged (rough) area for adhesive bonding, and it also appears that the adhesive penetrates into tiny holes of the concrete surface so as to build up an interlocking mechanism. Eventually, for strongest bonding conditions as a result of such an adhesive 'toughened' concrete surface, fracture occurred mainly cohesively within the mortar of the concrete. The 'refreshed' concrete surface with a high aggregate content resulted in the highest fracture energy (203 J/m^2), which may be attributed to the fact that a strong bonding between the aggregate and the adhesive exists. Fracture in these cases occurred by cohesive failure of the mortar but not in the much stronger aggregates, which instead can be pulled out of the concrete surface (Fig. 7). From these results, one can state that mechanical surface treatments with surface roughening mechanisms improve the bond strength between the concrete and composites. Especially sand blasting, preferably on a 'refreshed' concrete surface containing a high amount of aggregates was shown to produce the highest bond strength between the CFRP and the concrete.

4.2. *Effect of adhesives*

To highlight the difference, only the results for the smooth concrete surface treated by the abrasive paper (gp size#400) and the rough surface by sand blasting are discussed. As shown in Figs 8 and 9, applying vinyl ester resin adhesive on the rough surface resulted in a very weak adhesion fracture energy, 27 J/m^2, which is only about 20% of that for the Araldite super-strength adhesive. Similarly, the critical load for crack initiation was reduced from 215 to 79 N, and the maximum load from 283 to 98 N. Unlike the cases for the Araldite super-strength adhesive, there is no clear difference

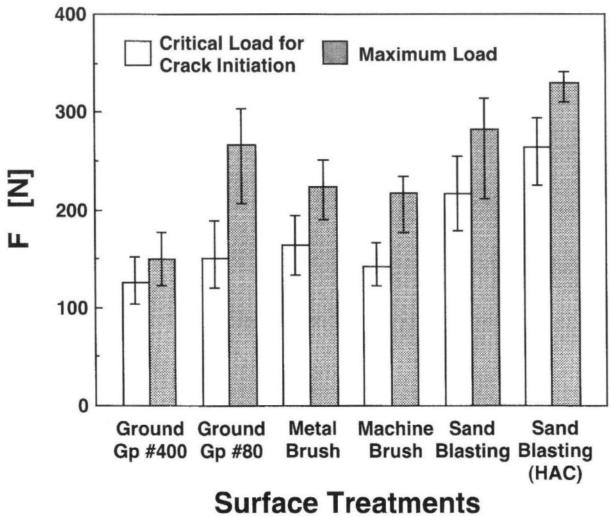


Figure 5. Critical loads for crack initiation and propagation as a function of surface treatments.

