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RATE AND SIZE EFFECTS IN CONCRETE FRACTURE: IMPLICATIONS FOR DAMS

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ABSTRACT

This paper reports the results of reduced-scale fracture tests of conrete with reduced-size aggregate and the results of large-scale fracture tests of dam concrete with large aggregate. In the latter, very large fracture specimens, up to 72 in. in dimension, have been tested. Static tests with times to the peak load ranging from 1 s to 260,000 s have been carried out. The size effect method, recently published as a RILEM Recommendation, has been used to determine the fracture energy, fracture toughness, effective length of the process zone, brittleness number and critical crack-tip opening displacement. The conclusions are: (1) The size effect law proposed by Bažant appears to be valid for various loading rates; (2) As the loading rate decreases, the response shifts closer to linear elastic fracture mechanics and the brittleness number increases; (3) there is a strong load relaxation in the post-peak states which is due to additional creep in the fracture process zone, the relative relaxation being about the same for all the post-peak states and about 1.7-times stronger that the basic relaxation due to linearly viscoelastic creep outside the fracture process zone. The results are of considerable interest for the fracture of concrete dams because the fractures in dams often develop over a very long period of time. Fracture properties obtained in normal-rate tests cannot be used for such analyses unless they are adjusted for the rate effect.

INTRODUCTION AND NATURE OF PROBLEM

The purpose of this paper is to briefly report the main experimental results of a collaborative project of Nortwestern University and University of Wisconsin, concerned with the rate effect and size effect in concrete fracture, with particular focus on dam concrete. Both problems are of keen interest for concrete dams.

The large size of aggregate used in dam concretes dictates the use of very large fracture specimens, whose study has already been pioneered by Swiss Federal Institute of Technology, Lausanne, and University of Colorado, Boulder (Brühwiller and Wittmann, Saouma, Broz, Brühwiller and Boggs). An effective approach in this regard is the new size effect method for testing fracture properties, proposed by Bažant and recently published as a new RILEM Recommendation (1990). This method implies extrapolation to infinite size and thus enables using smaller fracture specimens than would otherwise be required to obtain size-independent fracture properties.

Large fractures in dams often grow very slowly, over long periods of time. But the existing experimental results of fracture have been obtained under normal loading rates, with time to peak load of 10 min. or less. All the information on the effect of loading rate pertains to the dynamic range, for which the time to peak ranges from 10^{-8} s to 10^{-2} s. It is not clear if and how this information can be extrapolated to the static loading range. The preliminary results of the present investigation of the rate effect in the static range on reduced-scale specimens have already been briefly reported

(Bažant and Gettu, 1989, 1990, Bažant 1990), but the present paper gives the first report after completion of the experiments.

REDUCED-SCALE FRACTURE TESTS

Wedge-splitting compact tension specimens of various sizes up to 6 ft., with 3 in. maximum aggregate size, as well as reduced-scale three-point-bend fracture specimens with 13 mm maximum aggregate size, have been used. The size effect method proposed by Bažant and recently published as a new RILEM Recommendation (1990) (cf. also Bažant and Cedolin, 1991) has been employed to determine the fracture energy G_f, the effective length of the fracture process zone c_f, and the brittleness number β at various loading rates, chosen so that the time to peak load t_p varied from from 1 s to 260,000 s (72 hours) (this represents a range of over five orders of magnitude of the loading rate).

Table 1 summarizes the results of the tests of geometrically similar three-point bend fracture specimens of three different depths d, made of comcrete with reduced aggregate size. The main results are the peak loads P_{max} for various loading rates, from which the material fracture properties have been evaluated using the size effect method. In this evaluation it has been assumed that, despite creep, the material outside the fracture process zone can be treated as elastic. This means that creep has been taken into account according to the effective modulus method, well known from the theory of viscoelasticity. The use of the effective modulus for creep is in fact implied in all fracture studies of concrete, because the deformation of concrete in the usual static test (about 1 to 10 min. to peak load) contains about 30% creep. For the slowest rates used in the present tests, creep constitutes about 50% the total defromation, which is not that much different from the normal test. Thus the effective modulus method ought to be an acceptable approximation for handling creep. The material fracture properties obtained for the reduced-scale tests are listed in Table 2.

