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Failure Mechanism of Concrete

Combined Effects of Coarse Aggregates and Strength Level

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Concrete is a composite, and its properties depend on the properties of the component phases and the interaction between them. It is known that the interfaces are the weakest link in concrete, playing a very important role in the process of failure. This process is strongly related with the characteristics of the aggregates (especially coarse aggregates) and with the relative differences in strength between matrix and inclusions. This paper analyzes the mechanical behavior of high strength and conventional concretes prepared with coarse aggregates having significant differences in strength, shape and surface texture, porosity and absorption, and interface bond strength. Two different gravels and two different crushed stones were used. Concrete mixtures with water/cement ratios of 0.30 and 0.50 were designed. The effects of aggregate type and strength level on concrete failure mechanism, including tensile and compressive strength, stiffness, energy of fracture, and crack pattern, are discussed. Advanced Cement Based Materials 1998, 7, 41–48. *© 1998 Elsevier Science Ltd.*

KEY WORDS: Aggregate, Bond strength, Composite material, Compressive strength, Concrete, Crack propagation, Energy of fracture, Failure mechanism, High strength concretes, Interfaces, Tensile strength

The heterogeneous and multiphase characteristics of concrete and their direct influence on its mechanical behavior and durability have been recognized for many years. Recently, new and diverse methodologies have been applied to analyze crack formation and propagation in concrete.

Concrete is a composite, and its properties depend on the properties of the component phases and the interaction among them. Many studies on the different variables that modify cement paste-aggregate bond have been done [1–3], most of them on the interfaces of composite specimens especially designed for that purpose. Different techniques were used, including mechanical tests, analysis of the microstructure and compounds through scanning electron microscopic observations, X-ray diffraction, etc.

Aggregate surface texture is one of the most important factors affecting bond strength; rough surfaces usually have a higher bond than sawn surfaces. But it is much more difficult to study the interfaces with concrete, as new phenomena such as different stress concentration, microcracks, etc., that do not always exist in composite specimens (i.e., microcracks due to drying shrinkage or thermal changes) appear. In addition, in the composite many characteristics of the aggregates affect properties in fresh concrete, which later will modify the behavior of hardened concrete. For example, shape and texture change the workability, inducing differences in consolidation; similarly, any difference in fluidity of the matrix will result in a significant change in bond strength [1]. As a result, the analysis of the effect of any particular characteristic of the aggregate in concrete is more complex as aspects of fresh or hardened concrete are superposed, making it difficult to compare the effect of an isolated variable given the superposition with others.

There is general agreement about the importance of the matrix-aggregate bond. It is known that the transition zones (interfaces) are the weakest link of the composite material, playing a very important role in the process of concrete failure, as crack growth usually starts at the matrix-aggregate interfaces. Generally, the critical interfaces are those between coarse aggregate and mortar, which is why this level was selected for the following analysis.

Crack propagation usually starts at the interfaces, and the cracks grow through the matrix. Coarse aggregates arrest crack growth, producing meandering and branching of cracks, and some particles are fractured. This mechanism depends greatly on the characteristics of the aggregate, especially surface texture and shape, and on the strength differences between aggregates and matrix. Thus, the type of coarse aggregate is one of the most important variables affecting the behavior of high strength concretes (HSC) [4–6].

This paper analyzes the behavior of HSC and conventional concretes (CC) prepared with coarse aggregates having significant differences in mechanical prop-

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TABLE 1. Characteristics of the coarse aggregates

Aggregate	GCS	QCS	SRG	GRG
Absorption (%)	0.80	2.13	0.70	1.10
Flakiness index (%)	64	24	2	22
Elongation index (%)	33	17	23	24
Los Angeles abrasion (%)	22.3	61.5	19.8	16.4
Density	2.65	2.48	2.60	2.65
Rock strength				
Compression (MPa)	114	86	—	—
Flexure (MPa)	15.5	14.8	—	—
Estimated strength, punctual loading				
Compression (MPa)	190	130	180	190
Tensile (MPa)	14	10	14	12

erties, shape and surface texture, porosity and absorption, and bond strength.

