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Cracking in Reinforced Concrete.

Rißerscheinungen im Eisenbetonbau.

Fissurations dans le béton armé.

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The use in reinforced concrete construction of high tensile steel with increased working stresses must almost inevitably lead to increased cracking. In the past the cracking normally obtained had apparently no serious effect on the stability of the structure and was usually insufficient to cause important corrosion of the reinforcement. The cracking accompanying higher steel stresses, however, is proportionately greater than the increase in stress and it is possible that, with the higher stresses that could be allowed for high tensile steel on a yield point basis, the cracking will be more important.

The increased rapidity of hardening of modern cements is another factor which may seriously affect the cracking. Many complaints have been received at the Building Research Station recently of shrinkage cracking in cases where no trouble was previously experienced with the less rapid-hardening cements of 10—15 years ago.

In view of this tendency to increased cracking, therefore, work is being carried out under the supervision of Dr. *Glanville* at the Building Research Station, in co-operation with the Reinforced Concrete Association, to determine the factors that control cracking in reinforced concrete members. The present paper describes briefly some of this work.

Strain Capacity of Concrete.

It has long been thought that the criterion for failure of concrete in tension may be the ultimate tensile *strain* that can be sustained rather than an ultimate tensile strength. The strain capacity of concrete, i. e. the extension that can occur without the formation of cracks, has been determined by many investigators with widely different results. The lack of agreement is probably due to two main reasons: 1) variation in the initial stress conditions in the members before test and 2) variation in the accuracy of observing the appearance of cracks.

It appears that the effect of reinforcing steel is normally to increase the strain capacity of the concrete by only a small amount; when reinforced concrete members are stored in air, tensile stresses are set up in the concrete as a result of shrinkage, with an adverse effect on the subsequent strain capacity when the member is loaded. On the other hand, the presence of the reinforcement may lead to a considerable increase of the effective strain capacity under conditions of moist curing.

It is likely that the apparent increase in strain capacity due to the reinforcement observed by some workers was partly the result of insufficiently accurate observation of the appearance of the first crack. In tests at the Building Research Station, with a smooth whitened surface it has been found possible to detect cracks 0.0001 in. in width by eye, though normally the cracks are a little wider when they first appear. Crack widths are measured in all tests on reinforced concrete members, using portable microscopes with eyepiece scales.

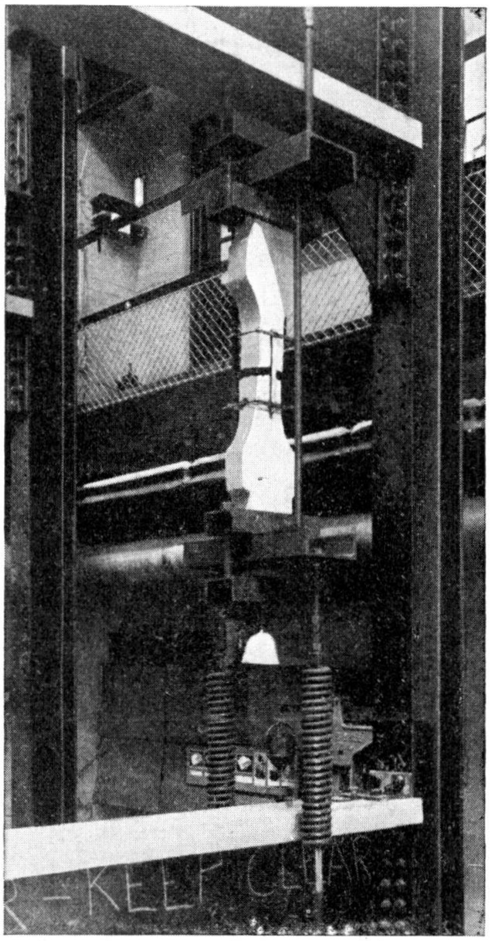

Fig. 1.
Measurement of Shrinkage Stresses in Restrained Concrete Members.

Shrinkage Cracking.

