

strength since in most practical applications it is common to specify concrete by its compressive strength, and some correlation between strength and other mechanical properties is usually expected. The design procedure followed the ACI method and resulted in slightly over-sanded concrete with good internal cohesion and workability. The concrete had low water-to-cement ratio and required substantial dosages of superplasticizers to achieve the desired workability (Table 1).

Experimental Methods

Loading Condition

Reinforced concrete beam specimens were cycled reversibly under loads that were 64 to 80% of their capacity until failure occurred. Loads were applied at a slow rate of 1 Hz (1 complete cycle per second). At these load levels, all major cracks appeared and progressed completely through the concrete within the first 10 000 cycles. These cracks were spaced 4 to 5 in. (102 to 127 mm) apart in the central third of the beam. Smaller secondary cracks developed during the test, mostly around the reinforcing bars as the bond deteriorated.

Curing Conditions

Concrete specimens were cast in reusable plywood forms and allowed to cure in the forms for the first 48 h covered with plastic sheets and wet burlap. The specimens were demolded after 48 h and transferred to a standard fog room where they were kept under 100% relative humidity and temperature of 73°F (23°C) for 60 days. The specimens were then moved to the controlled environment of the main testing area where they were stored for a period of 60 to 90 days before testing. Previous experience at our laboratory showed that similarly impermeable concrete re-

tained 99% of its internal humidity for longer periods of time, and the only moisture loss was from a thin skin layer directly exposed to the dry air.

Beams were tested to failure, which occurred as one or two rebars fractured in fatigue, resulting in complete loss of load capacity. Prior to the failure, with each cycle the major cracks would open and close up to 1 mm at the outer fiber. When load was removed after failure, the remaining steel bars pulled the cracks closed, so that it was difficult to see a crack unless it was previously marked (all cracks were marked with colored markers during the test).

Fatigue loading took two to three days, after which the fractured beams were stored in the same controlled environment for a minimum additional period of 90 days. No external moisture was applied to the concrete during that time.

Compressive Strength Testing of Cubes

The basic mechanical properties of the concrete are given in Table 2. An unreinforced concrete beam was extracted from the bottom of the failed reinforced beam (see Fig. 1) by cutting it with a diamond blade saw. The cutting process removed the reinforcing bars which were holding the cracked concrete together, and it was expected that the unreinforced beam will separate at the cracks. Upon examination of the cut surface, the cracks appeared to be filled with lighter materials with considerable strength, which allowed them to retain their integrity through the process of vigorous sawing and vibrating. The extracted beam was then cut into small cubes, approximately 2 by 2 in. (50 by 50 mm) using a slow action precise diamond blade saw. The cubes were tested for their density and ultrasonic pulse velocity and then capped and tested for compressive strength.

Ultrasonic pulse velocity was measured on the extracted beam before cutting and on the small cubes prior to compressive load-

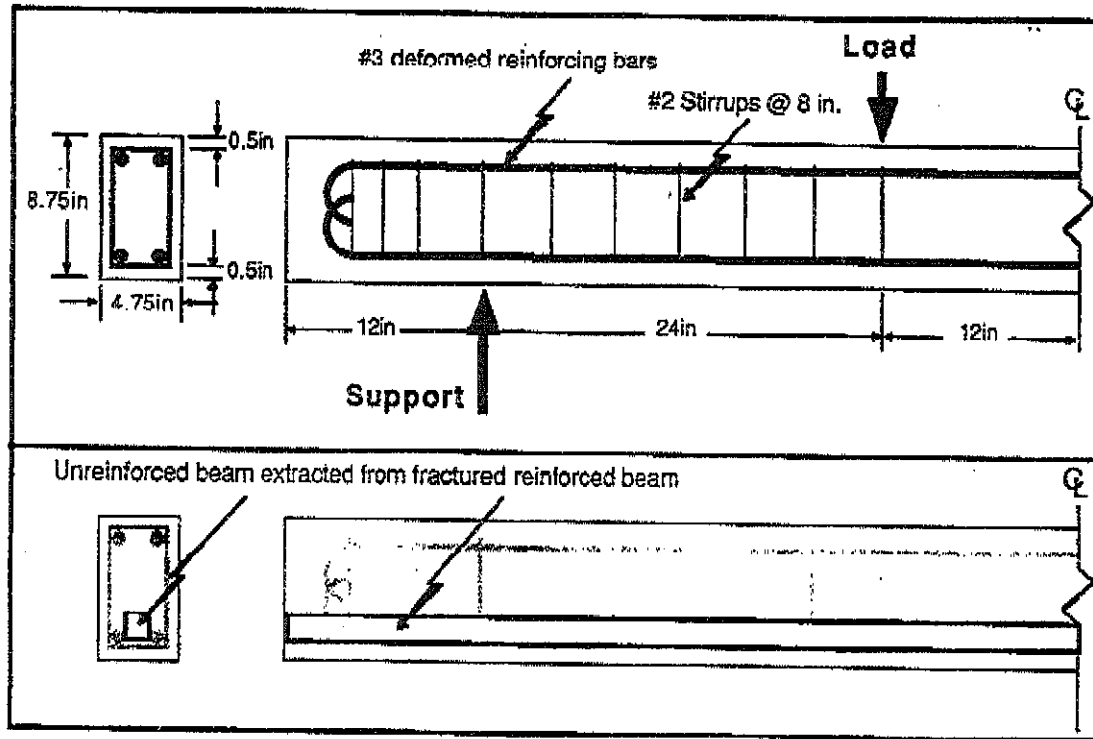
TABLE 1—Concrete proportions used in the program.