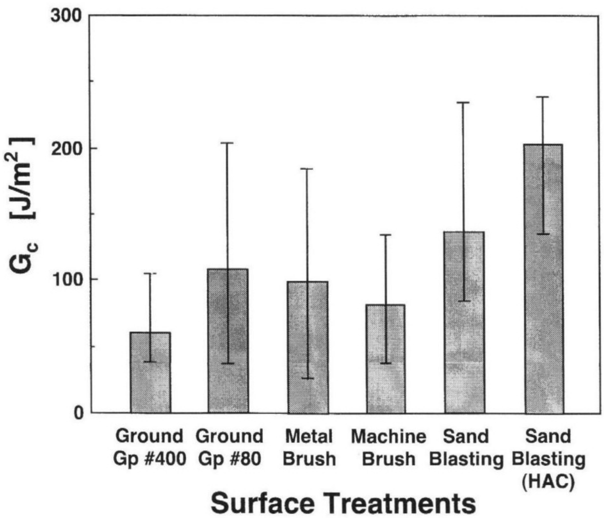
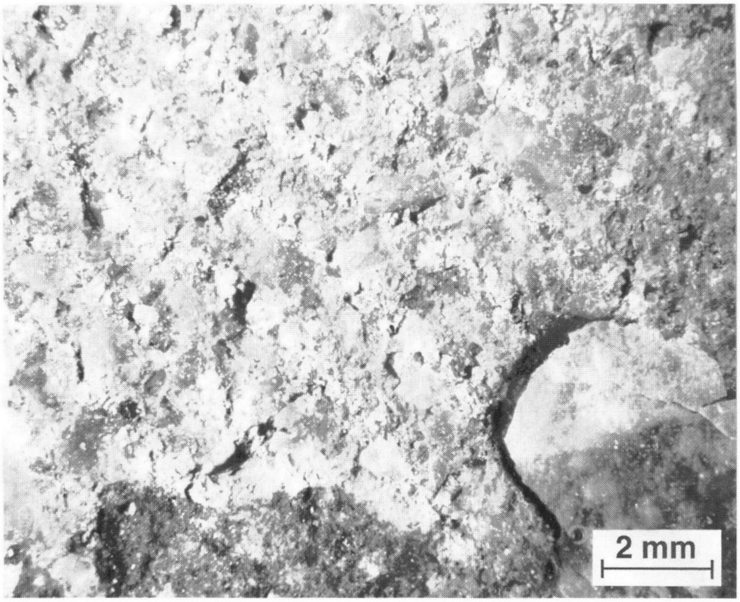
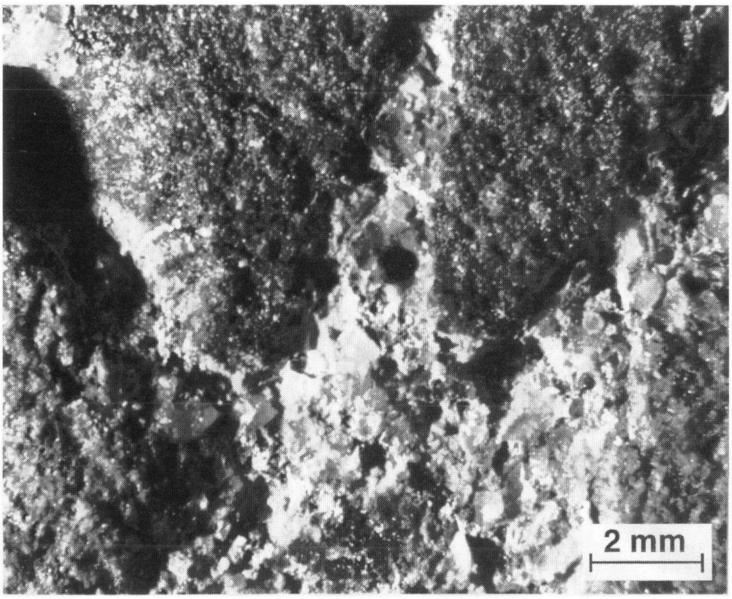


Figure 6. Fracture energy of crack growth as a function of surface treatments.

between fracture energies obtained for the smooth and the rough surfaces. Crack propagated mainly in the adhesive, leaving residues of vinyl ester resin on both the concrete and the composite surface (Fig. 10). This is probably the reason why, in this case, sand blasting did not improve the adhesion between the concrete and the composite. Based on these results, it can be expected that if a vinyl ester resin based fibre composite is applied directly on to the concrete, the bonding strength between the composite and the concrete would be very poor, compared to an epoxy resin based composite.



(a)



(b)

Figure 7. Fracture surfaces of concrete with sand blasting: (a) virgin surface; (b) refreshed surface with HAC.

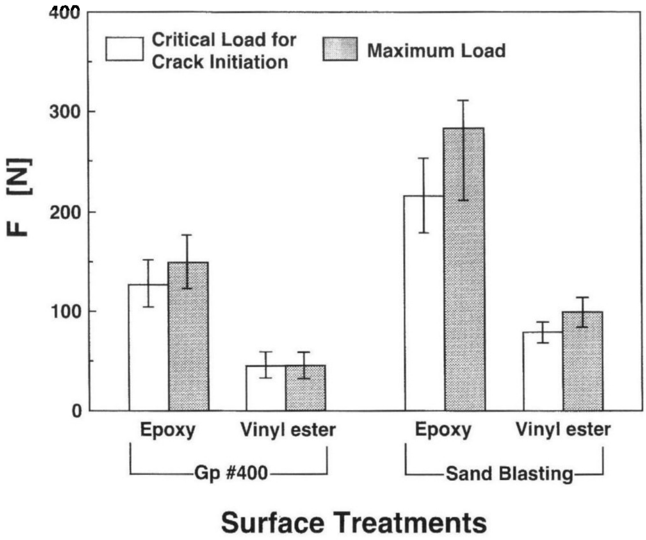


Figure 8. Effect of adhesives on critical loads for crack initiation and propagation.

