INFLUENCE OF THE AGGREGATE-MATRIX INTERFACE ON THE FRACTURE BEHAVIOUR OF CONCRETE

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ABSTRACT

The aggregate-matrix interface plays a major role in the fracture mechanisms and in the fracture response of concrete. In this work the influence of the interface on the macroscopic fracture parameters of concrete is investigated. Eleven concrete batches were cast with the same matrix. Different –crushed or rounded– aggregates from the same quarry were used, and several surface treatments were applied to improve or degrade the bond between the matrix and the particles. Fracture tests (three point bending tests and Brazilian splitting tests) were carried out to determine the fracture energy and other relevant fracture parameters of the concrete batches. The modulus of elasticity and the compressive strength were obtained by uniaxial compression tests. The macroscopic fracture behaviour was modeled by the cohesive crack model with a bilinear softening curve. The results show that concretes with the same matrix and aggregates, and similar behaviour under uniaxial compression, can give very different fracture responses. The work shows how the fracture behaviour is governed by the interfacial properties that are also behind the cracking mechanism.

INTRODUCTION

Plain concrete is a heterogeneous material formed by the combination of a hardened cement paste and rocky particles. From a mechanical point of view, plain concrete can be considered as a two-phase material made of a cement-based matrix (mortar) composed of the cement paste and the fine aggregates, and a particulate reinforcement (coarse aggregates). This approach is useful when analyzing the influence of the aggregates on the mechanical performance of concrete, particularly on the fracture behaviour, which is known to be affected by the size, shape and grading of the coarser aggregates.

In recent years many experimental studies have examined the influence of aggregates on the fracture parameters of concrete, mainly concentrating on the effects of the maximum aggregate size and on the quality of the aggregate [1].

In this paper experimental results are presented to show the influence of the aggregate-matrix interface on the fracture parameters of concrete. The influence of the shape of aggregates –usually affecting the interfacial strength– is also investigated. The macroscopic fracture behaviour of concrete is characterized by means of the cohesive crack model [2], which has shown its utility in modeling the fracture process in concrete and concrete-like materials when the failure mode is governed by a single macrocrack [3]. Using the cohesive crack model as a framework, the effect of the interface on the tensile strength, f_t, on the fracture energy, G_F, and on the complete softening curve is given in the paper.

MATERIALS AND TESTS

Materials and specimens

Concrete specimens were made with ordinary Portland cement (ASTM Type I) and siliceous aggregates. Silica sand with a grading within ASTM C33 standard limits and maximum size of 2 mm was used as fine aggregate for the matrix. The coarse aggregate was formed of rounded or crushed granite particles from a single size fraction of 5-7 mm. To preserve the properties of the parent rock, the crushed particles were obtained by grinding oversized fractions of rounded aggregates.

Eleven batches were cast, as summarized in Table 1. The volume fraction of coarse aggregate was kept constant for all the batches and equal to 40% . Two different matrixes, normal (N) and modified (H), were used to propitiate or inhibit the debonding of the aggregates. The cement, sand and water content of the two matrixes are given in Table 2, which also shows the use of a superplasticizer (Sikament®300) to improve the workability. Silica fume was added to matrix (H) to enhance the bond between the matrix and the aggregates

Three surface treatments were used to improve/weaken the interface between the coarse aggregates and the matrix. Bitumen and paraffin coatings were applied to reduce the bond, and an epoxy resin to increase it. All the coatings were dosed by weight, equal to 5% of the coarse aggregate. In addition, two shapes for the coarse aggregate –rounded and crushed– were used.

Four prismatic specimens of 40x40x180 mm^3 were cast from each concrete batch. After demoulding, samples were stored under lime-saturated water at 20±3 C to prevent microcracking until the time of the test. Before testing, a central notch 2 mm wide was sawn up to 25% of the specimen depth (10mm).

Mechanical Characterization

Three point bend tests on quarter-notched beams were performed according the RILEM method [4], enhanced with some additional suggestions by the authors [5-7]. Beams of 40mm depth were tested on bending, with a span to depth ratio equal to 4. During the test, load-point displacement and crack mouth opening displacement (CMOD) were continuously recorded From these tests the fracture energy, G_F, the critical crack opening, w_c , and the shape of the bilinear softening curve were determined following the method proposed by the authors [8].