The values of the nominal strenth σ_N for various rates and various specimen sizes are plotted in figure 1 (σ_N = maximum load divided by specimen depth and thickness, $\beta = d/d_0$ = brittleness number = relative specimen size, Bf_u and d_0 are the constants of the size effect law, obtained by data fitting). It is seen that the results of these carefully controlled reduced-scale laboratory tests agree with the size effect law proposed by Bažant (1984) (solid curves) quite well and that the scatted is about as low as one can expect from such a heterogeneous material as concrete. The results for all the rates and sizes are replotted as one graph in figure 2. This graph yields an important conclusion: With decreasing rate of fracture, the response shifts in the size effect plot to the right, i.e. closer to linear elastic fracture mechanics (LEFM). This means that *the brittleness number of concrete increases as the rate of fracture decrases.* Consequently, the long-time fracture behavior of conrete dams is even closer to LEFM than the short-time behavior. This result has significant implications for the analysis of dam fracture.

It is interesting to note that a parallel study of the rate effect in static fracture of limestone showed no such shift toward LEFM at decreasing rate of loading. This is probably explained by the fact that limestone, in contrast to concrete, exhibits no significant creep (at these rates). Thus it seems that the shift toward LEFM is caused by relaxation of the stresses near the fracture tip, caused by creep of the surrounding concrete.

figure 3 shows the dependence of apparent fracture toughness K_{Ic} and the effective length of the fracture process zone c_f on the loading rate, as determined by the size effect method. That the former increases with the loading rate is already well known, but that the latter decreased is a new result, which corresponds to the increasing brittleness number. (For the method of calculation of c_f, see Bažant and Kazemi, 1990a,b).

To understand the creep effects and the change of brittleness, the crack mouth opening displacement CMOD of some fracture tests has been arrested at various points of the load-deflection curve, both before and after the peak, and the subsequent load relaxation and constant displacement has been measured. Unlike for limestone, this relaxation has been found to be very strong for concrete. The measurements are shown in figure 4, which reveals a rather interesting new property. The relative relaxation is about the same for all the post-peak states, shortly after the peak as well as after considerable softening. Moreover, the relaxation is long-lived, just like creep, with the relaxation curves being approximately straight lines in the log-time plot. The downward slope of these lines is about 1.7-times larger than that for the relaxation at very small displacements, or the relaxation measured on companion unnotched specimens at small deformation, which falls into the realm of linearly viscoelastic creep. These observations are confirmed by the relative relaxation curves in figure 5, where the dashed line at bottom is the common post-peak relaxation, and the lines of smaller slopes are pre-peak relaxations. The fact that the slope of the relative relaxation curves is about the same for all the post-peak states is in agreement with a previous observation by Bažant, Gettu and Kazemi (1991) that the size of the fracture process zone of a propagating crack remains approximately constant for the post-peak states.

LARGE-SCALE FRACTURE TESTS

A second series of tests, carried out at the Univesity of Wisconsin, explored similar responses for a typical dam concrete with maximum aggregate size 3 in., using wedge-splitting compact tension specimens of square size with heights 12, 30 and 72 in. (the latter is probably the largest-size fracture specimen ever tested). The specimen geometry is shown in figure 6. After casting, specimens were allowed to cure in their molds for 5 days after which the molds were removed and the specimens were wrapped in plastic for an additional 28 days of curing. In view of the very large specimen size, and the need to use heavy equipment to move the specimens, these tests could not be carried out in a laboratory room with environmental controls. Furthermore, because of the difficulty in handling as well as some of the very slow load rates, testing of all specimens from one batch of concrete typically required one week's time to complete which exacerbates the effect of age on strength. It is no doubt for these reasons why the scatter of the results of these tests has been larger. One way to avoid contamination of the results by random scatter would be to further increase the size range, the rate range and the number of specimens within a particular batch of concrete, but this would be prohibitively expensive.

Nevertheless, a similar size effect was confirmed by these tests and a similar trend with regard to the loading rate has been observed, as revealed by the results in figure 7, and the basic data which are summarized in Table 3. In figure 7, we see a large shift toward LEFM (i.e. to the right) between the fast rate and the medium rate, but no further shift for the slow rate. Based on the reduced-scale tests, further shift has been expected. Its absence might well be merely one manifestation of statistical scatter. That the scatter is large is confirmed by figure 8, which shows the results of a greater number of tests in which the specimens were cast from four different batches of concrete. Note that results within a particular batch of concrete are more consistent than the average of all batches indicates.