Batch	Cement	Coarse	Sand	HRWR*	Water	W/C	Density
	kg/cu.m.						kg/cu.m.
LW-2a	550.6	769.9	611.8	6.3	138.3	0.25	2077
	pcy						pcf
LW-2a	930	1300	1030	10.8	234	0.25	130

* HRWR designates High Range Water Reducer

TABLE 2—Compressive strength, tensile strength (splitting test), and modulus of elasticity (Ec) of 3 by 6-in. cylinders, and modulus of rupture of 3 by 3 by 20-in. unreinforced beams.

BATCH	7 days	14 days	28 days	250 days	FINAL Fc	Tensile	Rupture	Ec
	[psi]	[psi]	[psi]	[psi]	[psi]	[psi]	[psi]	[ksi]
LW-2a	7025	9500	9650	9850	11100	1700	225	5500



1 in = 25.4 mm

FIG. 1—Details of full-size reinforced concrete beams and unreinforced concrete beam which was cut out of the fractured beam. The unreinforced beam was later cut into small cubes which were used in the microscopic evaluation described in the paper.

ing. It was found that the pulse velocity across the cracked surfaces did not deviate from the pulse velocity of the uncracked concrete, indicating a complete filling of the crack with material comparable in density to the concrete.

Compressive strength of the cracked cubes was between 65 to 85% of the compressive strength of the uncracked concrete cubes. The variation in strength appears to be a function of the orientation of the cracks (vertical or diagonal) and the number of healed cracks in a cube. Failure of cracked cubes originated in the healed crack, but did not necessarily follow the path of the original crack.

Results

Crack Arresting in LWA Concrete

Figure 2 is a low magnification micrograph showing a typical cracking pattern in high-strength light-weight concrete tested under cyclic loading. The aggregate is the porous material at the central part of the micrograph, surrounded by dense hardened cement paste (HCP) matrix. Due to the high density of the HCP, no defined crystal structure can be discerned even at very high magnification. A system of microcracks can be observed in the matrix close to the aggregate. A closer view of a crack branching as it penetrates the light-weight aggregate can be seen in Fig. 3. The crack splits into at least two distinct thinner cracks which propagate into the aggregate. Similar thinning of a crack upon penetration can also be observed in Fig. 4. In this case, the thinning occurred without any observable branching, which

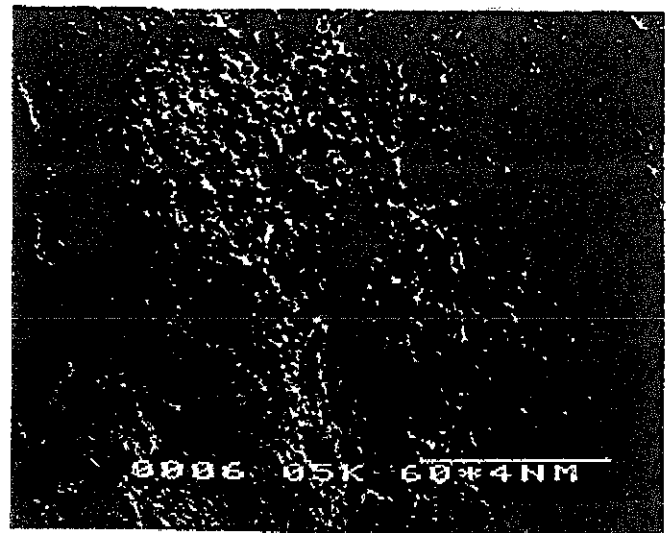


FIG. 2—Typical cracking pattern.

seems to indicate that during the propagation of the crack through the porous light-weight aggregate material there is a significant absorption of energy.

A mechanism of crack arresting by the porous structure of the light-weight aggregate is revealed in Fig. 5, where a crack which penetrates the aggregate disappears completely.