Compression tests were performed according to ASTM C39 and ASTM C469 standards to measure the compressive strength, f_c, and the modulus of elasticity in compression, E_c. The test specimens were prisms 40x40x80 mm^3 cut from the broken halves of the bending tests.

Brazilian splitting tests to measure the tensile strength, f_t, were conducted on 40x40x40 mm^3 cubes also cut from the specimens tested in bending. The splitting tests followed the guidelines prescribed in the ASTM C496 standard except for the size of the specimen and the width of the load-bearing strips, which was equal to 3mm –7.5% of the specimen depth–. Previous work by the authors has shown that the standardized width of 16% of the specimen depth is usually too high, and can lead to an erroneous estimation of f_t [9].

TABLE 1

COMPOSITION OF THE CONCRETE BATCHES

Batch	Aggregate Coating	Matrix	Aggregate Shape
N	-	Normal	-
H	-	Modified	-
NEC	Bitumen Emulsion	Normal	Crushed
NPC	Paraffin	Normal	Crushed
N0C	None	Normal	Crushed
NXC	Epoxy Resin	Normal	Crushed
NER	Bitumen Emulsion	Normal	Rounded
NPR	Paraffin	Normal	Rounded
N0R	None	Normal	Rounded
H0C	None	Modified	Crushed
H0R	None	Modified	Rounded

TABLE 2

MIX PROPORTIONS

Matrix	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)	Silica fume (kg/m^3)	$\frac{\text{Water}}{\text{Cement +Silica fume}}$
Normal (N)	832	1121	274	25	-	0.33
Modified (H)	750	1121	274	23	83	0.33

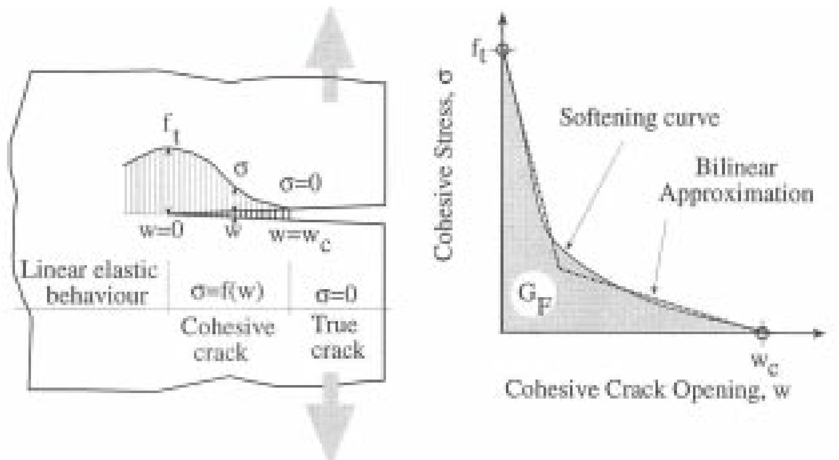

Figure 1: Cohesive crack and softening function.

FRACTURE CHARACTERIZATION

Macroscopic behaviour: The cohesive crack model

The cohesive crack model simulates the micro cracking and deterioration of the material in the fracture process zone [2]. This zone is modeled by means of a cohesive crack, which can transfer stress –the cohesive stress– from one face to the other. For a crack monotonically loaded in mode I –which is the most common testing situation– the cohesive stress at a given point σ is normal to the crack faces and is uniquely given by the softening curve as a function of the crack opening at this point w, $\sigma=f(w)$, as shown in Figure 1. The softening function is considered *by hypothesis* to be a material property, independent of geometry and size. The basic properties of a cohesive crack are reviewed in [3]. The stress at the tip of the cohesive crack is equal to the tensile strength of the material, f_t, and decreases progressively to zero when the crack reaches the critical crack opening w_c. The work done to produce a unit area of true crack –stress free– is the fracture energy, G_F, and coincides with the area under the softening curve. To simplify the computations, the bulk behaviour is assumed to be linear-elastic, although this approximation can be relaxed if necessary.

In this work the softening function is approximated by a bilinear function, shown in Figure 1. This simple diagram suffices to describe the pre-peak as well as the post-peak behaviour of the material, as already shown [10]. The four parameters needed for the bilinear approximation can be easily determined following the fit procedure by the authors [8], which makes use of the results of stable three point bending tests on notched beams and the Brazilian splitting test. The basic mechanical properties of the 11 batches investigated are given in Table 3. In the next section the fracture properties are analyzed in relation to the quality of the interface between matrix and aggregates.