CONCLUSIONS

1. The fracture behavior of dam concrete agrees reasonably well with the size effect law proposed by Bažant, and testing of geometrically similar fracture specimens of various sizes makes it possible to determine nonlinear fracture parameters of dam concrete quite easily.
2. The size effect law appears to be valid over a wide range of loading rates, spanning over five orders of magnitude (provided the effective modulus method is used to take creep into account).
3. The fracture toughness, effective length of the frature process zone, and effective critical crack-tip opening displacement decrease with decreasing rate of loading.
4. The load relaxation in the post-peak range at constant CMOD tends to a straight line in the logarithm of the elapsed time and is about 1.7 times stonger than the relaxation in unnotched specimens. This difference is explicable by additional creep in the fracture process zone and possibly also time-dependent crack growth.
5. There is no doubt strong interaction between fracture and creep in concrete, and prediction of long-time fracture behavior must take such interaction into account.

Remark: Development of a mathematical model describing the present results is under way and will be reported in a separate study.

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Table 1 : Fracture Test Data

series	specimen depth (mm)	CMOD rate (mm/s)	time to peak, t_p (s)	age at loading (days)	peak load (N)
Fast f'_c = 36.6 MPa ω = 1.3%	38	1.1×10^{-2}	0.9	28	2225
		8.4×10^{-3}	2.2	28	1800
		1.1×10^{-2}	1.5	28	1890
	76	1.4×10^{-2}	1.3	28	3625
		1.4×10^{-2}	2.2	28	3960
		1.4×10^{-2}	1.3	28	3025
	152	2.1×10^{-2}	1.3	28	6180
		2.1×10^{-2}	1.1	28	5940
		2.1×10^{-2}	1.1	28	5425
Usual f'_c = 36.5 MPa ω = 6.1%	38	1.8×10^{-5}	595	28	1825
		1.8×10^{-5}	595	28	1780
		2.4×10^{-5}	570	28	1645
	76	5.3×10^{-5}	460	28	3070
		3.6×10^{-5}	520	28	2800
		4.3×10^{-5}	505	28	2760
	152	7.1×10^{-5}	495	28	5025
		7.1×10^{-5}	360	28	4225
		7.1×10^{-5}	420	28	4200
Slow f'_c = 37.2 MPa ω = 5.5%	38	7.1×10^{-7}	10350	40	2315
		7.1×10^{-7}	17100	38	1935
		7.1×10^{-7}	13500	39	2180
	76	1.0×10^{-6}	10625	46	3580
		9.4×10^{-7}	17550	42	3515
		1.1×10^{-6}	11900	30	3180
	152	1.4×10^{-6}	15300	32	4270
		1.4×10^{-6}	14850	38	4180
		1.7×10^{-6}	14600	31	5295
Very Slow f'_c = 36.9 MPa ω = 4.4%	38	3.8×10^{-8}	266500	120	2135
	76	7.4×10^{-8}	255500	108	3180
	152	1.3×10^{-7}	236000	90	4580

f_c' = 28-day compressive strength of 76mmx152mm cylinders

ω = coefficient of variation of f'_c

Table 2: Material Fracture Parameters

series	avg. t_p (sec)	avg. age (days)	Bf_u (MPa)	d_0 (MPa)	ω	K_{Ic} (MPa$\sqrt{mm}$)	c_f (mm)	E (GPa)	G_f (N/m)	δ_{ef} (mm)
Fast	1.4	28	1.60	102.5	0.10	39.5	17.2	36.0	43.4	0.0146
Usual	500	28	1.68	41.3	0.06	26.3	6.9	28.6	24.1	0.0077
Slow	13650	38	2.94	13.3	0.09	26.1	2.2	24.1	28.4	0.0052
Very Slow	253000	106	3.47	8.5	0.01	24.6	1.4	22.4	26.9	0.0042