Experimental

Materials

Concretes were prepared using two types of cements (ordinary Portland cement for CC and high early-strength cement for HSC) and natural siliceous sand. A naphthalene based superplasticizer was used in HSC.

Four different types of coarse aggregates were used: granitic crushed stone (GCS), quartzitic crushed stone (QCS), siliceous river gravel (SRG), and a river gravel composed of particles of different types of rocks (GRG). These aggregates were selected because they present significant differences in mechanical properties, shape and texture, and bond strength. The same particle size distribution was adopted with a maximum aggregate size of 19 mm. The GCS presents irregular shape, rough texture, and low absorption. The QCS also has an irregular shape and rough texture, and it has the highest water absorption and the lowest strength. Aggregate SRG is a natural siliceous river gravel composed of strong particles with smooth surface and low porosity, whereas gravel GRG is composed of round particles of many different types of rocks (granite, migmatite, basalt, etc.) with a rough surface texture and higher porosity. Table 1 presents the characteristics of these aggregates including results of water absorption (24 hours), shape indexes [7], density, resistance to abrasion (Los Angeles), and strength. Tensile and compressive strength were estimated from punctual loading tests [8,9]. In the case of crushed stones, the compressive and flexural strength of the rock were also measured on drilled cores (100 × 200 mm) and sawn prisms (25 × 25-mm section), respectively.

The use of these coarse aggregates in concrete makes possible the analysis of the differences produced in concrete behavior by the changes in the shape of the aggregate and matrix-aggregate bond. The use of different water/cement ratios shows some interesting aspects related to the effect of aggregate characteristics on concrete failure mechanism.

Figure 1 shows matrix-aggregate bond strength (IMR) developed by the different types of rocks when mortar matrices with flexural strength (MMR) from 4 to 11 MPa are used. Bond strength was measured on specimens consisting of half aggregate and half mortar [1,10]. Flexural tests were performed with a mid-point loading system. As strength increases, the differences in bond strength due to the different surface textures increase. It is possible to see that quartzitic rocks (Qc) show the highest values of bond strength due to their surface texture and absorption. They are followed by granitic rock with rough surface (Gc). Rock surfaces were carefully sanded to obtain a surface texture similar to that of the respective crushed aggregates. Finally, a granitic rock with diamond sawn surface, not sanded

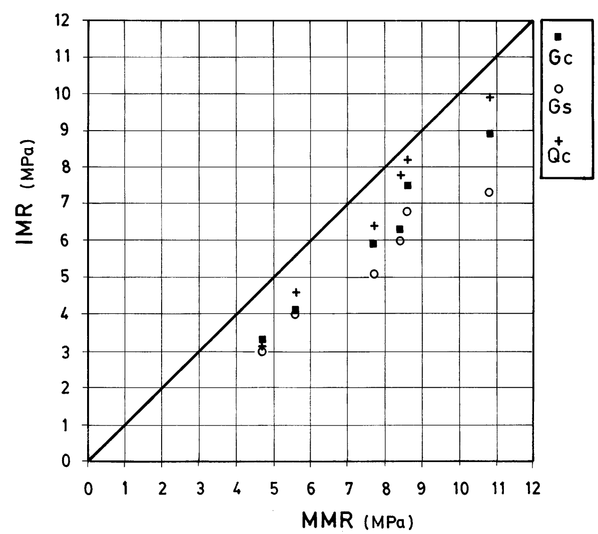

FIGURE 1. Variation of interface modulus of rupture (IMR) with mortar modulus of rupture (MMR) for rocks with different surface textures.

TABLE 2. Mixture proportions (kg/m^3)

Concrete	GCS-3	GCS-5	QCS-3	QCS-5	SRG-3	SRG-5	GRG-3	GRG-5	M-3	M-5
Water	144	175	153	180	144	167	144	170	180	242
Cement	480	360	495	375	480	348	480	355	600	500
Fine aggregate	780	825	735	815	780	825	780	825	1470	1335
Coarse aggregate	970	1000	920	940	980	1010	980	1030	—	—
Superplasticizer (%)	2.5	—	3.0	—	1.8	—	2.0	—	2.4	—
Water/cement ratio	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5
Slump (mm)	45	65	125	45	120	110	80	140	—	—

(*Gs*), representing SRG aggregate, which has the smoother surface texture and lower absorption, was tested. This rock achieves the lowest values of bond strength. It must be noted that in all cases fluid mortars were used, as this consistency is characteristic of HSC matrices. The bond strength of matrices with lower fluidity may be smaller [1].

