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Softening Reversal and Other Effects of a Change in Loading Rate on Fracture of Concrete


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The time dependence of concrete fracture, and particularly the effect of loading rate, has so far been studied mainly in the dynamic range. The present study extends a preceding investigation of the rate effect in the static range that covered times to peak from 1 to 300,000 sec. Geometrically similar three-point-bend specimens of three different sizes are subjected to either a sudden 1000-fold increase of the loading rate or a 10-fold sudden decrease of the loading rate. It is found that the post-peak softening can be reversed to hardening, followed by a second load peak that can be either higher or lower than the previous load peak. The rise to the second peak depends on the previous post-peak load drop from the first peak load. A sudden decrease in the loading rate causes initially a steeper softening slope. The source of these time-dependent effects appears to be not only the thermally activated nature of the process of bond ruptures in the fracture process zone but also the effect of creep, both a nonlinear creep in the fracture process zone and a linear creep in the bulk of the specimen. The results of this study and a previous study suggest that there is a significant difference in fracture behavior for short-time and long-time loads. The phenomena observed are of interest, for example, for the analysis of concrete dams with cracks that evolve over many years. Mathematical modeling of the present test results is left for a subsequent study.

Keywords: concretes; cracking (fracturing); creep properties; failure; loading rate; viscoelasticity.

Understanding of fracture mechanics of concrete is necessary for improving the design of concrete structures against various types of brittle failure, and particularly for taking into account the size effect and ductility limitations. Although the classical fracture mechanics is a rate-independent (time-independent) theory, the fracture properties of all materials depend upon the loading rate. One source of the rate sensitivity is the process of rupture of interatomic or intermolecular bonds at the tips of microcracks, which represents a thermally activated process governed by a certain activation energy. The rate sensitivity is explained by the fact that the probability that the thermal vibration energy of an atom or molecule would exceed the activation energy barrier of the bond increases with the superimposed potential due to applied stress or load.

A second source of rate sensitivity is creep (or stress relaxation) in the fracture process zone, as well as in the bulk of the specimen. The creep effect is negligible at very fast, dynamic loading rates, but inertia (or wave propagation) effects complicate dynamic fracture. The creep effect becomes important only at sufficiently slow loading rates, complicating the fracture theory, while the inertia effects vanish. Whereas Shah and Chandra (1970), Wittmann and Zaitsev (1972), Liu et al. (1989), and others have already suggested that concrete fracture is affected by creep, a detailed investigation of this effect has not been conducted. On the other hand, the rate effect in concrete fracture has been extensively investigated in the dynamic range of loading, in which the maximum load is reached in less than one second (see Mindess and Shah 1986). In a material such as concrete, which exhibits pronounced creep under long-time loading, the rate effect in the static range and the contribution of creep to it may be expected to be particularly strong.

For this reason, a preceding study by Bažant and Gettu (1992) investigated the rate effect in the static range experimentally, using crack mouth opening displacement (CMOD) rates with times-to-peak load ranging from 1 to 300,000 sec (3.5 days). The size effect method, coupled with the effective modulus approximation of creep, has been used to determine the rate dependence of fracture properties. The fracture toughness was found to decrease with a decreasing rate, as a continuation of the trend previously known for the dynamic range. As a new, surprising result, the effective length of the fracture process zone was found to decrease with decreasing rate, which implies that for slow loading the brittleness number increases and the response shifts closer to linear elastic fracture mechanics (LEFM). Load relaxation at constant CMOD in the post-peak regime was also investigated and found to be very pronounced. The time curves of relaxing load were found to be approximately straight lines in the log-

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arithm of the elapsed time and the load drop to be several times larger than for a linearly viscoelastic relaxation of unnotched specimens for the same relaxation duration. The difference between these two relaxations has been attributed to time-dependent processes, principally creep, in the fracture process zone.

From Bažant and Gettu's (1992) study it became clear that there is a strong interaction between fracture and creep, which must be taken into account in predicting the long-term load-carrying capacity of structures with cracks. This is particularly important for analyzing the failure of concrete dams, in which large fractures often develop gradually over a period of many years.

As far as materials other than concrete are concerned, the effects of loading rate in the static range were recently investigated by Bažant, Bai, and Gettu (1991) on limestone. The effect of the loading rate was found to be significant, but less pronounced than for concrete, and no shift of brittleness with a decreasing loading rate has been observed. This is no doubt explained by the fact that limestone does not exhibit any significant creep, and so most of the rate effect must be due to the thermally activated process of bond ruptures.