ω = coefficient of variation of the deviations of the fit from test data

Table 3: Material Fracture Parameters of Large Aggregate Concrete

load rate	A	C (in)	do (in)	G_f (lb/in)
fast	0.115E-5	0.384E-3	333.913	7.502
medium	0.995E-5	0.333E-3	33.503	0.868
slow	0.975E-5	0.333E-3	34.154	0.885

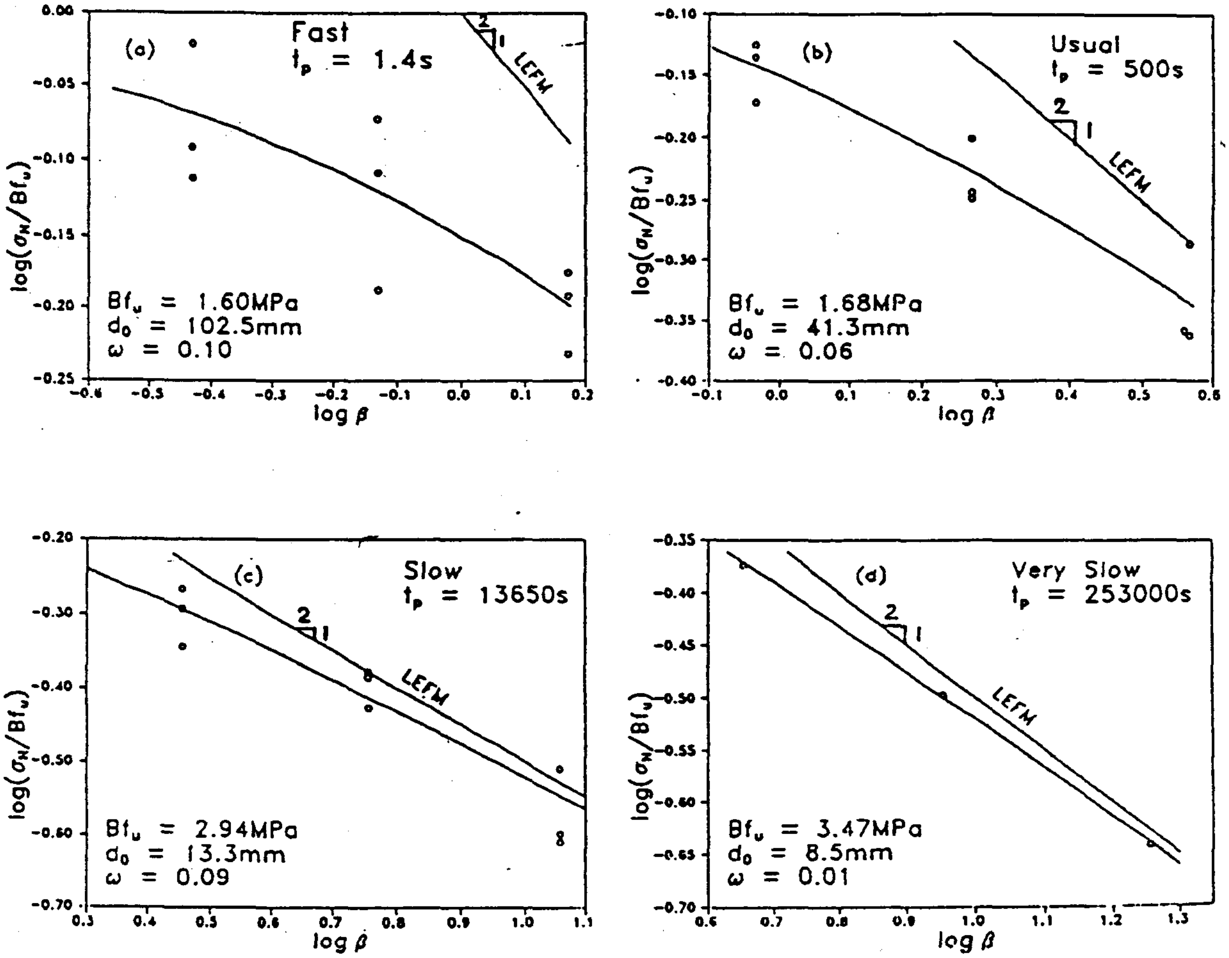

Figure 1. Optimum size effect curves for the test data.