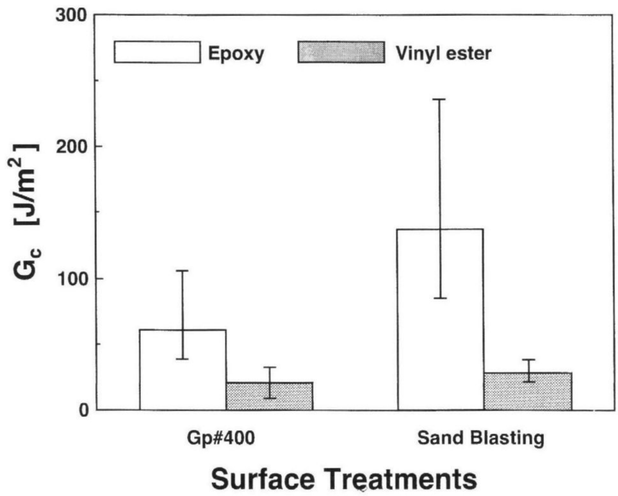
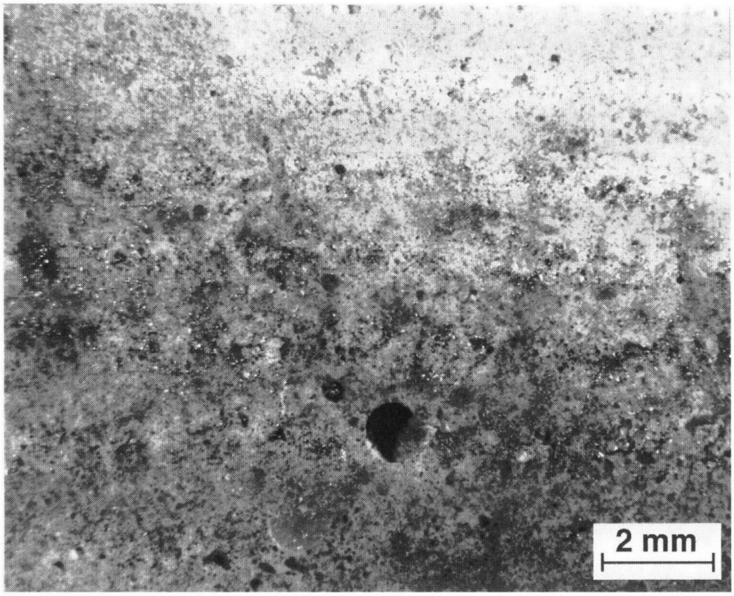


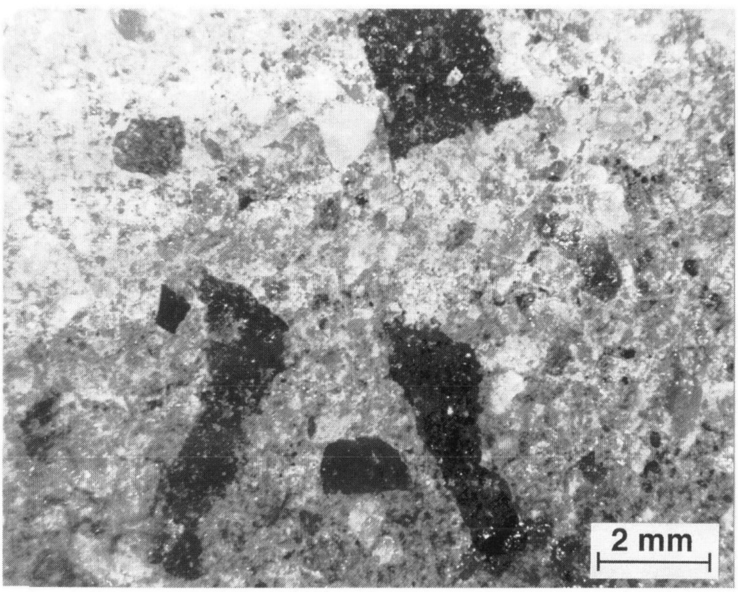
Figure 9. Effect of adhesives on fracture energy of crack growth.

