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Adhesive power measurements of bonds between old and new concrete

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A simple procedure for measuring the adhesive bond of cement-bonded materials is introduced and tested with an old–new concrete bond. Cubic or cylindrical specimens with a notch and the interface in their middle are split under stable crack growth conditions. The load is recorded as a function of the crack opening displacement. From this curve, the maximum load (notch tensile stress) and the fracture energy (G_F) can be determined. The course of the curve characterizes the mechanical behaviour of the material bond in the crack opening mode and is an important basis for a numerical treatment of interface problems. Different pre-treatments of the old concrete surface have an important influence on the adhesion of the material compound. Good adhesive properties have been measured after sand-blast treatment and poorer properties after a dispersion emulsion treatment.

1. Introduction

In order to reorganize or to protect concrete constructions, quite often layers of concrete or of cement-bonded materials are used. To be sure that such preventive measures are lasting, one must take care that the material bonding between the applied layer and the construction materials resists mechanical and chemical loads for a long time. In particular the adhesive bond has to considered carefully besides the properties of the materials. The adhesive power of a compound is usually determined by the chemical and mechanical compatibility of the material components [1] and by other material properties like plastic deformation [2]. In addition, the pre-treatment of the surface of concrete or cement-bonded material components to be reorganized is most important.

Concrete surfaces which have to be coated are usually pre-treated with different procedures, such as sand blasting, water-jet treatment or grinding [3]. The adhesive power of such compounds is determined with different testing procedures (e.g. tensile test, tear-off test, splitting test) [3–6]. As a result of such proof tests, a maximum stress (load per unit area) is usually obtained, which is the adhesion tensile stress for tensile loading and the shear stress for shear loading. However, it is almost impossible to decide whether the compounds have been separated in a brittle or ductile manner. The above-mentioned testing methods have been criticized as they are characterized by extensive scatter in the results, cannot be compared well among each other, do not simulate failures which are typically found in service, do not yield material properties, and there-fore can be used only for qualitative comparison purposes [4].

Introduction of fracture mechanics methods and tests have improved the situation. According to the authors' knowledge, Hilsdorf and co-workers [3, 8] did the pioneer work in this field. With LEB and compact tension (CT) specimens of concrete and of cement-bonded materials, they performed fracture toughness tests and showed that more conclusive results are obtained with these procedures than with the above-mentioned conventional tests. Linear elastic fracture mechanics (LEFM) has not succeeded in civil engineering apart from the field of large buildings like dams [8]. Recently, the fictitious crack model [9], the blunt crack model [10] and other models (see literature cited in [8]) have been developed for concrete. Today the fracture energy concept [11] is of great interest for concrete fracture mechanics. The fracture energy G_F which is related to the strain-softening curve reveals a sort of material law in the fracture energy concept. It is necessary to know this law for numerical simulation of fracture phenomena of concrete due to cracking.

It is the aim of the following work to use the strain-softening curves to characterize the adhesive bonds between cement-bonded materials. For measurements of the strain-softening curves a method is used which has been developed recently for homogeneous concrete and cement-bonded materials [12, 13]. The experiments were performed on compounds of old and new concrete with differently pre-treated surfaces of old concrete.

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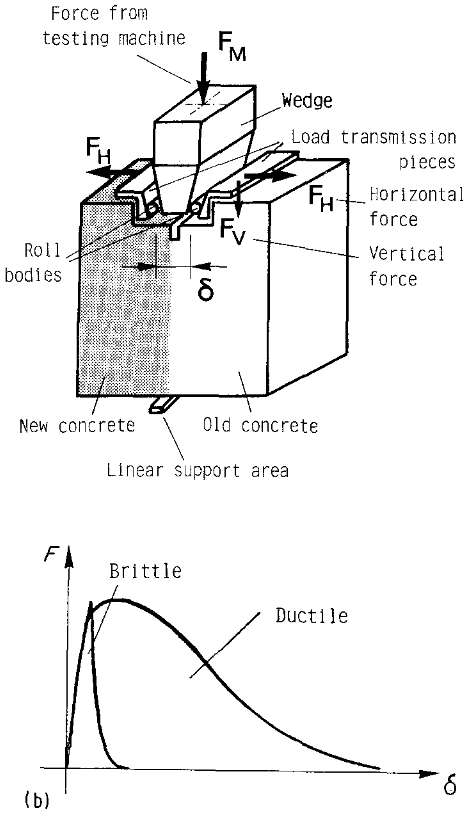

Figure 1 (a) Principle of testing method and (b) schematic course of the strain-softening curve of "brittle" and "ductile" compounds.