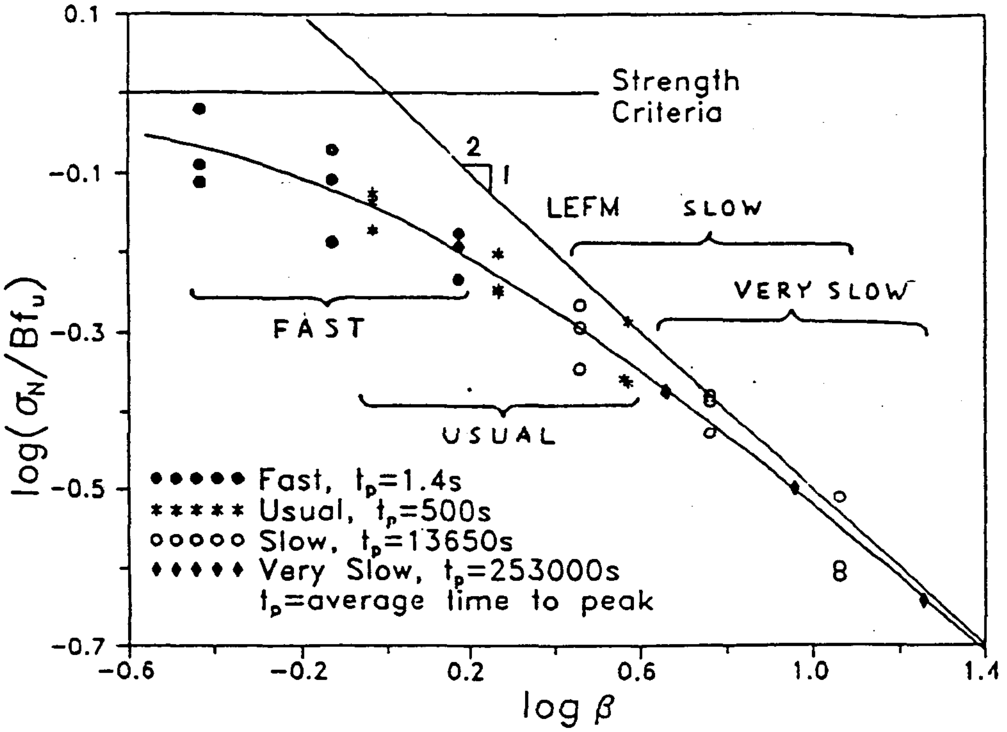

Figure 2. Change in mode of failure with loading rate.

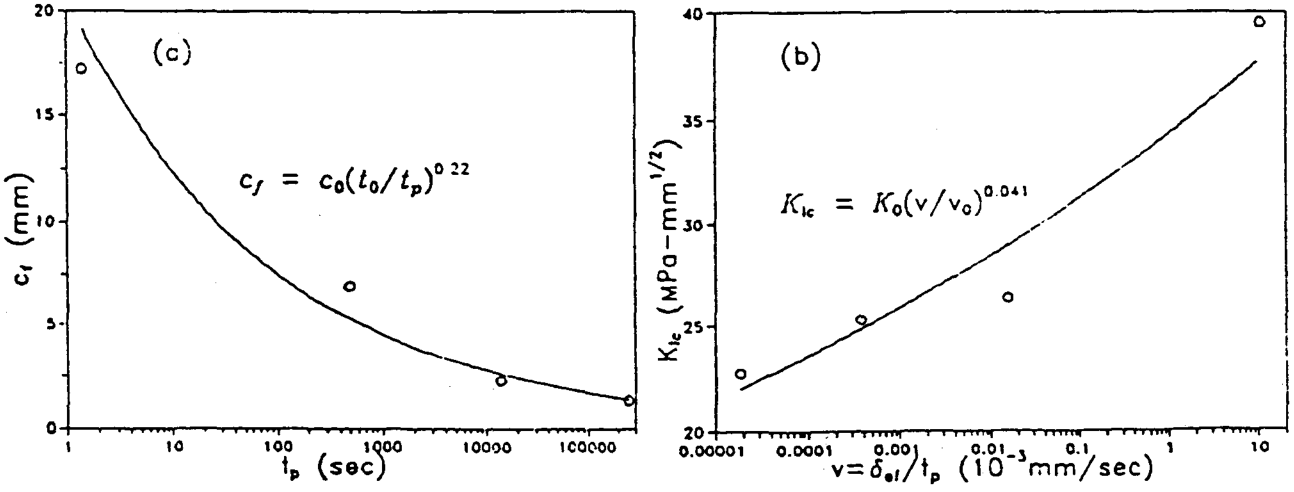

Figure 3. Effect of time to peak load on (a) fracture process zone size and (b) fracture toughness