TABLE 3

MECHANICAL PROPERTIES OF THE CONCRETES INVESTIGATED.
MEAN VALUES AND 68% CONFIDENCE INTERVAL.

Batch	f_c (MPa)	E_c (GPa)	f_t (MPa)	G_F (J/m^2)
N	71.1±0.2	34.3±0.1	4.00±0.10	67.2±2.0
H	67.6±0.6	31.4±0.3	4.04±0.09	69.5±1.2
NEC	21.0±0.3	19.7±0.7	2.19±0.03	125.8±6.3
NPC	36.1±1.3	25.6±0.6	2.99±0.10	141.1±9.0
N0C	73.2±2.0	33.1±0.8	4.15±0.05	136.0±4.8
NXC	67.0±0.9	34.3±0.3	4.16±0.08	134.3±6.3
NER	21.9±0.5	22.5±0.5	2.46±0.07	67.8±2.5
NPR	41.5±0.8	33.7±0.6	3.11±0.04	77.0±6.7
N0R	63.8±2.6	39.8±1.0	3.93±0.05	94.7±5.7
H0C	87.5±0.3	34.7±0.5	4.89±0.12	127.5±6.6
H0R	67.6±3.5	40.0±0.4	4.93±0.10	87.1±3.8

TABLE 4

CHARACTERIZATION OF THE CRACKED SURFACES
MEAN VALUES AND 68% CONFIDENCE INTERVAL.

Batch	% Broken	% Debonded	R_a(mm)	R_q(mm)
N	–	–	0.306±0.001	0.388±0.007
H	–	–	0.495±0.024	0.595±0.029
NEC	3.4±0.5	46.6±0.9	Not Measured	Not Measured
NPC	6.2±1.0	38.6±2.1	0.901±0.080	1.097±0.070
N0C	17.3±1.2	18.1±1.6	1.146±0.169	1.338±0.183
NXC	12.0±1.4	27.2±1.5	Not Measured	Not Measured
NER	3.7±0.6	48.6±0.1	Not Measured	Not Measured
NPR	4.8±1.0	38.3±1.9	1.075±0.218	1.278±0.241
N0R	12.0±0.4	27.4±1.7	0.972±0.013	1.177±0.007
H0C	22.2±1.2	9.5±0.9	0.577±0.081	0.708±0.100
H0R	12.0±1.5	25.0±0.7	0.972±0.013	1.177±0.007

$$R_a = \frac{1}{L}\int_0^L |z(x)|\, dx \quad , \quad R_q = \sqrt{\frac{1}{L}\int_0^L z^2(xdx} \qquad \text{with} \qquad 0 = \int_0^L z(x)\, dx$$

Crack surface characterization

The cracked surfaces of the specimens tested under three point bending were analyzed to obtain their composition and topography. The projected area of broken and debonded particles were optically measured on all the specimens tested and the results are given in Table 4. The topographic analysis of the crack surfaces was performed by means of a laser profilemeter. Ten profiles, 3mm spaced and parallel to the crack front, were measured on one of the cracked halves of the specimens. The profile points were recorded every 20μm along the path, with a resolution of 3μm in height. From these values, the average roughness, R_a, and the RMS roughness, R_q, were calculated for every concrete batch, as shown in Table 4.

RESULTS AND DISCUSSION

Cracking mechanism

Figure 2 shows the fraction of broken particles of coarse aggregate for the 11 concretes fabricated. The area of broken particles increases as the interface becomes stronger. The minimum area of broken particles –the maximum debonded area– is obtained in concretes with a weak interface produced by coating with bitumen or paraffin. In these concretes most of the aggregates –up to 93%– debond during the fracture process, irrespective of whether they are rounded or crushed. The natural interface between the siliceous aggregate and the mortar was seen to be a strong joint, even more than when the aggregate is coated with epoxy resin. The use of matrix H produces the higher fractions of broken areas for both crushed and rounded particles. The extreme situation is reached for H0C concrete, with crushed aggregates, in which the debonded area is reduced by up to 30% of the total area of particles present in the crack surface.