The preceding study of Bažant and Gettu (1992) was limited to constant loading rates. The purpose of the present study, on which preliminary reports were made in several conference papers by Bažant and Gettu (1989, 1990, 1992), is to present the experimental results on the effect of a sudden change of loading rate. Knowledge of this effect is essential for formulating a time-dependent mathematical model for the fracture process zone, which will be the subject of a subsequent study. By adopting the *R*-curve (resistance curve) model for nonlinear fracture, the effect of the constant loading rate has already been successfully described in three brief conference papers (Bažant and Gettu 1989; Bažant 1990; and Bažant and Jirásek 1992), and it may be expected that an extension of this approach would work also in the case of sudden changes of the loading rate.

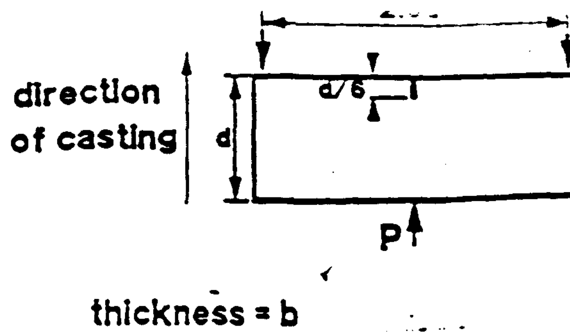

Fig. 1—Geometry of the three-point-bend fracture specimens tested

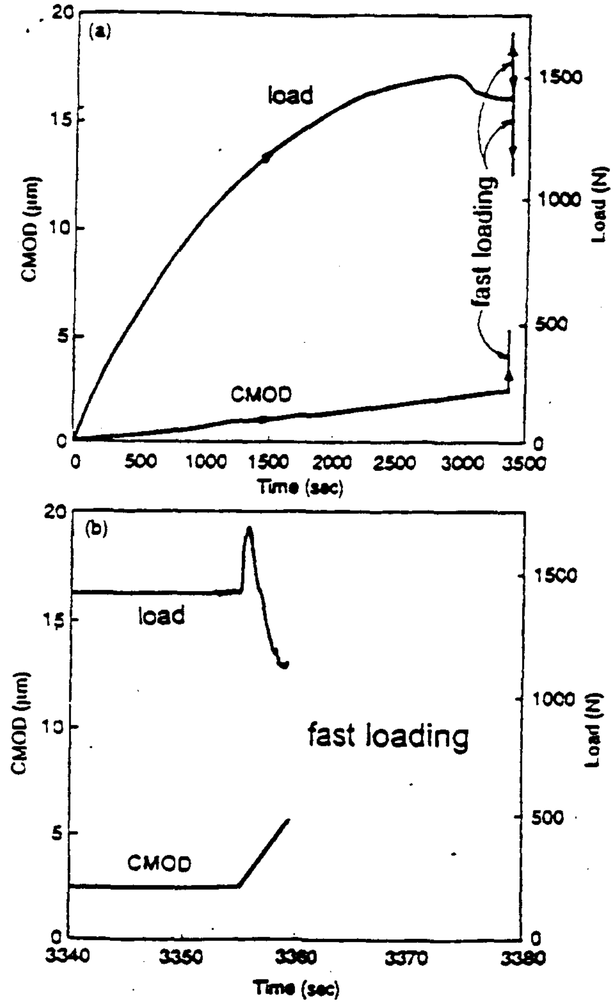

Fig. 2—Typical recorded time histories of CMOD and load achieved by the controls of the test equipment used. Part (b) is an expanded version of (a)

MATERIAL, TEST SPECIMENS, AND TEST PROCEDURE

The material studied was plain concrete, with a mix ratio of cement:sand:gravel:water = 1:2:2:0.6, by weight. ASTM Type I portland cement was used. The aggregate consisted of crushed limestone gravel of maximum grain size of 13 mm (0.5 in.) and siliceous sand passing standard sieve No. 2, corresponding to maximum grain size 5 mm. The average stan-