Mixture Proportions

HSC and CC were prepared with each type of coarse aggregate. Mixture proportions are shown in Table 2. In a complementary way two mortars (M) with the same water cement/ratio were also made.

Testing Methods

Cylinders of 100 × 200 mm were used to evaluate compressive strength, modulus of elasticity, and splitting tensile strength. Beams of 70 × 70-mm section with 270-mm span and central point loading were adopted to evaluate flexural strength (modulus of rupture).

Specimens were stored in a moist room (20°C, 90% RH) until the time of testing with the exception of 24-hour tests. The determination of G_F was performed according to the RILEM 50-FMC Committee recommendation using 100 × 100 × 840 sawn notched beams (span 800 mm and notch depth 50 mm) [11]. Tests were performed on a deformation-controlled testing machine. Major details of the testing procedure have been presented previously [12].

Results and Discussion

Table 3 presents the most significant properties of hardened concretes. To facilitate the discussion of test results, Table 4 summarizes the notations used. Compressive strength, modulus of elasticity, flexural strength (central point loading), and splitting strength were measured up to 180 days. In addition, energy of fracture (G_F) tests were performed at 28 days. The mechanical properties of the mortar were only measured at 28 days. The values given are the mean of four tests. The coefficients of variation were on the order of 4% for compressive tests, 5% for flexural tests, and 11% for splitting tests. In the case of G_F they were on the order of 10% for mortars and 20% for most concretes, with the exception of QCS concretes for which it was only 6%, indicating a more homogeneous fracture behavior.

Figure 2 shows the results of compressive strength obtained for the different concretes. As expected, the relative evolution of strength is higher in CC than in HSC, due to the different types of cements and the porosity of the mixes (water/cement ratio). It must be noted that CC prepared with the QCS (which develops the highest bond strength) achieves the highest compressive strength.

In HSC the differences produced by the type of coarse aggregate were greater than in CC. At this strength level, due to the shape and surface texture of the aggregates, concretes prepared with gravels have smaller compressive strengths than concretes including crushed stone. When SRG is used, which has a very smooth surface texture, the concrete achieves the smallest values of compressive strength. In the case of concretes incorporating crushed stones, from early ages up to 28 days QCS-3 has the highest compressive strength, but at 180 days, although it has higher bond strength, it shows lower compressive strength than GCS-3. In this case the strength of the quartzitic rock becomes a limit for concrete strength.

Regarding crack pattern, it can be seen that there also appear some differences in the characteristics of concrete failure surfaces. In HSC when SRG (smooth surface) is used, crack growth easily starts at the interfaces and continues through the matrix. As a result, fractured surfaces usually present extensive bond failure and no fractured aggregates. In the case of concretes prepared with GRG, the occurrence of cracking through aggregates increases; nevertheless, not many fractured aggregates can be seen. Finally, in concrete incorporating QCS, an excellent bond strength develops between matrix and aggregates. As a consequence, cracks do not necessary start at the interfaces, they develop through matrix and aggregates, most aggregates are broken, and fracture surfaces become less tortuous. In GCS the occurrence of fractured aggregates is greatly reduced.