The roughness of the cracked surfaces is not well correlated with the main cracking mechanism –breaking or debonding of the aggregates– as is deduced from Table 4. Concretes with the same matrix N and rounded or crushed aggregates show contrasting behaviour: in batches with rounded particles, R_q remains constant or slightly lower when the interface becomes stronger and the broken fraction of particles increases, whereas the opposite trend is observed in concretes with crushed aggregates.

Tensile Strength

Figure 3 shows the influence of the interface on the tensile strength. For the ordinary matrix (N) the modification of the bond between the particles and the matrix makes f_t vary by a factor close to 2, and the matrix strength seems to be the upper limit as reported in other published works [11]. Results in Figure 3 suggest that the effect of the interface is appreciable only when the fraction of broken particles is fewer than 20%; otherwise f_t is practically unaffected. No significant differences come up in relation to the use of crushed or rounded aggregates. A remarkable fact from Figure 3 not usually reflected in the literature, is that the use of an adherent matrix (H) can improve f_t to well over the matrix strength.

Fracture energy

The strength of the interface affects the fracture energy in different ways depending on the shape of the particles. This is shown in Figure 4 where concretes with crushed aggregates have a higher G_F, as stated by the authors in a previous work [11]. For this kind of concrete, the interface has no influence on the fracture energy, possibly due to fact that the decrease in energy consumption by the interfaces is offset by the interlock mechanisms at the end of the softening curve (revealed by a larger critical crack opening, w_c). A less efficient interlock mechanism for the concretes with rounded particles –which have shown lower values of w_c– will result in a reduction of G_F when the fraction of debonded aggregates increases, as is shown in Figure 4. In all the batches, the addition of strong particles to the matrix improved the fracture energy, and this effect was particularly important in concretes with crushed aggregates, where G_F was multiplied by 2 in relation to the matrix.

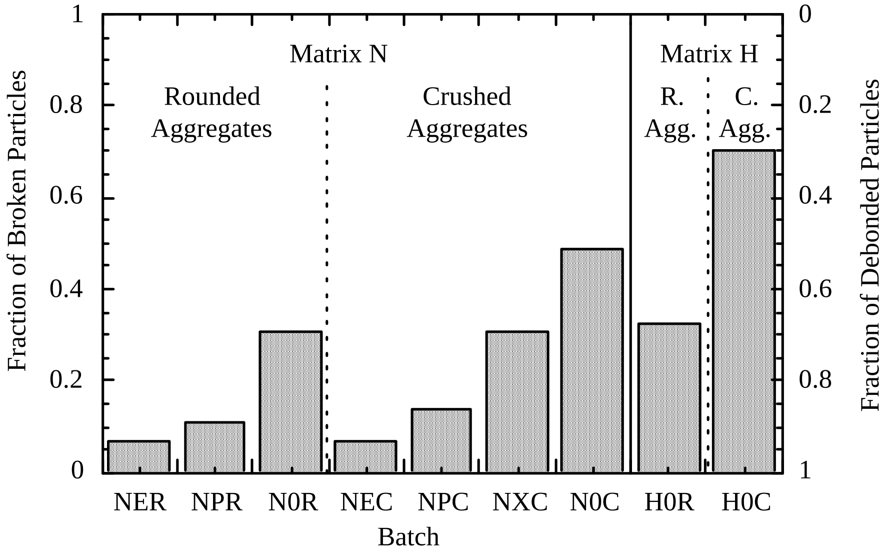

Figure 2 : Fraction of broken/debonded particles in the concretes investigated.