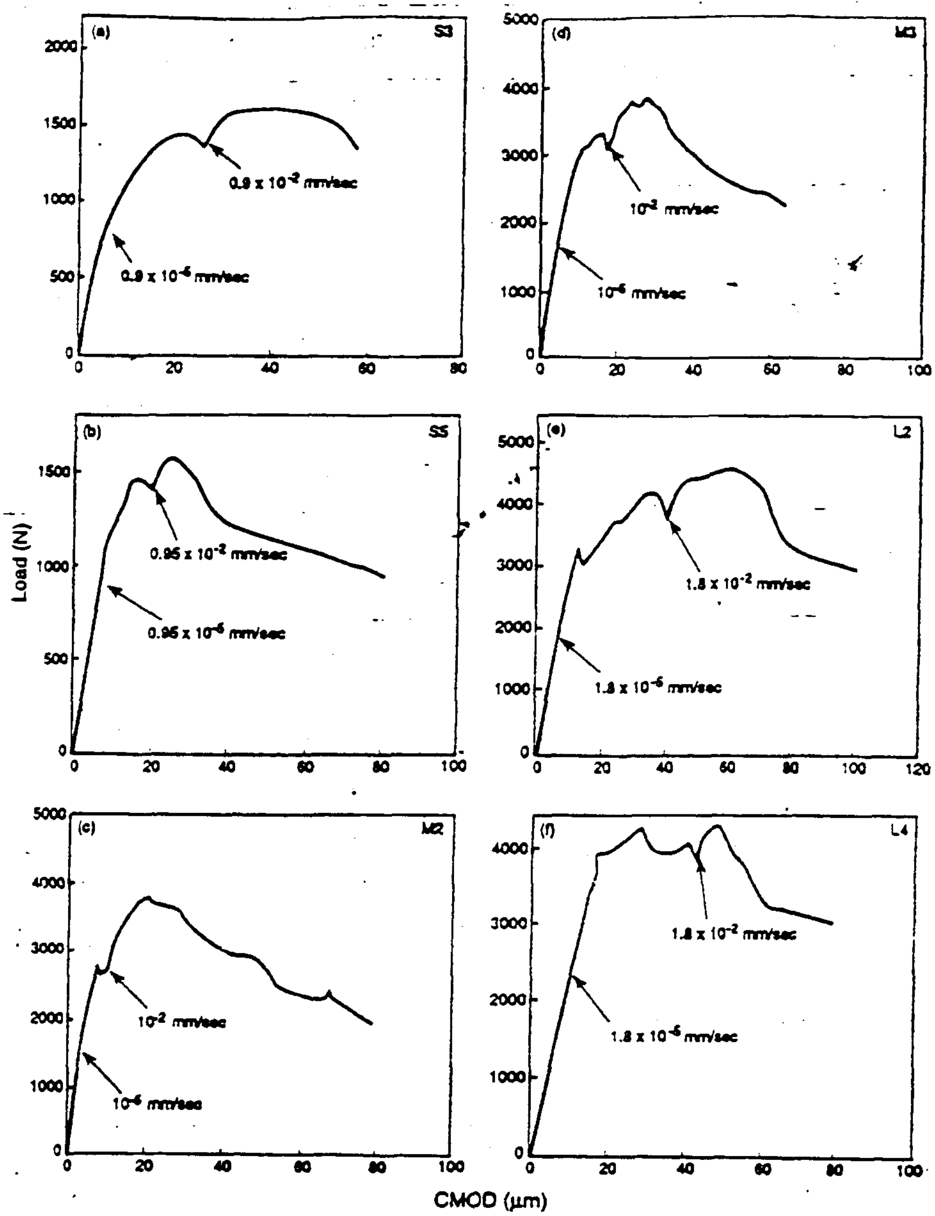

Fig. 3(a)-(f)—Measured responses for a 1000-fold rate increase after a load drop to 90 to 95 percent P_u (S-small, M-medium, L-large specimen)

dard 28-day cylinder strength of the concrete was f_c' = 37 MPa (5370 psi).

The specimens were three-point-bent notched beams shown in Fig. 1. Specimens of three sizes, characterized by beam depths d = 38, 76, and 152 mm (1.5, 3, and 6 in.), were tested (labeled as S—small, M—middle, L—large). The specimens of different sizes were geometrically similar in two dimensions, and the beam thickness b = 38 mm (1.5 in.) was constant for specimens of all the sizes. The beam length was $8d/3$, the span was $2.5d$, and the notch length was $d/6$. The specimens were cast with the notch face at the bottom. The notches were cut with a diamond band saw, and were 1.8 mm (0.07 in.) wide.