TABLE 3. Test results

Series	Age (days)	*f′c* (MPa)	*E* (GPa)	*MR* (MPa)	*ft* (MPa)	G_F (N/m)	f_{net} (MPa)	δ_0 (mm)	l_{ch} (mm)
GCS-3	1	45.1	41.9	6.7	4.3				
	3	53.9	43.5	8.4	5.4				
	7	60.6	47.3	10.0	5.8				
	28	74.6	48.4	10.5	5.7	215	7.6	1.6	310
	180	92.3	52.5	10.5	5.7				
QCS-3	1	34.9	33.0	6.2	3.5				
	3	54.9	37.5	7.7	4.4				
	7	67.1	38.5	8.9	4.8				
	28	79.4	38.8	9.9	5.0	135	6.3	1.0	210
	180	81.3	37.2	10.4	5.3				
SRG-3	1	34.8	42.7	6.3	3.4				
	3	43.4	45.9	7.3	3.8				
	7	51.9	49.3	8.5	3.9				
	28	61.4	49.7	9.6	4.3	170	5.4	1.4	455
	180	64.6	51.9	9.8	4.4				
GRG-3	1	35.2	37.0	7.1	3.5				
	3	46.5	40.8	7.4	3.8				
	7	54.2	42.0	9.0	4.3				
	28	60.9	45.5	9.3	4.6	180	6.0	1.3	385
	180	69.1	47.1	9.5	4.5				
GCS-5	3	13.6	24.3	4.5	2.8				
	7	20.3	32.1	5.5	3.4				
	28	30.1	39.1	6.7	3.8	165	5.1	1.6	445
	180	38.7	41.7	7.4	4.0				
QCS-5	3	16.2	#	4.2	2.1				
	7	25.2	29.5	5.5	2.8				
	28	33.1	33.0	6.1	3.0	130	5.1	1.2	475
	180	48.0	35.4	7.4	3.5				
SRG-5	3	13.8	43.3	3.7	1.7				
	7	21.5	44.6	4.6	2.4				
	28	29.6	46.4	5.2	2.8	140	4.9	1.5	830
	180	39.2	47.4	6.9	3.1				
GRG-5	3	14.0	31.6	3.7	1.6				
	7	22.4	38.3	5.2	2.1				
	28	31.0	43.0	6.4	3.2	140	5.5	1.4	590
	180	43.6	41.6	7.7	3.6				
M-3	28	79.0	37.4	#	5.6	75	7.5	0.7	90
M-5	28	34.6	31.8	#	3.6	55	5.3	0.6	135

#Not measured.

In CC the fracture surfaces show a large number of interface (bond) cracks; this phenomenon increases as the adherence of the aggregate decreases. It must be noted that many fractures through aggregates were also seen in CC prepared with quartzitic aggregates.

Figure 3 plots the relationship between compressive strength and modulus of elasticity. As expected, concretes prepared with stiffer aggregates achieve higher values of modulus of elasticity. For the same compressive strength level, the elastic modulus of concretes prepared with different aggregate types varies around 15 GPa. SRG shows the highest values and QCS the lowest (which are similar to those of mortar).

Comparing the flexural strength it appears that, especially in HSC, quartzitic concretes have lower tensile strength than GCS concretes despite the highest bond of QCS. This fact is even more evident in fracture tests (G_F) where the differences in failure mechanism between QCS and GCS concretes are greater, as will be discussed later. Gravel concretes present the lowest values of flexural strength.

Figure 4a shows the relationships obtained between modulus of rupture and compressive strength (MR/f′c). It is known that this relationship decreases as concrete compressive strength level increases; the variation of this relationship is higher in CC than in HSC. Concretes prepared with the different aggregates behave in a similar way, with QCS-3 having the smallest relationship for HSC.

The variation of relationships between tensile splitting strength and compressive strength (ft/f′c) with compressive strength (Figure 4b) is similar to that one corresponding to flexural strength (Figure 4a), but GCS concretes achieve the highest values of splitting tensile

TABLE 4. Notations

Coarse aggregates	GCS	Granitic crushed stone
	QCS	Quartzitic crushed stone
	SRG	Siliceous river gravel
	GRG	River gravel from different types of rocks
Concretes	HSC	High strength concretes
	CC	Conventional concretes
	GCS-3	HSC (w/c = 0.30) prepared with aggregate GCS
	QCS-3	HSC (w/c = 0.30) prepared with aggregate QCS
	SRG-3	HSC (w/c = 0.30) prepared with aggregate SRG
	GRG-3	HSC (w/c = 0.30) prepared with aggregate GRG
	GCS-5	CC (w/c = 0.50) prepared with aggregate GCS
	QCS-5	CC (w/c = 0.50) prepared with aggregate QCS
	SRG-5	CC (w/c = 0.50) prepared with aggregate SRG
	GRG-5	CC (w/c = 0.50) prepared with aggregate GRG
Mortars	M-3	Mortar with w/c = 0.30
	M-5	Mortar with w/c = 0.50
	f′c	Compressive strength
	E	Modulus of elasticity
	MR	Modulus of rupture, flexural strength
	ft	Splitting tensile strength
	G_F	Energy of fracture
	f_{net}	Flexural strength of notched beams
	δ_0	Maximum displacement
	l_{ch}	Characteristic length

Note: w/c = water/cement ratio.

strength. Thus, it can be considered that aggregate shape and texture have a greater influence in splitting tests than in other tensile tests.