2. Testing method

The principle of the testing method is shown schematically in Fig. 1a. It is the measuring procedure according to Tschegg and Linsbauer [12] which is applied now for bond proof experiments. A cubic specimen with a rectangular groove and a starter notch is split by wedge-load equipment at the interface of the two materials. The interface between the two materials subdivides the cube into two identical parts. The interface, starter notch and linear support area are in a vertical plane.

Splitting must take place during stable crack propagation, which is possible only with a stiff loading system (wedge-loading system + testing machine). The wedge-load unit itself is extremely stiff, i.e. it stores little deformation energy. Such experiments can therefore be performed with mechanical spindle drive machines or in hydraulic machines under strain or stroke control. At both ends of the starter notch, displacement gauges are mounted close to the notch tip in order to measure the crack opening displacement. The force $\bar{F}$ is determined with a load cell in the testing machine. Knowing the wedge angle (angle approximately 5–10°) one can calculate the force F in the horizontal direction which causes splitting of the specimen. The vertical force component is small because of the small wedge angle. This load helps to stabilize the crack growth plane to remain within the interface planes. The influence of the vertical force component on the crack growth behaviour has been investigated in studies of concrete [14]. No measurable influence could be detected. It is therefore assumed that the same is true for interface tests.

In order to reduce friction between the wedge and both sliding pieces, roll bodies were placed in between [12, 15]. By this means the influence of friction is small enough to be neglected.

F and δ were recorded by an X–Y recorder. The course of the recorded curve is plotted schematically in Fig. 1b for brittle and ductile separation of a bond. In both cases the same maximum load is obtained, though the mechanical behaviour during separation of the bond is completely different. Therefore, measurement of the maximum load is not appropriate to determine whether crack propagation is ductile or not. If, however, the area beneath the F–δ curve is used to characterize bond separation, brittle and ductile behaviour may be recognized very well. The area beneath the F–δ curve is the fracture energy, which is larger for ductile bond separations than for brittle ones. If this energy value is divided by the fracture surface area, the fracture energy value G_F is obtained [8, 9].

Cubic-shaped specimens of cement-bonded materials as used by civil engineers may be produced easily and quickly. If however specimens have to be taken from constructions, then drill cores may be used for testing purposes. The starter notch and groove may be introduced by a rock-saw in such cases. The specimens may be tested in the horizontal position (the load device is introduced into the cylinder surface) as well as in the vertical position (load device is inroduced into the front surface of the cylinder). In Fig. 2, specimens of cubic shape (Fig. 2a), cylindrical shape in horizontal position (Fig. 2b) and in vertical position (Fig. 2c) are shown.

3. Preparation of specimens

In order to test the adhesive bonding of old–new concrete, cubic specimens (see Fig. 2a) with an edge length of 150 mm were produced. Two steps of manufacturing were necessary: (i) preparing the old concrete parts and surface treatment of these and (ii) concreting the new concrete. For the first step, conventional concrete forms were divided into two identical halves with a form sheet and were subsequently grouted with concrete of B500 quality (for mechanical properties of the old concrete see Table I). The semi-cubes were removed from the forms after two days and stored in water for three months. A square area of each semi-cube was then treated while it was wet in the following manner:

(a) it was ground superficially with a hand wire brush (this treatment is called "no" in the following), or

(b) it was sand-blasted ("sand blast"), or

(c) it was treated with a needle hammer ("needle hammer"), or

(d) it was roughened by hand with a wire brush and an emulsion (plastic dispersion) was applied as an adhesive bridge (emulsion: water:concrete = 1:3:4) (called "emulsion" in the following).