The specimens were cured in water for 65 days, at which time they were tested (within a few hours after retrieval from the water bath). During the tests, the specimens had their surfaces sealed with siliconized acrylic latex to prevent moisture loss. The specimens and their material were the same as in the preceding study by Bažant and Gettu (1992).

The specimens were tested at controlled CMOD rates. To bring the effects of the loading rate to light, the loading rate must change by several orders of magnitude, and the change of loading rate must be sudden, almost instantaneous. This can be achieved only in a computer-controlled closed-loop testing machine. The testing frame must also be sufficiently stiff and the pumps sufficiently powerful to make such a sudden change of loading rate possible. These conditions were met by using an MTS closed-loop testing machine (20-kip load frame using test star digital controls).

Fig. 2(a,b) shows, as an example, the record of the CMOD time history produced by the loading equipment. It is seen from Fig. 2(a) that, compared to the previous history, the loading rate changes practically instantaneously since the time curve immediately becomes an almost vertical line. In Fig. 2(b), the time scale is greatly expanded to show the detail of the CMOD history at the time of the rate change. Here one can discern some imperfections (such as load oscilla-

Specification*	Age, day	First rate, mm/sec	First peak P_u	Rate change	Second rate, mm/sec	Second peak P_u'
S1	66	0.7×10^{-5}	1575 N 20 μm 2940 sec	0.91 P_u 1428 N 23 μm 3350 sec	0.7×10^{-2}	1.10 P_u 1726 N 27 μm 3355 sec
S3	66	0.9×10^{-5}	1468 N 21 μm 2730 sec	0.95 P_u 1388 N 26 μm 3070 sec	0.9×10^{-2}	1.12 P_u 1646 N 37 μm 3076 sec
S5	66	0.95×10^{-5}	1486 N 15 μm 1700 sec	0.93 P_u 1379 N 20 μm 2145 sec	0.95×10^{-2}	1.07 P_u 1588 N 24 μm 2150 sec
M2	64	1.0×10^{-5}	2758 N 8 μm 800 sec	0.97 P_u 2669 N 10 μm 1000 sec	1.0×10^{-2}	1.35 P_u 3725 N 20 μm 1001 sec
M3	64	1.0×10^{-5}	3292 N 15.6 μm 1560 sec	0.91 P_u 3003 N 16.2 μm 1680 sec	1.0×10^{-2}	1.16 P_u 3803 N 27.0 μm 1687 sec
L1	67	1.4×10^{-5}	4279 N 35.6 μm 2516 sec	0.91 P_u 3874 N 53.0 μm 3785 sec	1.4×10^{-2}	1.03 P_u 4408 N 64.2 μm 3789.9 sec
L2	67	1.8×10^{-5}	4248 N 30.4 μm 1690 sec	0.90 P_u 3817 N 44.2 μm 2450.4 sec	1.8×10^{-2}	1.02 P_u 4319 N 49.4 μm 2453.9 sec
L4	67	1.8×10^{-5}	4163 N 35.9 μm 2020.4 sec	0.89 P_u 3701 N 39.8 μm 2235.4 sec	1.8×10^{-2}	1.07 P_u 4469 N 60.6 μm 2242.3 sec

* S(d=38 mm); M(d=76 mm); L(d=152 mm).

Table 2—Specimen test series

Specimen*	Age, days	First rate, mm/sec	First peak, P_u	Rate change	Second rate, mm/sec	Second peak, P_u'
S2	66	1.0×10^{-5}	1600 N 12 μm 1150 sec	0.63 P_u 1001 N 45 μm 4520 sec	1.0×10^{-2}	0.71 P_u 1134 N 54 μm 4527 sec
M5	55	1.0×10^{-5}	4404 N 15 μm 1500 sec	0.66 P_u 2891 N 30.5 μm 3115 sec	1.0×10^{-2}	0.75 P_u 3314 N 37 μm 3119 sec
L3	67	1.8×10^{-5}	3345 N 25.9 μm 1420 sec	0.64 P_u 2148 N 91.7 μm 5115 sec	1.8×10^{-2}	0.77 P_u 2562 N 134 μm
S4	66	2.0×10^{-5}	1824 N 16 μm 1105.4 sec	0.26 P_u 467 N 144 μm 7060.3 sec	5.0×10^{-2}	No second peak

* S(d=38 mm); M(d=76 mm); L(d=152 mm).

tions just before the steep rise); however, these imperfections are insignificant compared to the duration of the test.