Fracture tests make it possible to obtain new elements for the analysis of the effect of coarse aggregate on the failure mechanism of concrete.

Figure 5 shows the variation of fracture energy and the characteristic length with concrete compressive strength. Figure 6 represents the ratio between load and maximum load vs. displacement curves of HSC and CC. Each curve corresponds to an individual test that best represents the mean behavior of the series.

It is known that the energy of fracture increases as concrete strength increases (Figure 5a); however, as with tensile strength, the increments in toughness decrease as the strength level increases. The energy of fracture varies with aggregate maximum size, always being greater in concrete than in mortar. For the same aggregate size, the energy of fracture depends on aggregate type, as its strength, stiffness, shape, and

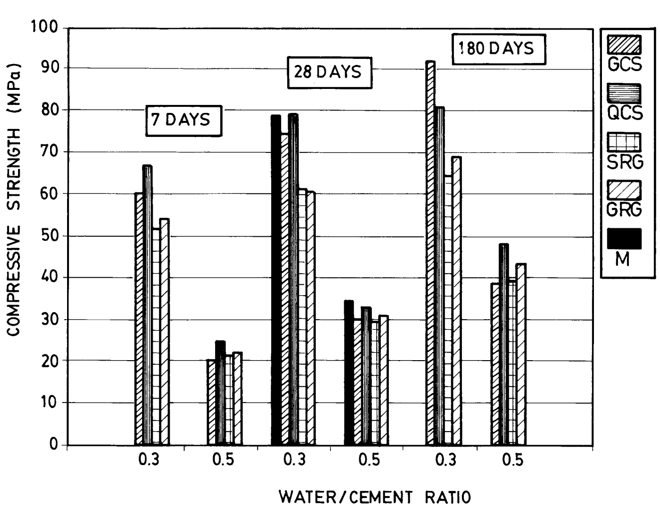

FIGURE 2. Compressive strength of concretes and mortars.

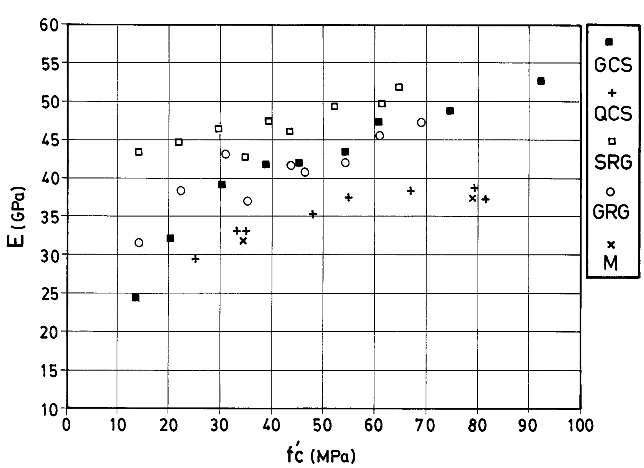

FIGURE 3. Variation of the modulus of elasticity (E) with the compressive strength (f′c).

