Microcracking and Stress-Strain Curves for Concrete in Tension

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1. INTRODUCTION

The direct tension test for concrete is not commonly practised despite the fact that the test is of considerable theoretical and practical significance to understand structural behaviour of concrete. Although not recommended as a Standard test, its validity and general characteristics are being studied in a number of university laboratories.

Evans [1], and Todd [2] tested a number of plain concrete specimens in direct tension and their results indicated that stress-strain curves did not contain any appreciable inelastic deformation. During the tests, it became apparent that sudden failure of the specimen prevented any observations beyond the peak stress i.e. along the falling branch of the curve.

Complete stress-strain curves for concrete in compression have been known for some time, but it was not until 1963, that Rusch and Hilsdorf [3] demonstrated the existence of such characteristics for concrete in direct tension. Hughes and Chapman [4] have recently supplemented these findings.

It is accepted that the shape of the stress-strain curve is the property of the material, but it can also be affected by the experimental conditions, namely (i) the technique used in the test, and (ii) the length and location of the strain gauges, Blakey and Beresford [5] in studying the second aspect, observed that the magnitude of the inelastic strains in the tension zone in bending tests depended mainly on the fracture plane passing through the gauge length.

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2. DESCRIPTION OF THE TESTS

To obtain a complete stress-strain curve for concrete in direct tension, it was essential to eliminate occurrence of sudden failure near the peak stress. This was achieved by modifying a 100 ton Universal Testing Machine so that its stiffness characteristics were steeper than the steepest portion of the falling branch of the stress-strain curve. A frame consisting of bright mild steel bars and black mild steel plates was constructed in between the two crossheads of the testing machine. It applied a tensile restraint to the displacement of the crossheads and thus the deformation of the specimen could be precisely controlled. This arrangement (fig. 1) was also advantageous since the load was initially applied to the frame displacing the plates apart and which

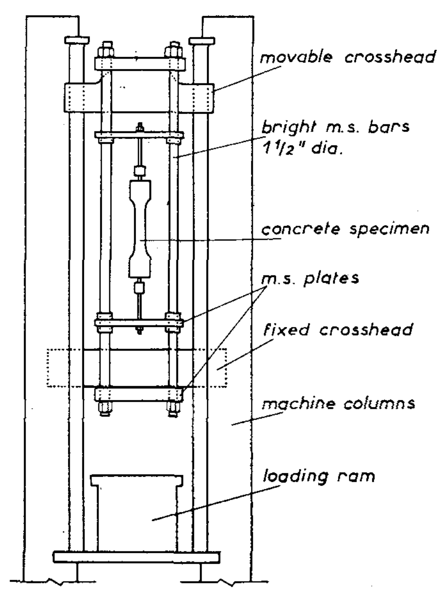

FIG. 1. — **Modified tension machine (100 tons).**

in turn applied the load to the specimen. The bars were designed to obtain an extension equal to the total elongation of the specimen consisting of the overall elongation and the local deformation due to initiation of a microcrack.

In the tests, either 1 inch SR or PL-60 Japanese Ers gauges were used. The load in the specimen was determined by loading a calibrated rod in line with the specimen. A binocular microscope was used to detect the presence of microcracks and to measure the crack width, the advantage being that the magnification of the microscope could be increased in steps from 25 to 240 by using a different pair of lenses.

To begin the test, the specimen was loosely fixed in the testing machine and the surface of the specimen was carefully examined for presence of any pre-existing microcracks. After taking up any slack, the specimen could be further strained by increasing the load on the frame.

The specimen was further strained at a rate of 10 microstrains per minute. This was achieved by driving the machine manually while observing the progressive change in the longitudinal tensile strain. When the surface of the specimen was observed for microcracks, it was found difficult to maintain the constant rate of strain. Therefore, a limiting rate of 25 microstrains per minute was adopted ensuring that the specimen did not fail abruptly, particularly near the peak stress and along the falling branch of the curve. However, this did not affect the test performance seriously as the change was necessary for a short period only.

3. DISCUSSION

a) *Extensibility of Concrete :* Kaplan [6] showed that in a direct tension test for concrete cracking occurred between 30 to 80 microstrains, the extensibility depending upon the proportion of coarse aggregate in the mix. The present tests indicate that the extensibility varies between 90 to 140 microstrains and the corresponding stress as 68 to 89 % of the maximum stress. The difference between these two series of tests is mainly due to the method adopted to deter-