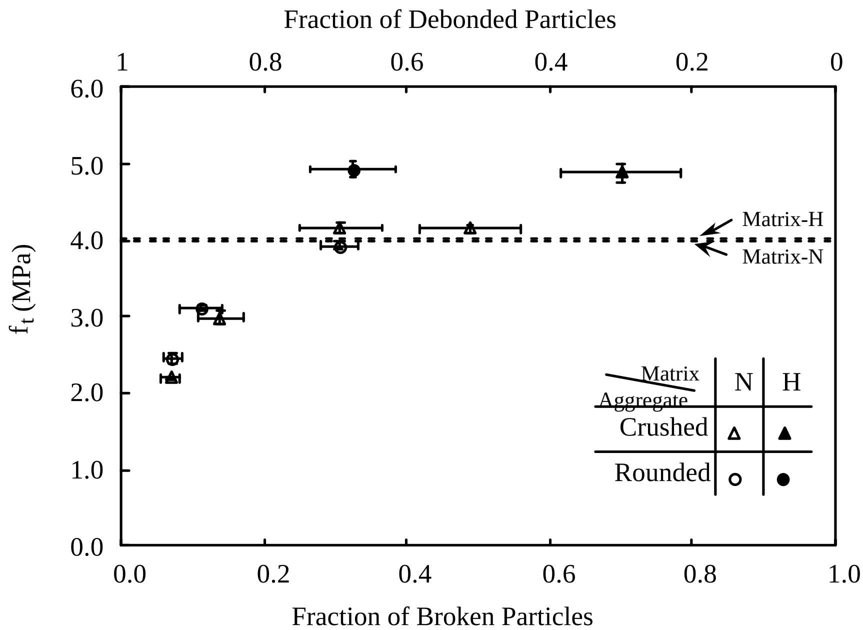

Figure 3 : Variation of the tensile strength with the fraction of broken particles

Critical crack opening

The dependence of w_c on the matrix-aggregate interface is shown in Figure 5. For both crushed and rounded aggregates w_c decreases as the fraction of broken particles increases, approaching the value corresponding to the matrix that appears to be the lower bound. This behaviour is congruent with an increment of the interlock mechanism produced by the debonding of aggregates. Concretes with debonded crushed aggregates, where the interlock is extreme, show the larger values of w_c up to 3.5 times greater than that of the matrix. The critical crack opening, w_c, seems to be correlated with R_q, in spite of the large scatter present.

Softening curve

Figure 6 plots the non-dimensional softening function for two concretes with extreme behaviour : the NEC concrete batch, with most of the particles debonded (93%), and the N0C batch where a large number of the aggregates were broken (49%). Figure 6 also shows the softening curve corresponding to the common matrix N. The initial part of the softening is very similar in the two concretes and the mortar matrix. The differences emerge at the tail of the softening curve where the concrete with the weaker interface displays a larger critical crack opening.

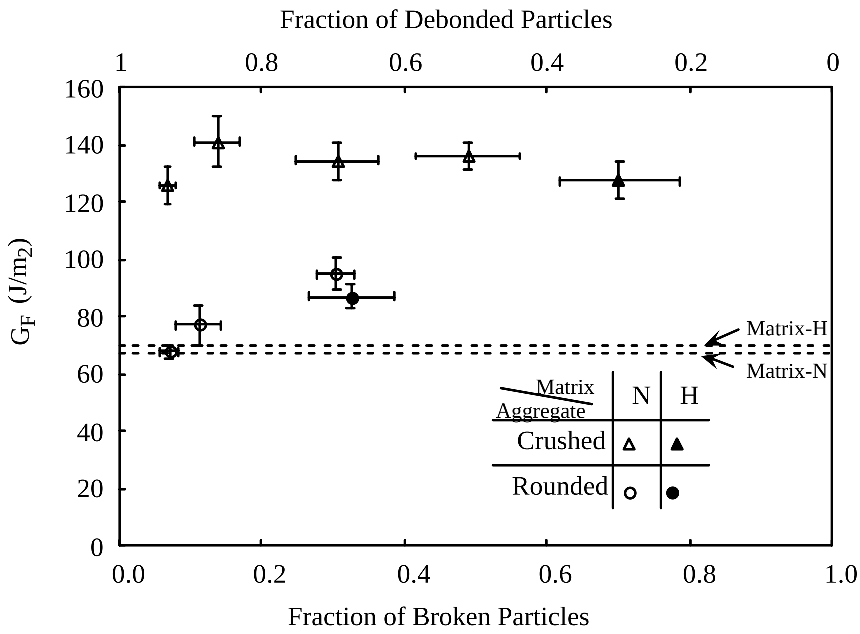

Figure 4 : Variation of the fracture energy with the fraction of broken particles