Immediately after these surface treatments the semi-cubes were moistened and then, in the second step, the

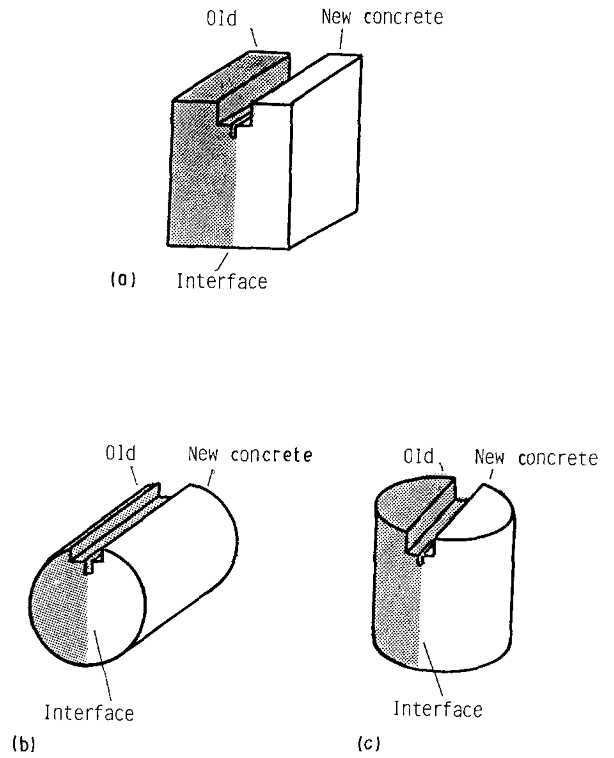

Figure 2 Specimen shape of a (a) cubic specimen, (b) drill core specimen in horizontal position, (c) cylindrical specimen in vertical position.

TABLE I Concrete compositions and 28-day compressive strengths

	Old concrete (B500)	New concrete (B400)
Max. grain size, $d_{\max}$ (mm)	16	16
Water/cement ratio	0.45	0.52
Cement (kg m^{-3})	450	350
Compressive strength (N mm^{-2})	52	44

new concrete was added into a cube concrete form (for quality of the new concrete B400 see Table I). In order to minimize cutting work with a rock saw, a rectangular wedge (width 40 mm, depth 200 mm) and starter notch (12 mm depth and 0.2 mm width) were formed with the aid of a form sheet during production of new and old concrete. After two days, the cubes were removed from the forms and stored in water again. The adhesive power of the old–new concrete bond was tested 28 days after specimen manufacturing. Four cubes of each specimen type were produced and tested in order to determine the scatter of the results.

In addition, four homogeneous cubes (without an interface) of new concrete (B400) were prepared. After storing them for 28 days in water, they were tested in the same way as the cubes with the interfaces.

4. Results

Characteristic diagrams from splitting tests on interface specimens of old–new concrete with different surface treatments of the old concrete and of homogeneous concrete specimens (B400) are shown in Fig. 3. Note that all diagrams in this figure are drawn to the same scale. Numerical values, accuracy of measurement and standard deviation are summarized in Table II for the homogeneous new-concrete cubes and in Table III for specimens with interfaces. In Fig. 4, the maximum load values and the fracture energy values (G_F) of the test series are schematically shown as columns with absolute values on the left-hand scale and relative values in relation to the new concrete on the right-hand scale.