TABLE I

Curve No.	Mix Proportion	Strain at first crack	At intermediate points			
			total strain	crack width (inch)	residual strain	% error
1	2	3	4	5	6	7
1	1:1:2 — 0.45 45 days	100	250 435 900	1/7500 1/4740 1/1560	15 125 170	6.0 28.7 19.0
2	1:2:4 — 0.60 42 days	120	370 410 1200	1/4740 1/3120 1/800	0 0 25	0 0 2.0
3	1:3:6 — 0.90 42 days	125	225 425 700	1/3750 1/1560 1/780	10 15 25	2.6 — 3.0
4	1:1:2 — 0,45 65 days	160	400 1000 1930	1/4740 1/2400 1/780	30 425 450	7.5 42.5 23.0
5	1:2:4 — 60 270 days	120	520 800 1260 2000 2800	1/3750 1/1875 1/1560 1/900 1/450	40 150 500 780 450	8.0 19.0 39.0 39.0 16.0
6	1:3:6 — 0.90	130	260 550	1/3750 1/1560	20 130	— 23.0
7	3:1 — 0.45 (no fines) 31 days	200	550	1/3120	30	6.0
8	3:1 — 0.45 (no fines) 42 days	140	230 525 900	1/7500 1/3120 1/1200	40 65 10	— 12.4 1.0
9	3:1 — 0.45 (no fines) 105 days	120	280 650 1200	1/6240 1/3120 1/900	15 180 35	— 27.5 —

Note — All strains in micro unit.
The residual strain has been calculated by taking into account the strain corresponding to the crackwidth in the gauge length and the strain observed at the initiation of first crack.

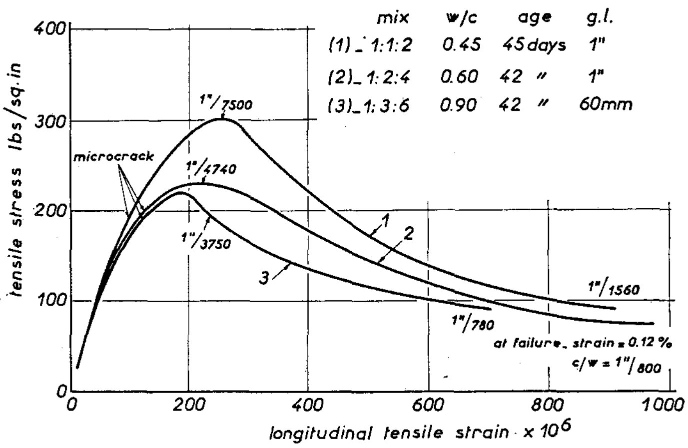

FIG. 2a. — **Complete stress strain curves in direct tension.**

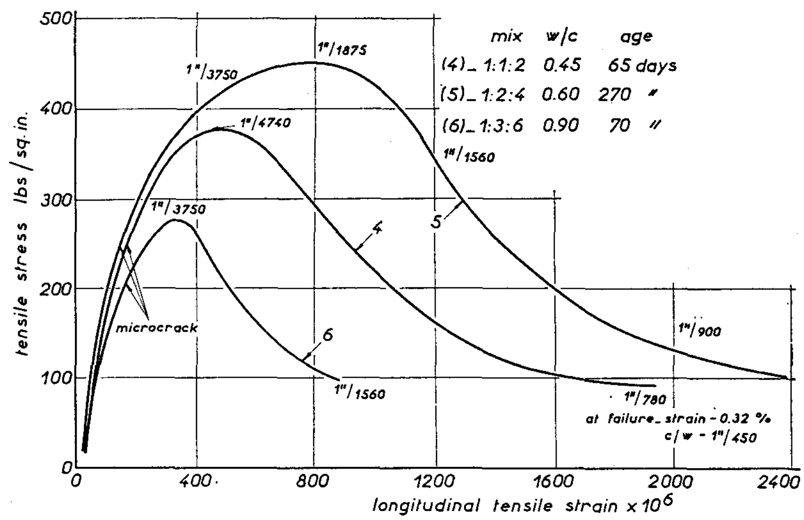

FIG. 2b. — **Complete stress strain curves in direct tension (Contd).**

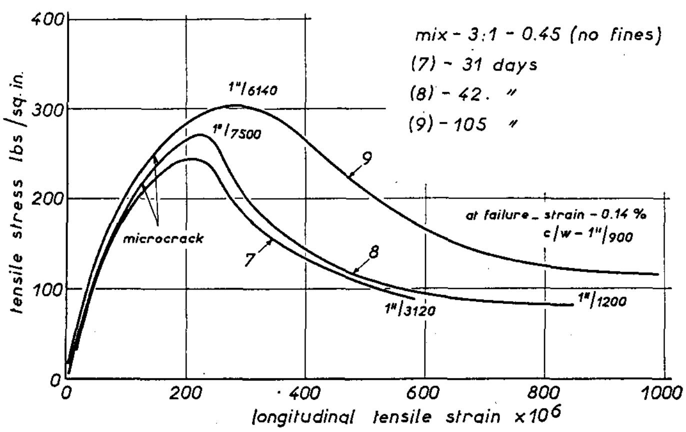

FIG. 2c. — **Complete stress strain curves in direct tension (Contd).**

mine the extensibility of concrete. Kaplan used a proportional limit of two microstrains to determine from the stress-strain curves the point where the first crack occurred whereas a microscope (240 *x*) was used by the authors to locate the initiation of a microcrack. The results of the present test supplement the experiences and data obtained by Evans [1].