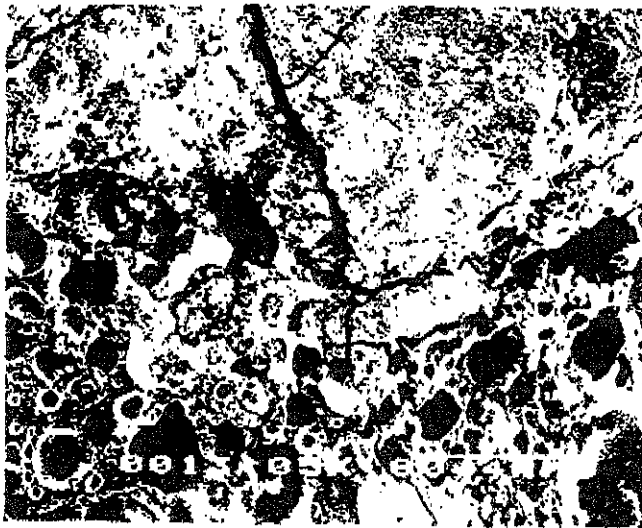


FIG. 3—Cracking branching in the aggregate.



FIG. 5—Crack arrest at the light-weight aggregate.

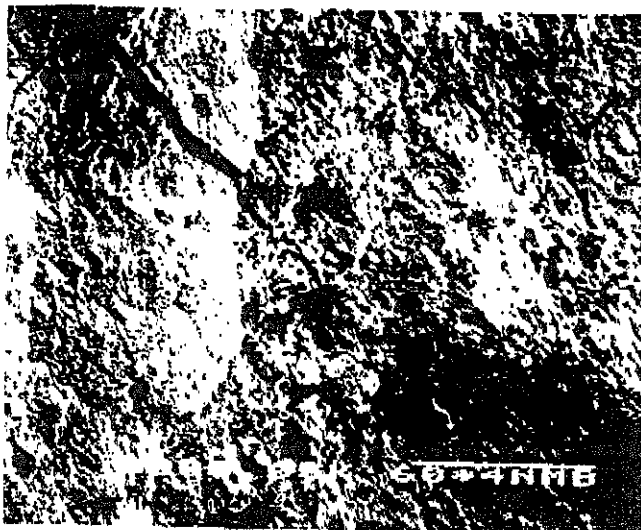


FIG. 4—Crack penetration in the aggregate.



FIG. 6—Cracking at the steel-concrete interface.

Cracking at Steel-Concrete Interface

Researchers [4,5] observed an intense cracking around the reinforcing steel ribs after loading a reinforced concrete specimen to failure. This phenomena can be seen in Fig. 6, where the steel rib is in the upper left corner. The consequences of this intense stress concentration and subsequent cracking can be seen in Fig. 7, where the crack runs through the aggregate without any major deflection.

Healing

In Figure 8 we can see a large crack filled with new material which appears lighter in the micrograph. It is interesting to observe that smaller cracks in the close vicinity were not filled with the same material. Two explanations are possible: (1) the healing

smaller cracks were induced during the specimen preparation for the SEM (exposed to vacuum). Figure 9 appears to indicate that the latter assumption is more realistic because secondary cracks can be seen in the "healed" area. It was interesting to observe that a similar healing process took place in the steel-concrete interface shown in Fig. 10.

Conclusions

The experimental results indicate that in high-strength concrete, cracks induced by loading propagate mostly through the light-weight aggregate particles, as opposed to the expected interfacial bond failures. The crack path is deflected when a crack penetrates the aggregate, and crack branching and crack arrest at the aggregate interface were observed.



FIG. 7--Crack through the aggregate.

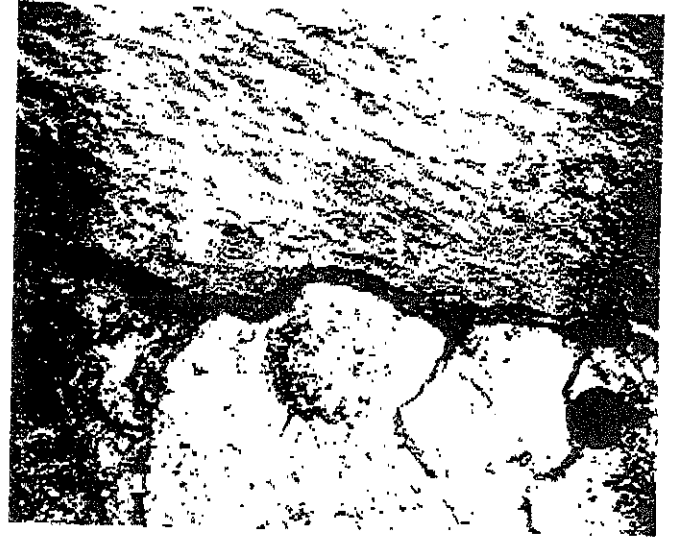


FIG. 10 Healing of the cracks at the steel-concrete interface (steel at the top of the micrograph).



FIG. 8--Healing of the cracks.



ning electron microscopy analysis of broken concrete samples. The healing process may explain why ultrasonic pulse velocity across cracked surface did not deviate from the pulse velocity of the uncracked concrete and gave no indication of the present cracking and degradation.

References

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