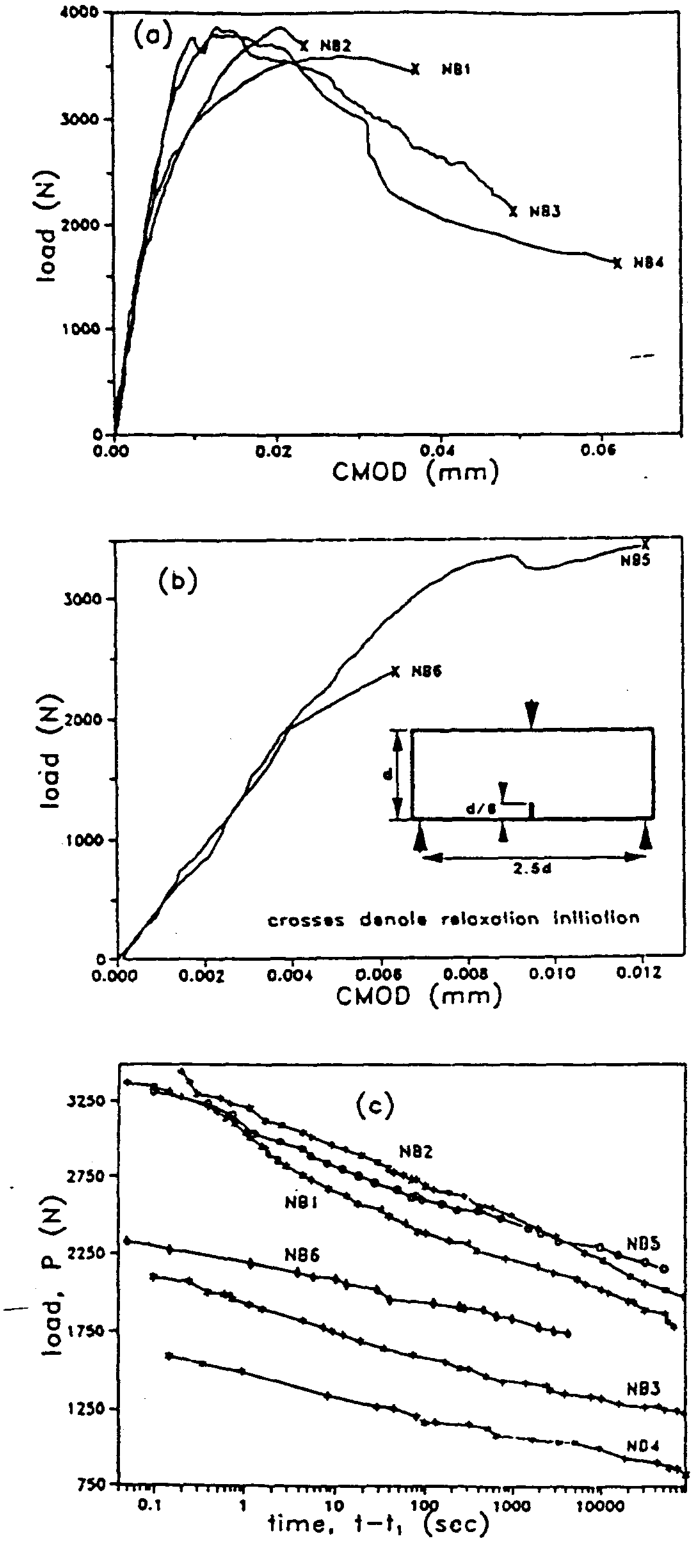

Figure 4. Relaxation tests of fracture specimens on post-peak state, for various CMOD rates: (a) load-CMOD curves before relaxation of specimens loaded beyond the peak, (b) load-CMOD curves before relaxation of specimens at and before peak. (c) load relaxation.