b) *Microcracking and Strains:* In the tests, large strains were observed and these were phenomenal as compared to the strains recorded by others [4]. Therefore, an attempt was made to correlate the recorded strains and corresponding crack widths. It can be seen from Table I that the large strains mainly occur due to initiation of microcracks within the gauge length.

The main difference between these tests using a modified testing machine and tension tests using an ordinary testing machine is the existence of the falling branch of the stress-strain curve. In both types of the tests, the specimen fails due to a microcrack traversing across the entire cross-section and separating the specimen into two parts. However, in the tests using a modified testing machine, the crack propagation is sensibly controlled by restricting the effect of the strain energy stored in the machine parts. Immediately after a microcrack is initiated, the strain energy in the specimen is gradually transferred to the loading device, i. e. bars and the plates of the framework. Although it is difficult to check fully a crack propagating on the surface

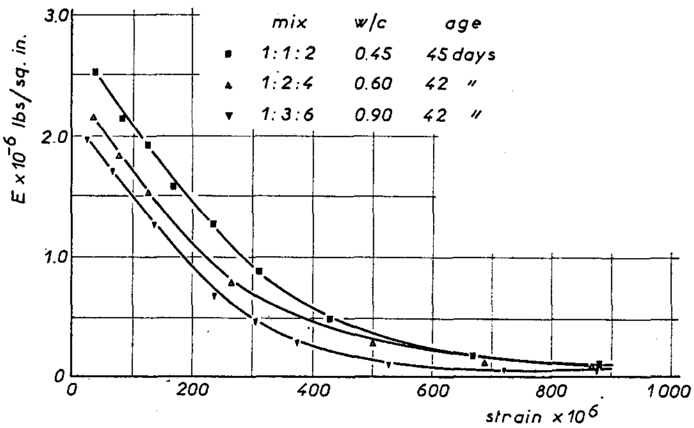

FIG. 3. — Graph showing variation of E with strain.

of the specimen, the velocity of the crack propagation is partially retarded, by restricting the amount of strain energy stored in the specimen, the fact which made the observation of the microcracks much easier.

c) *Modulus of Elasticity (E):* The modulus of elasticity is calculated as the secant modulus and its variation with the strain increase is shown in figure 3. It can be seen that the values of E are low to some extent, the reasons being that the strains were measured over a short length and all the stress-strain curves included the effect of a microcrack initiating within the gauge length.

On the falling branch of the stress-strain curve, the value of E falls rapidly, reaches 0.25×10^6 lbs/sq. in. at about 600 microstrains. Beyond this, the curve becomes asymptotic. Therefore, large strains observed during the tests did not affect E even though a large difference existed between the strains observed near the failure of two specimens of the same mix proportion. This was not due to variation in the structural behaviour of the specimen but due to a wider microcrack existing within the gauge lengths.

d) *Mechanism of Failure of the Specimen:* It can be observed from the stress-strain curves that the specimen fails on the falling branch, at a stress which varies between 25 to 40 % of the maximum stress. In the tests, as failure was approached the strain commenced to increase rapidly and it was necessary to decrease the load on the frame to maintain the strain rate within the limit of 25 microstrains per minute.

This became difficult just before failure when the strain increased very rapidly and the strain rate could not be maintained within limits by operating the machine controlmanually. The specimen usually failed at this point.

4. SIGNIFICANCE OF COMPLETE STRESS-STRAIN CURVES

A knowledge of complete stress-strain curves is now essential as it gives more information about the mode of failure of concrete. The phenomenon of redistribution of stress in certain localized regions of a complex structure is closely associated with the ability of concrete to undergo large deformations without total failure. These tests have demonstrated that specimens in direct tension can sustain large strains at some percentage of maximum stress.

These tests have also illustrated the importance of understanding the effect of crack propagation on the shape of the stress-strain curves, since it is quite possible that the characteristic shape of the load deformation curve for fundamentally different materials, can, by selecting appropriate testing conditions be made to look very much alike.

5. SUMMARY

These tests have shown that complete stress-strain curves for concrete in direct tension also exist and such curves can only be obtained by using a modified testing machine. To perform the test successfully, it is essential that the crack should initiate within the gauge length, so as to indicate the extent of failure in the specimen by the rate of strain increase. The large strain values observed in these tests are primarily due to initiation of a microcrack within the gauge length.

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