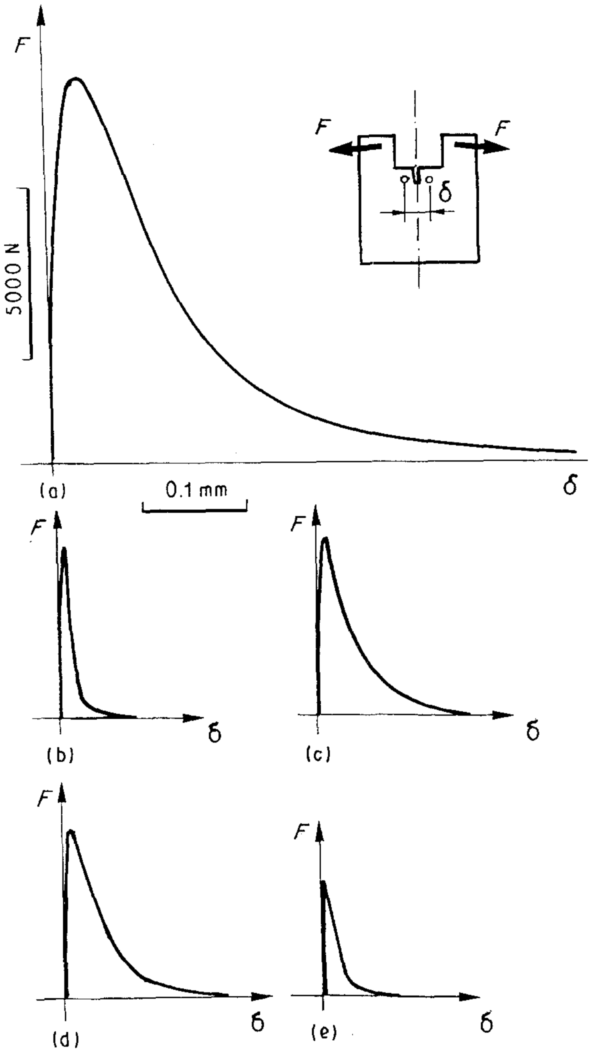

Figure 3 Load–displacement diagrams for (a) homogeneous concrete (new concrete B400) and for pre-treatments of old concrete surface: (b) "no", (c) "sand blast', (d) "needle hammer", (e) "emulsion". All diagrams are drawn to the same scale.

The diagram shows immediately that the maximum strength of the interface specimens is only approximately half that of the homogeneous new-concrete specimens. The different pre-treatments of old concrete do not influence the maximum load much. "No", "needle hammer" and "sand blast" treatments are rather similar as to their maximum load, whereas the "emulsion" treatment yields somewhat lower values of the maximum load. Comparison of the G_F values of the different pre-treatments shows quite another result: the fracture energy of interface specimens is at most a quarter of the value for homogeneous specimens. The highest fracture energy is obtained with interface specimens which were "sand blast" pre-treated. Specimens with "needle hammer" pre-treatment show slightly lower values, whereas "no" and

TABLE II Maximum load and G_F of homogeneous specimens

Specimen No.	Max. load (N)	Standard deviation (N)	Standard deviation (%)	G_F (N m^{-1})	Standard deviation (N m^{-1})	Standard deviation (%)
1	8907			77.4		
2	9707			69.7		
3	10278			69.75		
4	10963			71.8		
5	10735			74.9		
Mean	9916	860	8.7	72.7	6.73	9.2

TABLE III Maximum load and G_F of specimens with interfaces (values are mean values of 4 measurements)

Treatment	Max. load (N)	Standard deviation (N)	Standard deviation (%)	G_F (N m^{-1})	Standard deviation (N m^{-1})	Standard deviation (%)
“No”	5420	210	3.8	6.21	0.35	5.6
“Sand blast”	5410	270	4.9	14.11	0.42	3.0
“Needle hammer”	4990	240	4.8	12.33	0.51	4.25
“Emulsion”	2890	190	6.5	5.2	0.32	6.1

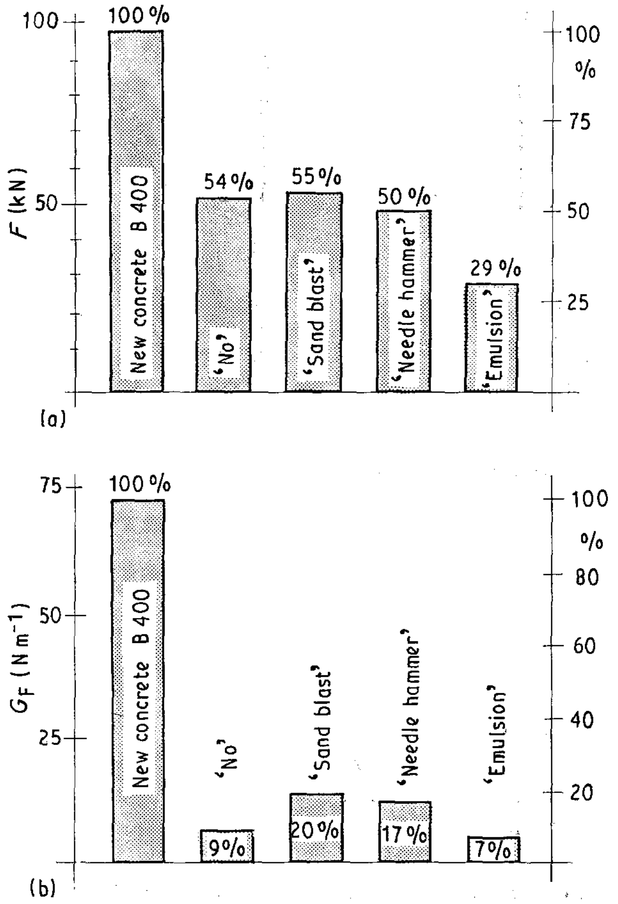

Figure 4 Comparison of results for (a) maximum load (left axis shows absolute values, right axis relative values in relation to homogeneous new concrete B400); (b) fracture energy G_F (left axis: absolute values, right axis: relative values in relation to homogeneous concrete B400).