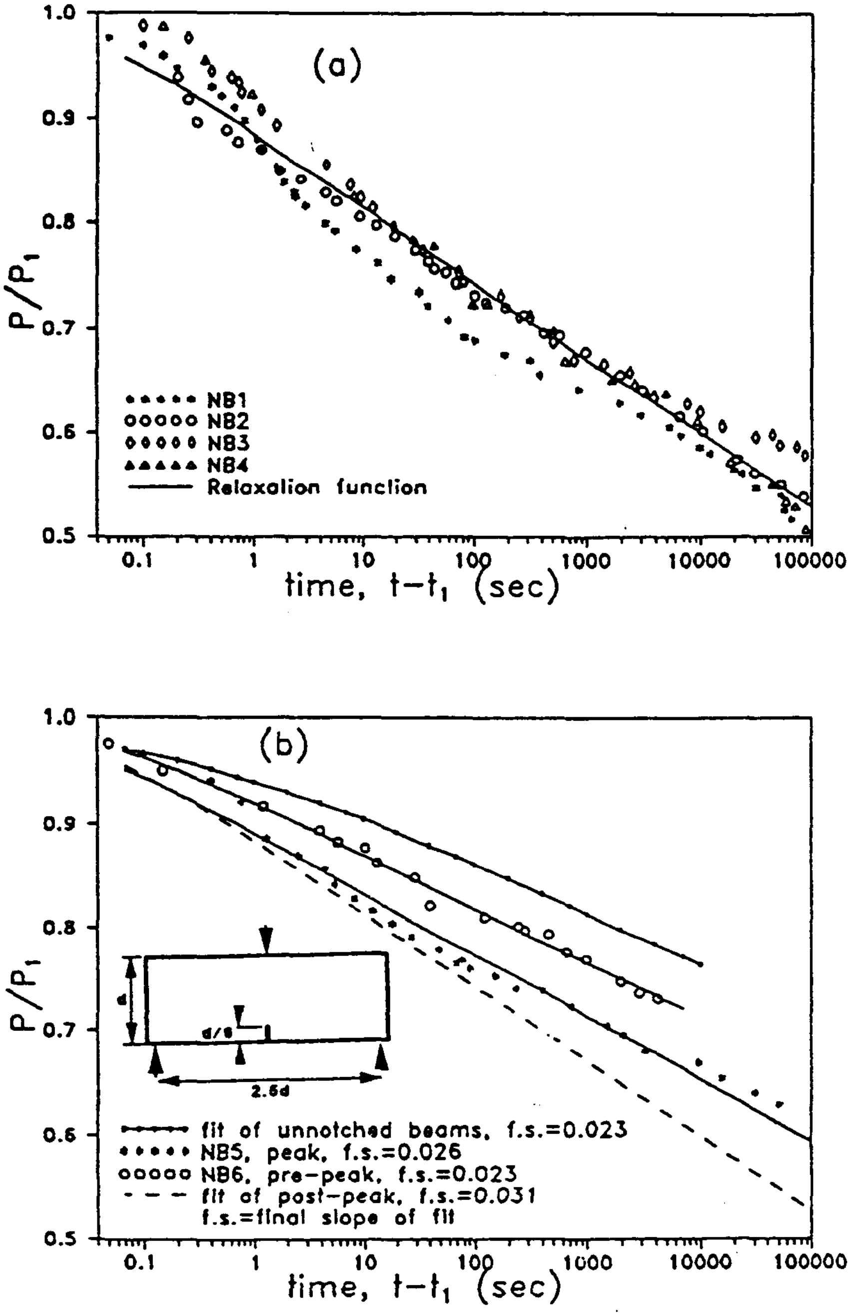

Figure 5. Rate effects on (a) load-CMOD response and (b) load-deflection response.

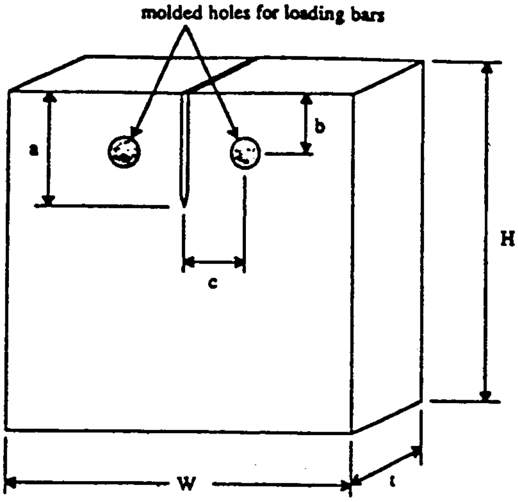

Figure 6. The specimen used in the large aggregate concrete tests.