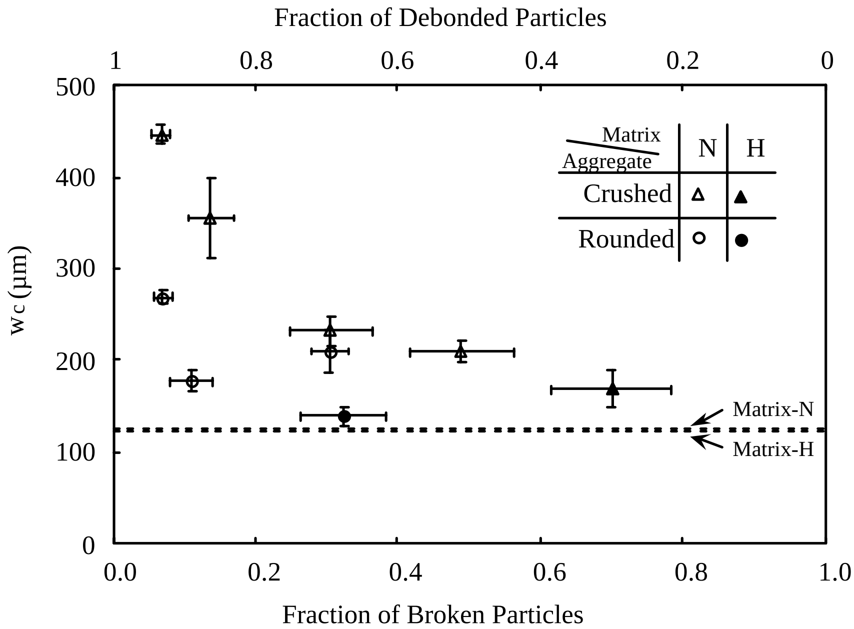

Figure 5 : Variation of the critical crack opening with the fraction of broken particles

CONCLUSIONS

This experimental work shows the influence of the interface between matrix and aggregates on the fracture properties of concrete. The conclusions may be summarized as follows:

- The tensile strength, f_t, can vary by a factor close to 2 depending on the interface. It appears that a weak interface has a marked effect only when the broken particles are under 20%. The use of an adherent matrix can improve f_t to well over the matrix strength.

- Concretes with crushed aggregates show a higher value of G_F, and the interface has no noticeable effect, possibly due to a more pronounced interlock at the end of the softening curve which compensates the loss of energy consumption in weak interfaces. This effect is not observed in concretes with rounded particles.

-The critical crack opening decreases when the interface is strong, approaching the value corresponding to the matrix, and increases when the crack is rough.

-The initial part of the non-dimensional softening curve seems to be controlled by the matrix. The interface between matrix and aggregates influences the tail of the softening with higher values of the dimensionless critical crack opening, $w_c f_t/G_F$, when the bond is feeble.

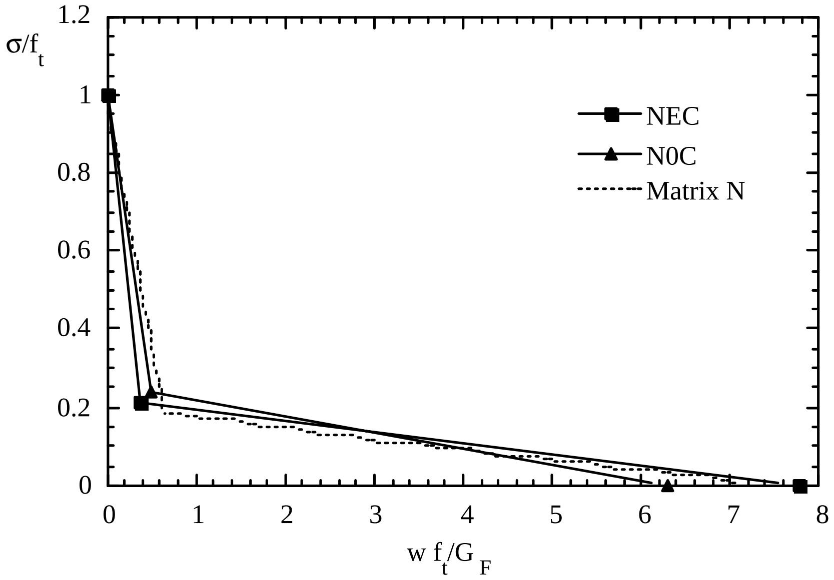

Figure 6 : Influence of the interface of crushed aggregates on the softening curve.

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