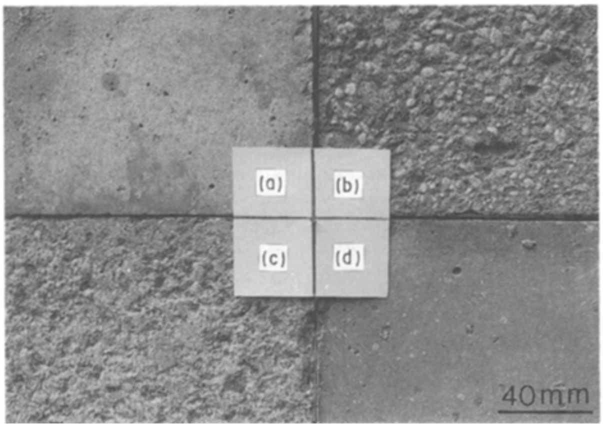

Figure 5 Fracture surfaces of old concrete after different pre-treatments of the old concrete surface: (a) “no”, (b) “sand blast”, (c) “needle hammer”, (d) “emulsion”.

“emulsion” treatments are characterized by much lower values of the fracture energy. This drastic reduction of the fracture energy compared with the other pre-treatments is mainly caused by a steep drop of the strain-softening curve after reaching the maximum load. Fracturing is more “brittle” in comparison with specimens prepared by sand-blasting.

In Fig. 5, photographs of the old concrete fracture surfaces of interface specimens are reproduced. The roughest fracture surface originates from a specimen which was “sand blasted’ (Fig. 5b). The size of the single aggregates may be recognized. In addition it has been observed that the crack partially propagates in old concrete after this sort of pre-treatment only. After “needle hammer” treatment (Fig. 5c) individual aggregates on the fracture surface can no longer be resolved. Therefore the surface structure of this sort of specimen is very different from that after “sand blast” treatment.

After “no” (Fig. 5a) and “emulsion” treatment (Fig. 5d) the fracture surfaces are unstructured and flat. Though the macroscopic appearances of section Fig. 5a and Fig. 5d are similar, they are microscopically different: Fig. 5a shows microporosity whereas this is absent in Fig. 5d, showing a flat fracture surface which appears glossy.

Correlating the roughness of the fracture surfaces with the G_F values, one may recognise the following coincidence. Rough fracture surfaces and those with many microcracks are characterized by high G_F values, whereas glossy fracture surfaces with only few microcracks correlate with low G_F values.

5. Discussion

The old–new concrete bond has been characterized mechanically by measuring the strain-softening curve with the procedure described above. The maximum load and the fracture energy G_F have been determined from the strain-softening curve. With the notched-bar tensile test, the notch tensile strength may be obtained from the maximum load. Due to its well defined testing conditions, this testing method is characterized by low scattering of the test results for maximum load or notched-bar tensile strength in comparison with test results from tear-off tests. The value of the fracture energy (G_F) allows one to estimate the value of the "ductility" during rupturing of the bond of old–new concrete. This form of ductility is the higher the more microcracks are formed in the brittle inhomogeneous cement-bonded material, or in other words the larger is the fracture process zone.

During crack propagation in an interface of different cement-bonded materials, different sorts of fracture process zones may be formed. The extreme cases are the following:

(a) The fracture process zone is formed on one side of the material compound. All "deformation" is concentrated in this area, which means that the deformation capacity of this area is soon exhausted so that the material compound will soon be separated at the weakest area. Little energy will therefore be needed for crack propagation until the material is separated completely, owing to the small "deformation volume".

(b) The fracture process zone is formed on both sides of the material compound. The "deformation volume" is therefore larger, which means that more energy is necessary for driving the crack.