4.3. Effects of primer

As expected, the silane primer improved the adhesion bonding of the composite to the concrete surface (Figs 11 and 12). Especially, the fracture energy for the smooth concrete surface was enhanced from 61 J/m^2 to 126 J/m^2 for the Araldite adhesive, which is equivalent to the good bonding obtained for the rough concrete surface produced by sand blasting. At the same time, the critical load for crack initiation was increased from 125 to 211 N, and the maximum load from 147 to 240 N. It is interesting to



(a)



(b)

Figure 10. Fracture surfaces of concrete with cohesive failure within vinyl ester adhesive: (a) gp#400 paper; (b) sand blasting.

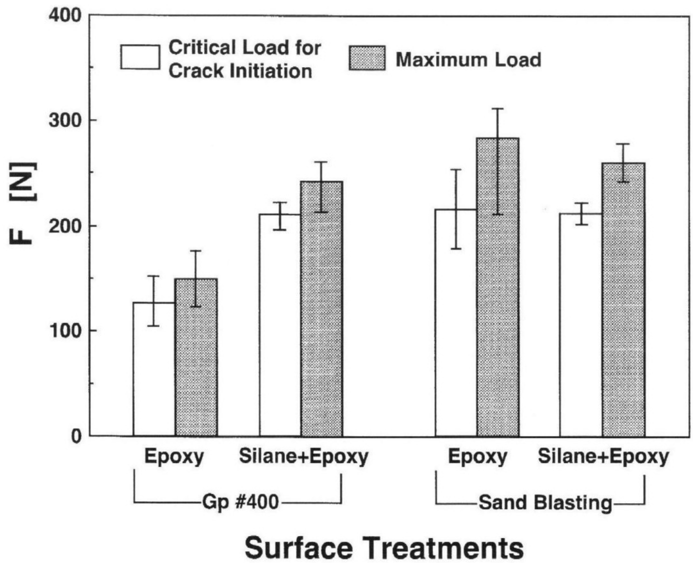


Figure 11. Effect of primer on critical loads for crack initiation and propagation.