EFFECT OF SUDDEN INCREASE OR DECREASE OF LOADING RATE

For a sufficiently large increase of the loading rate, the results shown in Fig. 3 reveal that the post-peak softening can be reversed to hardening that is followed by a second peak, after which a new post-peak softening branch begins. The second peak can be higher or lower than the first peak at the previous slow rate of loading, depending on the ratio of rate increase and on the magnitude of the load decrease prior to the increase of rate. Fig. 3(c) shows a typical response, in which the initial loading rate was 10^{-5} mm/sec (CMOD rate) and, relatively soon after the peak load P_u, the loading rate was suddenly increased 1000 times to 10^{-2} mm/sec, at the moment when the load had dropped to 97 percent of P_u. The second peak P_u' occurs at 3725 N (837 lbf). For loading his-

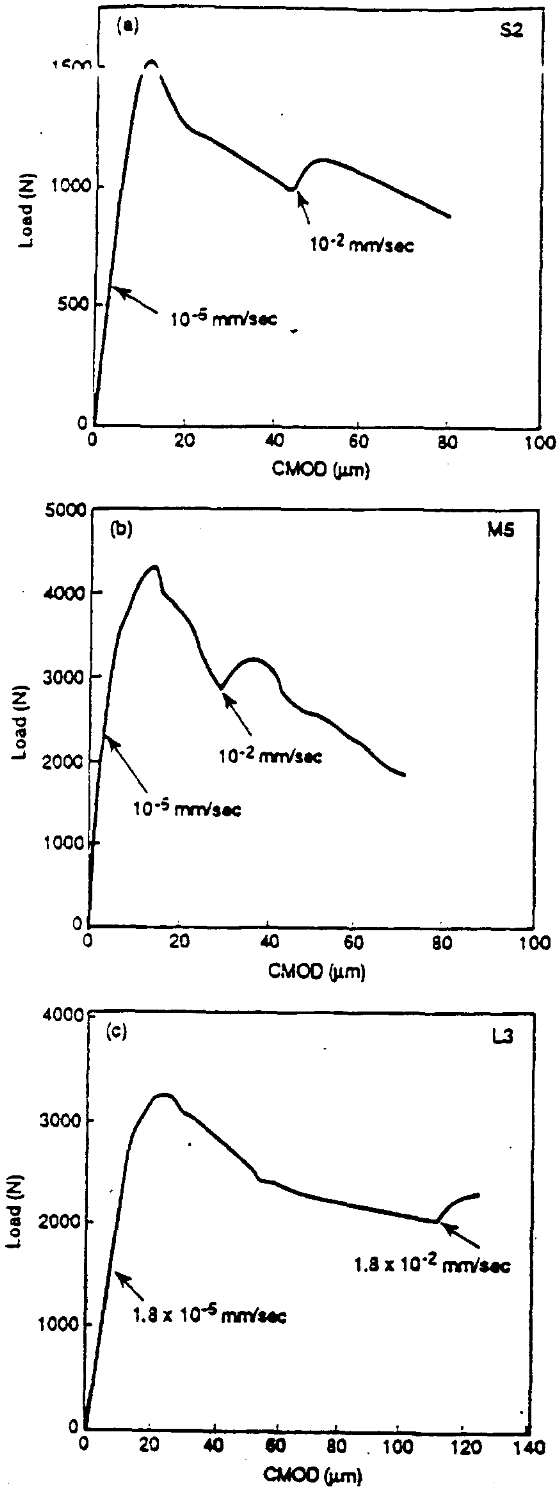

Fig. 4(a)-(c)—Measured responses for a 1000-fold rate increase after a load drop to 0.65 P_u (S-small, M-medium, L-large specimen)

tories of this type, the second peak P_u' generally occurs at the load of about 110 to 135 percent of the first peak P_u.

The test results obtained on various individual specimens are given in Table 1. The response diagrams of load versus CMOD are shown in Fig. 3(a) through (f) for specimens of three sizes (small, medium, large) and for different values of the load drop from the previous peak at which the rate was chosen to be suddenly increased.