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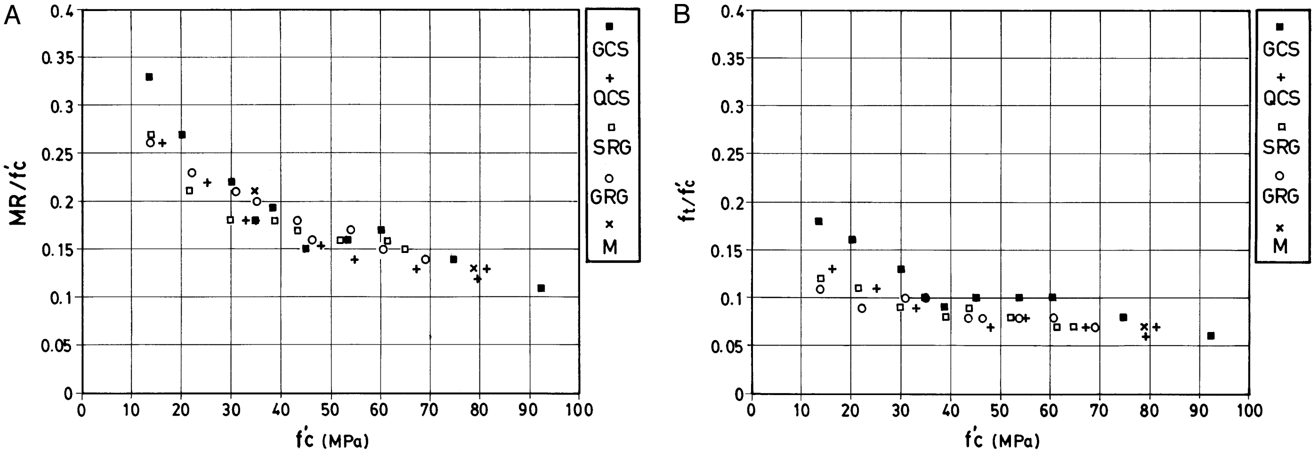

FIGURE 4. Variation of the relationship between tensile and compressive strength with compressive strength of concretes and mortars. (A) Flexural tests: MR/f′c vs. f′c. (B) Splitting tests: ft/f′c vs. f′c.

surface texture affect the fracture process. This can be observed especially in HSC. With regard to the sensitivity to cracking of the material, the characteristic lengths (Figure 5b) decrease greatly as concrete strength increases, with the values of HSC lower than those of CC.

The final displacement depends on the size and type of the aggregate, and it is always lower in mortar than in concrete. The highest values of δ_o are achieved by GCS concretes, probably because the shape and texture of this aggregate enhance the development of tortuous fracture surfaces. Concretes prepared with quartzitic aggregates have smaller δ_o, and gravel concretes show intermediate values. In general, for the same aggregate, final displacements are similar for concretes with different strengths, but δ_o tends to decrease from QCS-5 to QCS-3.

Differences in fracture behavior of CC and HSC are also observed in load-displacement curves (Figure 6).

In normal concrete, GCS-5 presents values of G_F substantially higher than the other concretes (on the order of 20%), probably due to a greater branching of cracks induced by sharp edges and surface texture of the aggregate particles. Gravel concretes show smaller final displacements and steeper softening branches. Concrete with quartzitic aggregates presents even smaller values of energy of fracture. These aggregates develop very high interface bonds, and although there is some crack branching, it is not significant. Consequently, there is a reduction in final displacement.

As strength level increases, different behaviors can be observed in concretes prepared with the different aggregate types. In mortar the increment in G_F mainly appears due to the increase in strength. In concrete with GCS the energy of fracture increases and the final displacement is similar, but there is a steeper gradient in the softening curve that can be attributed to the