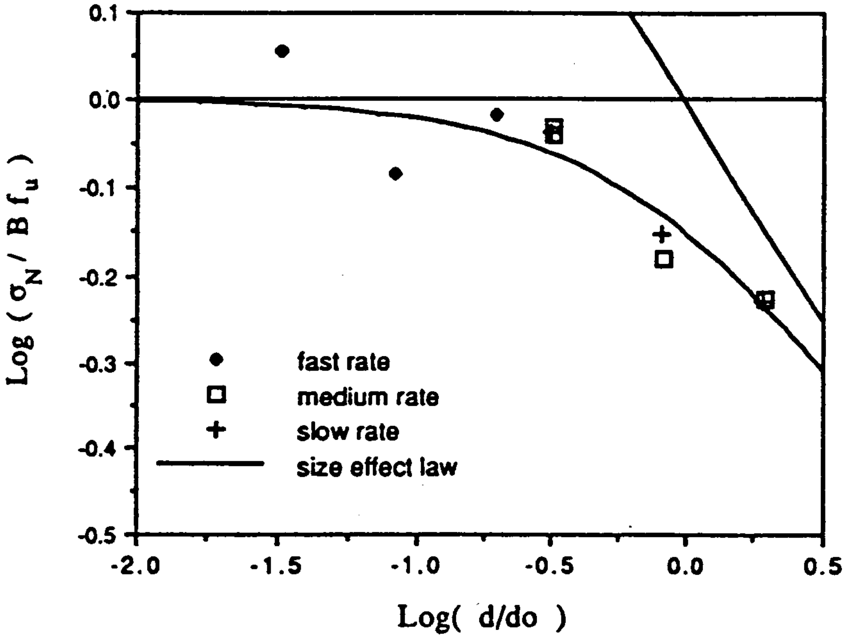

Figure 7. Size effect plot of large aggregate concrete test data from all specimen sizes, and all loading rates of batch 4 concrete.

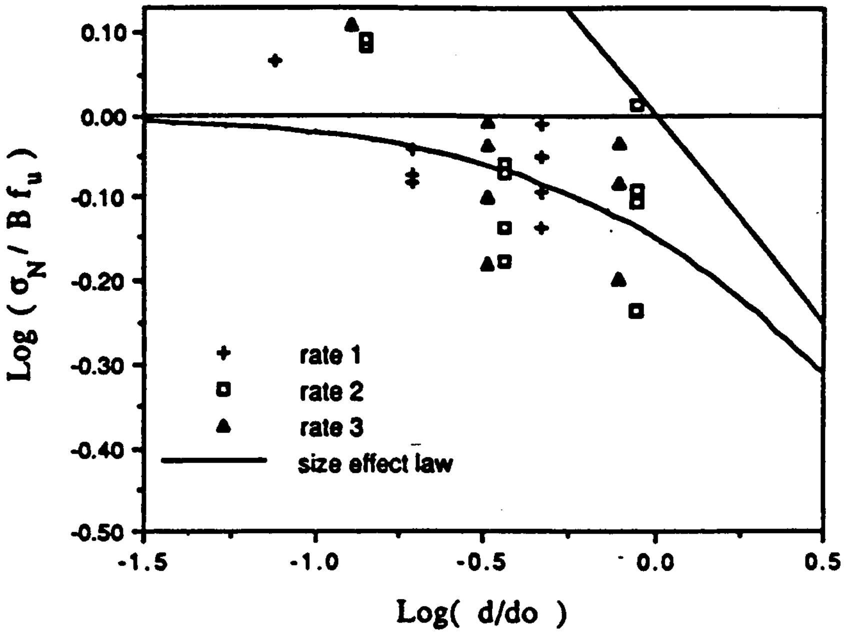

Figure 8. Size effect plot of large aggregate concrete test data from all specimen sizes, and all loading rates for all the four batches concrete tested.