In practice these two extreme cases will not occur alone for old–new concrete bonds with differently prepared old-concrete surfaces. To the authors' knowledge, it is not at present sufficiently known which parameters or material values determine whether the crack will propagate according to (a) or (b). The most important parameters are probably the "ductility" (capability of forming microcracks without complete separation), the adhesion of the two materials, the geometrical form of the interface (peak-to-valley height), as well as the microstructure and porosity of the interfaces. Another influence may be expected from surface layers which are attached to the old concrete (e.g. plastic dispersions and other plastic layers), as these can influence the formation of the shape and size of the fracture process zone.

A detailed analysis of the cracking process of old–new concrete with different pre-treatments and different adhesive bond layers allows an understanding of the mechanisms. Fracture models are developed now which should help to answer these open questions [16].

The results of this work show that the strain-softening curve for stable crack propagation may be determined for an old–new concrete compound with a testing procedure [12] similar to the procedure for homogeneous concrete specimens [13]. The curves which characterize the material can therefore be used for numerical calculations of the crack growth behaviour in a similar manner as for homogeneous concrete. This means that the mechanical behaviour of cracked material compounds can easily be determined with this testing method (e.g. tension strength and crack opening displacements at different loads). This possibility seems to be of interest for practical problems in the field of civil engineering.

It remains an open question to determine the influence of specimen size on the strain-softening curves and on the fracture energy. This problem has not been studied so far, though measurements on homogeneous concrete pieces have shown that an influence of specimen size exists and is mainly dependent on the concrete aggregate size. It may be expected that the influence of specimen size is small owing to the rather small fracture process zone of material compounds in comparison with homogenous concrete. An experimental examination of this question is planned.

Besides using the strain-softening curve described above to characterize interface cracks in compounds of cement-bonded materials, crack resistance curves (R-curves) in the LEFM concept (K versus Δa) or in the J-concept (J versus Δa) may be used. A major problem in applying these concepts to concrete and cement-bonded materials is that the crack length and crack increment cannot be determined too exactly. Problems and rather large statistical errors are quite common when crack lengths in concrete and cement-bonded materials are measured. Therefore, all concepts are problematic which have to work with an assumed certain crack length for usual construction parts. Contrary to this, crack length or crack increment do not enter into the measurement when the fracture energy (G_F) concept is used; this is very advantageous. On the other hand, calculation with the fracture energy concept has to be performed numerically, which is considered as a drawback of this method.

The procedure described opens the possibility for construction engineers to perform measurements of maximum load and fracture energy G_F of compounds of cement-bonded materials. Certainly this represents some progress compared with conventional procedures: the procedure described is performed easily, is inexpensive and needs only simple and inexpensive specimens (e.g. cubes or cylinders).

6. Conclusions

1. The testing procedure [12] is appropriate to characterize compounds of cement-bonded materials

mechanically. Specimens are notched cubes or cylinders, which are easily and inexpensively produced. The testing procedure is simple and can be performed in a straightforward and inexpensive way.

2. The testing sequence is first to determine the strain-softening curve. Then from this the maximum load (and from this the notch tensile strength) and the fracture energy (G_F) are obtained. The course of the strain-softening curve may be considered as a sort of characterization of the mechanical behaviour of the material compound and is an important basis for numerical calculations.

3. The standard deviation of the measured values is on average 4% and is essentially lower compared with other procedures which characterize material compounds (e.g. the tear-off test).

4. The influence of pre-treatments of old concrete surfaces before producing the compound was studied with treatments "no", "sand blast", "needle hammer" and "emulsion". As to the maximum load, the treatments "no", "sand blast" and "needle hammer" lead to similar values, whereas a value about 25% lower is obtained after an "emulsion" treatment. "Sand blast" and "needle hammer" reveal similar fracture energy (G_F) values, whereas the values after "no" and "emulsion" are only about 60% of the "sand blast" values.

5. If the maximum load and fracture energy of interface specimens are compared with values obtained from homogeneous concrete with the same testing procedure, the following result is found: the maximum load after "sand blast", "needle hammer" and "no" treatments is about 50% of the value for homogeneous concrete. On the other hand the fracture energy values of compound specimens with "sand blast" and "needle hammer" treatments are about 25% and with "no" and "emulsion" about 10% of the value for homogeneous concrete.

6. These results demonstrate that measurement of maximum loads alone does not constitute a reliable base for classifying the adhesive power of bonds and for predicting the cracking behaviour of concrete-bonded materials. It is necessary to measure fracture energy (G_F) values, in a way such as that demonstrated in this work.

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