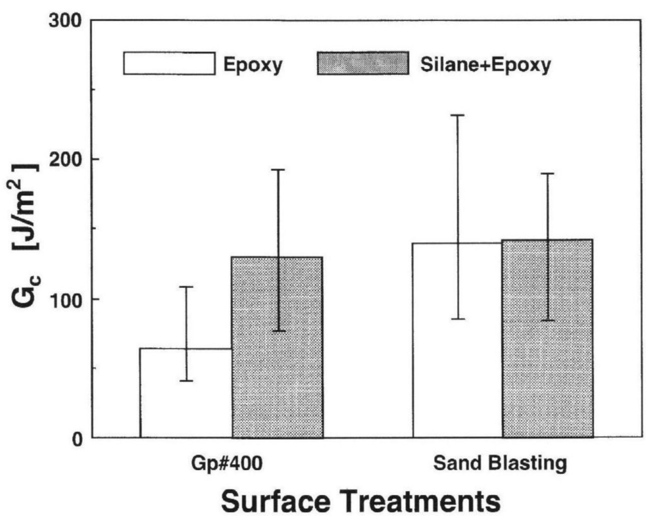
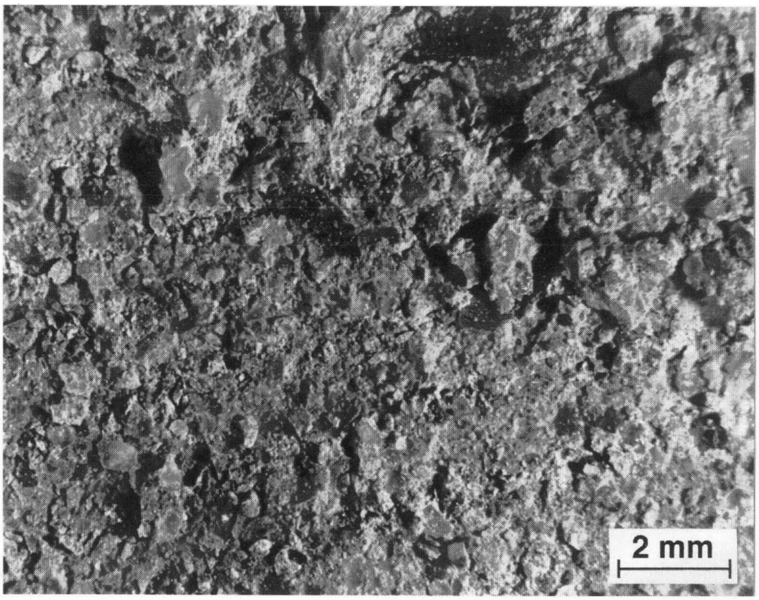
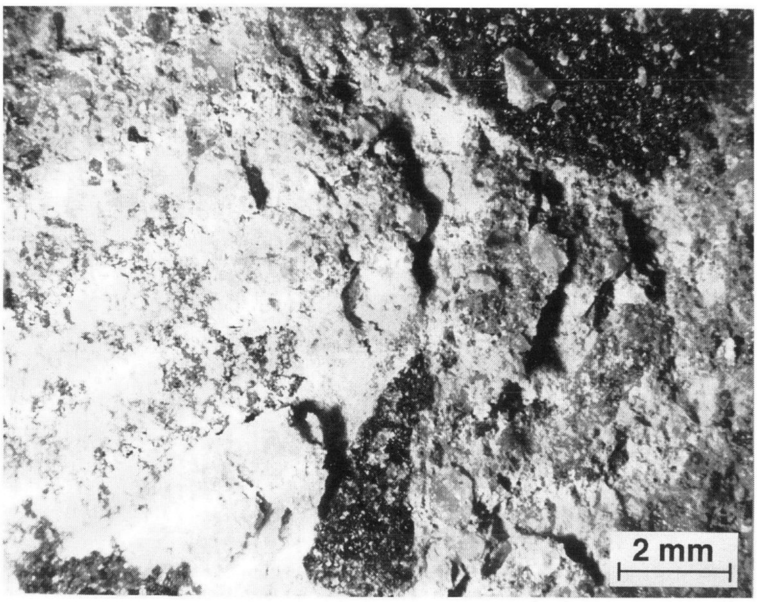


Figure 12. Effect of primer on fracture energy of crack growth.

see that application of the primer does not further enhance adhesion bonding between the rough concrete surface and the composite. The post-fracture surfaces show very similar features in this case (Fig. 13). This is because the crack propagated cohesively within the mortar of the concrete rather than in the adhesive layer, and a large amount of aggregate and mortar particles was found on the composite side. This means that for adhesion bonding between a composite and the concrete, the bonding strength is



(a)



(b)

Figure 13. Fracture surfaces showing cohesive failure within mortar of concrete: (a) gp#400 paper; (b) sand blasting.

limited by the strength of the substrate. To further improve the integrity of adhesion bonding, the performance of the substrate (i.e. the concrete in this study) has to be improved.

5. CONCLUSIONS

A special testing procedure was developed to evaluate fracture energy of adhesion bonding between concrete and a carbon fibre reinforced epoxy composite. Different mechanical abrasive procedures on concrete surfaces were investigated, and the application of a silane primer on the concrete surface was studied. It was found that the adhesion bonding between the composite and the concrete is highly dependent on the method of concrete surface treatment as well as on the type of adhesive. It is possible to establish a high quality bonding between composite and concrete, which is essential for using prestressed fibre reinforced plastic sheets to strengthen deteriorated concrete structures. Applying a silane primer as coupling agent on the concrete surface helps to significantly improve the bonding strength, especially for poorly treated surfaces.

When the adhesion is strong enough to prevent any cracking within the adhesive, debonding cracks will primarily propagate cohesively within the substrates. It means that for adhesion bonding between a composite and the concrete, the bonding strength is limited by the strength of the concrete substrate. Therefore, the concrete itself still plays an important role in the integrity of repaired or strengthened infrastructure.

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