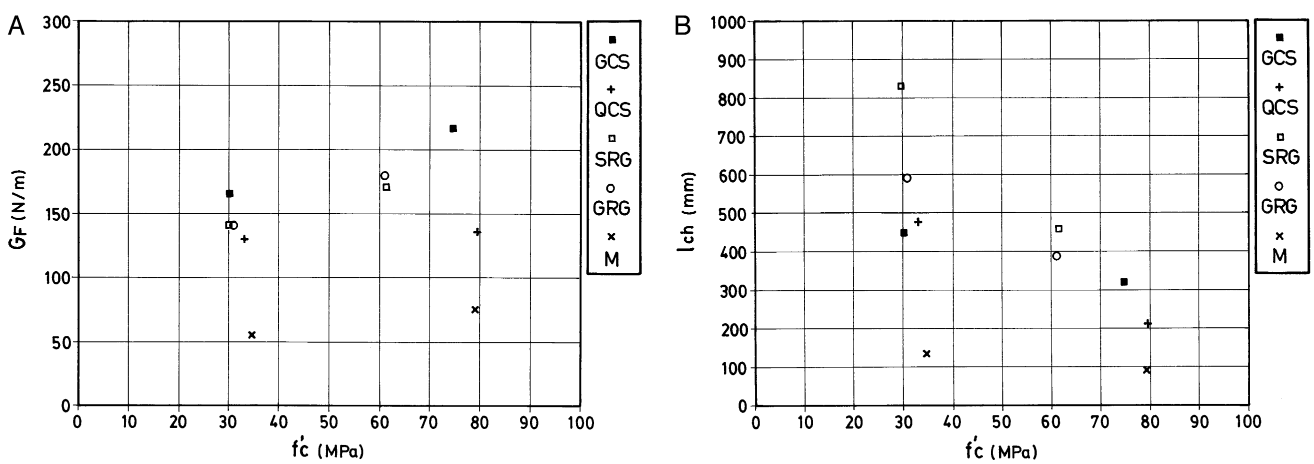

FIGURE 5. Variation of the energy of fracture and the characteristic length with the compressive strength of concretes and mortars. (A) Energy of fracture (G_F). (B) Characteristic length (l_{ch}).

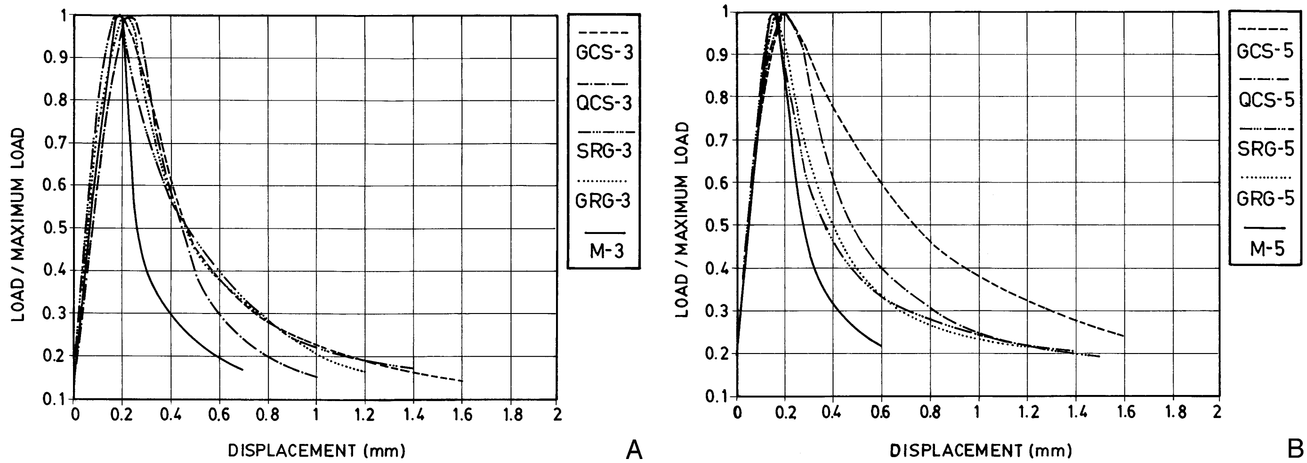

FIGURE 6. Load - displacement curves of concretes and mortars. (A) High strength concretes. (B) Conventional concretes.

increasing amount of cracks passing through aggregate observed on the fracture surfaces.

Gravel concretes do not show major changes in the failure mechanism when strength level increases. Cracks grow principally by debonding failure, especially in concretes prepared with the smoothest aggregate (SRG). Comparing GCS-3 with gravel concretes, the increase in f_{net} is greater than in G_F, probably due to the modifications in cracking pattern (cracks through aggregates in GCS-3) mentioned above.