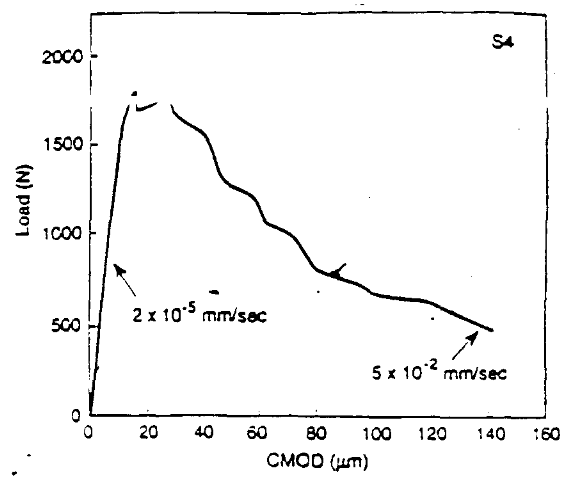

Fig. 5—Measured responses for a 1000-fold rate increase after a load drop to 0.26 P_u

Some load-CMOD diagrams exhibit small pseudo-peaks [S5, L2, L4 in Fig. 3(b), (e), and (f)] before the first peak is reached. In some specimens, one can see a relatively flat region [M2 and L2, Fig. 3(c) and (e)] occurring after the first peak. These two phenomena are probably not systematic and are caused by random effects, specimen microstructural heterogeneity, and similar influences.

In another test series, the faster rate started after a much-greater load drop, namely, from P_u to 0.65 P_u. The second peak still ocurred; however, it was lower, only about 0.75 P_u [see Table 2 and Fig. 4(a) through (c)].

In the single specimen tested, no second peak was found when the faster rate started after a much greater load drop, from P_u to 0.26 P_u (Fig. 5).

In a second group of tests, the specimens were loaded at the fast rate and, in the post-peak regime, the loading rate was suddenly decreased 10 times, from 10^{-4} to 10^{-5} mm/sec. The results are shown in Fig. 6(a) through (c) and also given in Table 3. The sudden decrease in loading rate was always accompanied by an almost instantaneous drop in load followed by a conventional post-peak softening reponse.

DISCUSSION OF RESULTS AND CONCLUSIONS

Testing several identical specimens at the same loading history reveals that there can be substantial scatter. This is exemplified by Specimens MA1 and MA2 [Fig. 6(b) and (c)]. In future extensions of this program, it would therefore be desirable to test a larger number of specimens and conduct their statistical evaluation. Nevertheless, despite the limited scope of the presently reported tests, the results show, overall, a coherent picture. Similar effects are seen for different but similar loading histories, and certain trends are clearly discernible. From these overall trends, the following conclusions may be drawn.

1. An increase of the loading rate in the post-peak regime causes a stiffening of the response, and if the rate increase is sufficiently large (several orders of magnitude), the post-peak softening is reversed to hardening and is followed by second peak.