It is significant to analyze the behavior of QCS at both strength levels with regard to the excellent bond developed by this aggregate. Note that although the strength increases, there is a negligible increase in G_F. In addition, it shows the greatest reduction in final displacement. Even in conventional concretes a low fracture energy was measured with quartzitic aggregates, and a mechanism including cracks through aggregates mainly develops. The location of the crack produced in notched beams probably enhances this mechanism. This phenomenon becomes more significant in HSC. In QCS-5 the softening curve is placed between GCS-5 and gravel concretes, whereas in QCS-3 it has a steeper gradient and is placed between gravel and mortar. In the case of HSC, quartzitic concrete shows strong differences in the fracture process, achieving the smallest values of G_F and l_{ch}, with its behavior similar to that of an "homogeneous" material such as mortar.

Conclusions

The influence of the type of coarse aggregate increases as strength level increases, as matrix strength is close to rock strength the probability of crack development through aggregates increases, and the mechanisms of cracking are modified compared with conventional concrete. At the same time, there is a strong relationship between interface strength and concrete failure behavior. The strength of the composite differs from the strength of the component phases due to limitations in bond strength. Adhesion and mechanical interlocking between matrix and aggregates are the main factors responsible for adherence development.

Comparing conventional and high strength concretes prepared with coarse aggregates that show differences in shape (natural gravels and crushed stone) and interface bond strength, the following conclusions can be made:

- Gravel concretes achieved lower values of compressive strength than crushed aggregates, being the lowest for the aggregate with the lowest bond strength (smoothest surface texture). The main failure mechanism includes extensive debonding. The smallest differences in failure mechanisms between conventional and high strength concretes were observed when concretes were prepared with these aggregates. This type of aggregate shows almost no changes when the strength is modified from the level of normal to high strength concretes.
- When concretes were prepared with GCS, rough surface texture, angular shape, and very strong aggregate particles enhanced mechanical interlocking, increasing concrete strength and toughness, showing a very tortuous fracture surface. The load-displacement curves (G_F test) have a more extended softening branch. In HSC, as strength increases some changes appeared in the mechanism of failure, making it possible to observe several cracks passing through coarse aggregates.
- When QCS were used, the excellent interface bonds developed by aggregate particles added to their relative low strength and a not very angular shape, leading to behavior more similar to an "homoge-

neous" material such as mortar. A typical failure mechanism with cracking through aggregates was observed not only in high strength concrete but also in conventional concrete. The energy of fracture of these concretes is the lowest measured, and, although compressive strength was increased from 33.1 to 79.4 MPa, there were no increases in the energy.

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References

1. Giaccio, G.; Zerbino, R. In *8th Int. Congress on the Chemistry of Cement*, Vol. 6; Rio de Janeiro, Sept. 1986; pp 331–333.
2. Liaisons Pates de Ciment Materiaux Associes. RILEM Colloque International, INSA-UPS, Toulouse, France, 1982.
3. Interfaces in Cementitious Composites, *Proc. of the RILEM International Conference*; Maso, J.C., Ed.; E & FN SPON: LMDC, INSA-UPS, Toulouse, France, 1992.
4. Mehta, P.K.; Aitcin, P.C. *ACI Mater. J.* **1990,** *87*, 103–107.
5. Giaccio, G.; Rocco, C.; Violini, D.; Zappitelli, J.; Zerbino, R. *ACI Mater. J.* **1992,** *89*, 242–246.
6. Tighiouart, B.; Benmkrane, B.; Baalbaki, W. *Mater. Struct.* **1994,** *27*, 211–221.
7. NLT-354/91 Spanish Standard "Indices de lajas y agujas de los áridos para carreteras" (in Spanish).
8. Suggested Method for Determining Point Load Strength, *Int. J. Rock Mech. Min. Sci. Geomech.* Abstract, **1985,** *22*, 51–60.
9. Coates, D.F. *Monografía 874, Energy, Mines and Resources*, CANADA. Transl. 3rd ed. ETS Ing. Minas, Madrid, 1973 (in Spanish).
10. Giaccio, G.; Giovambattista, A.; Zerbino, R. *Proc. Colloquia 85 Int. Sym, GLARILEM.* Bs.As. 1985; pp 251–262 (in Spanish).
11. RILEM 50-FMC Committee. *Mater. Struct.* **1985,** *18*, 285–290.
12. Giaccio, G; Rocco, C.; Zerbino, R. *Mater. Struct.* **1993,** *26*, 381–386.