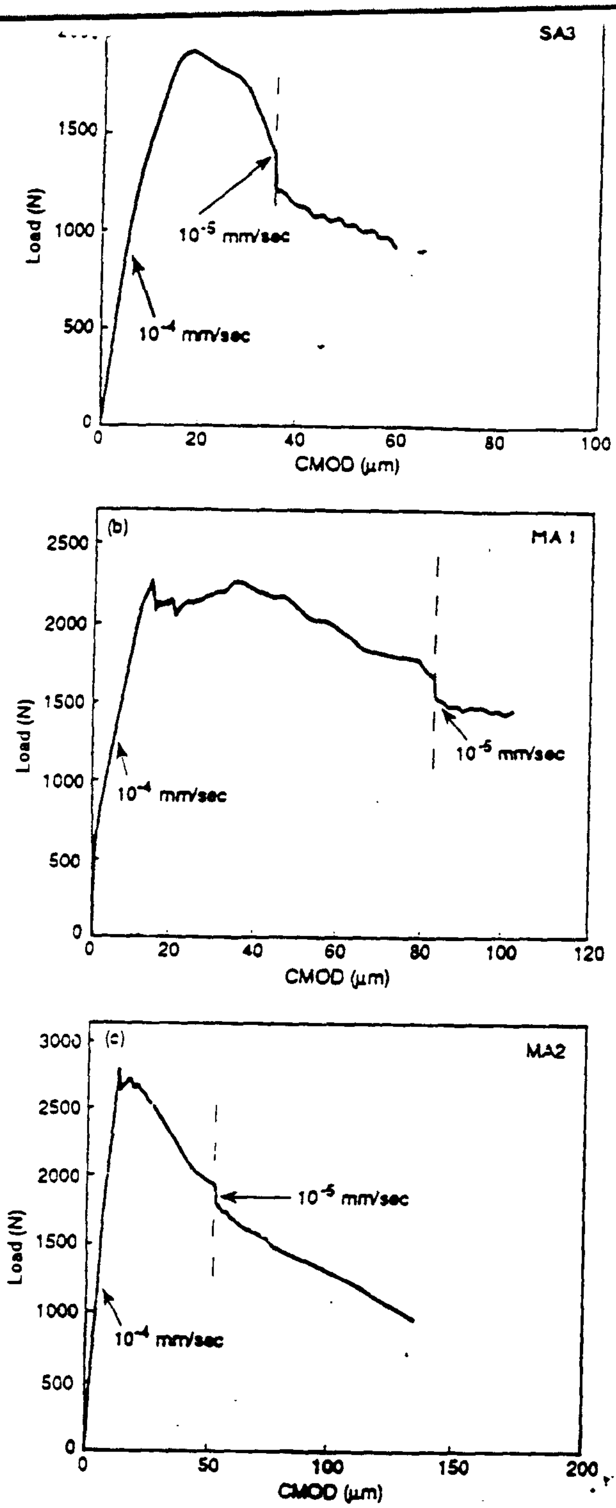

Fig. 6(a)-(c)—Measured responses for a 10-fold rate decrease (S-small, M-medium)

2. The second peak may be larger or lower than the first peak under the previous constant rate of loading. The greater the post-peak load drop prior to the rate increase, the smaller is the rise to the second peak.

3. After a decrease of the loading rate, the descending post-peak slope first becomes steeper, but later the previous slope is resumed again.

4. The effects of the loading rate change are similar for specimens of various sizes (the data for specimens of various

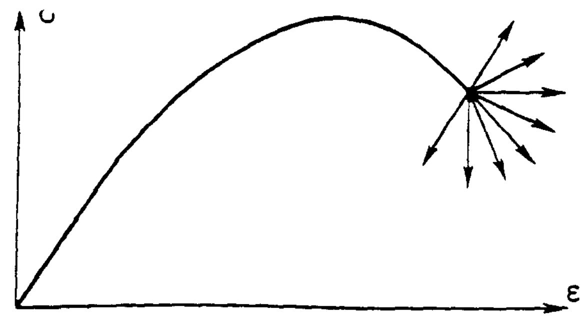

Fig. 7—Load deflection slopes accessible by changing the loading rate in the post-peak softening regime

sizes will be needed for developing a mathematical model).

It is also interesting to compare the present results to the results of relaxation tests from Bažant and Gettu (1992). The relaxation tests correspond to a decrease of the loading rate to zero. The present results show that the response to a decrease of the loading rate gradually approaches the relaxation tests.

On the basis of this study, as well as the previous study by Bažant and Gettu (1992), one may infer that by a certain sudden change of the loading rate it is possible to produce any of the loading slopes shown by arrows in Fig. 7.

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Table 3—Test results—Second group

Specification	Age, day	First rate, mm/sec	First peak, P_u	Rate change	Second rate, mm/sec
SA1	68	1.0×10^{-5}	2103 N 27 μm 2778 sec	0.82 P_u 1717 N 43 μm 4444 sec	1.0×10^{-8}
SA2	68	5.0×10^{-4}	2259 N 26 μm 53 sec	0.81 P_u 1828 N 53 μm 108 sec	5.0×10^{-5}
SA3	68	1.0×10^{-4}	2028 N 19 μm 182 sec	0.70 P_u 1419 N 35 μm 344 sec	1.0×10^{-5}
MA1	68	1.0×10^{-4}	2268 N 33 μm 321 sec	0.74 P_u 1668 N 82 μm 789 sec	1.0×10^{-5}
MA2	68	1.0×10^{-4}	2820 N 14 μm 132 sec	0.64 P_u 1806 N 52 μm 537 sec	1.0×10^{-5}

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