Shrinkage of concrete is probably the most frequent cause of cracking and also the most difficult to remedy or prevent. In the case of unrestrained reinforced concrete members, shrinkage induces tensile stresses in the concrete so that, particularly with high percentages of steel, cracking may occur even when no external load is applied. In practice, however, some degree of end restraint is almost always present, particularly in monolithic frameworks. The effect of creep of the concrete is to reduce the concrete stresses so that in this connection creep is helpful in reducing the tendency to crack. The resistance of a concrete to cracking for any particular end conditions can be obtained roughly from a study of the shrinkage, creep, elasticity and strength properties of the concrete, the combined effects being estimated mathematically. Although this method gives a fair comparative idea of the resistance to cracking there is sometimes doubt as to the exact creep properties of the concrete at stresses just below the ultimate tensile strength and a more direct experimental method has therefore been developed.

A special apparatus was designed in which concrete specimens, with extensometers attached to the central portion, were maintained under tensile loads by means of springs and these loads were adjusted periodically so that the shrinkage movements were entirely balanced by the elastic movements and creep due to

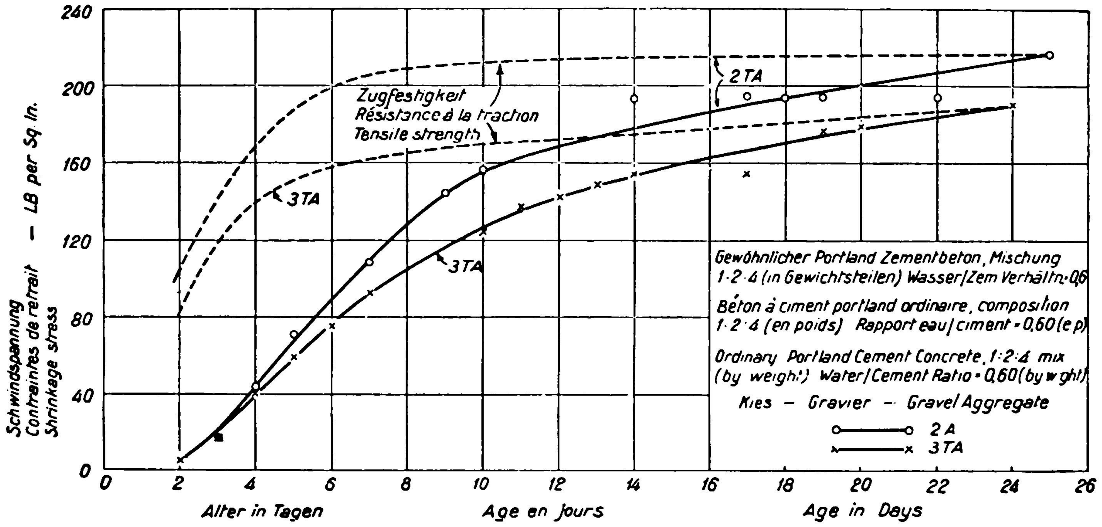

Fig. 2.

Resistance to Shrinkage cracking of completely restrained ordinary Portland Cement Concrete.

loading. By this means the actual shrinkage stresses set up in a completely restrained member could be measured. A photograph of the apparatus after failure of a specimen is shown in Fig. 1.

The results of duplicate tests on ordinary Portland, rapid-hardening Portland and high alumina cement concretes are shown in Fig. 2—4. A 1:2:4 mix (by weight) with a water/cement ratio of 0.60 was used in all cases. It will be seen from the figures that the shrinkage stresses are little different for the Portland cement concretes, but as failure is approached with ordinary Portland cement the development of stress decreases considerably as a result of large creep movements. This effect is not so great with rapid-hardening Portland cement, the stress increasing steadily until the tensile strength is reached and cracking occurs. With the high alumina cement concrete there is a rapid increase in stress, the factor of safety against cracking being negligible shortly after the commencement of the test.

Other tests have indicated that an increase of water content is not necessarily followed by a greater tendency to crack, and that the resistance to cracking is markedly affected by the type of aggregate used. It is realised that in practice complete restraint will not usually be imposed and that the relative resistances to cracking of various concretes may be somewhat altered by the degree of fixity. Further tests are therefore being made in which the end fixity is not complete.

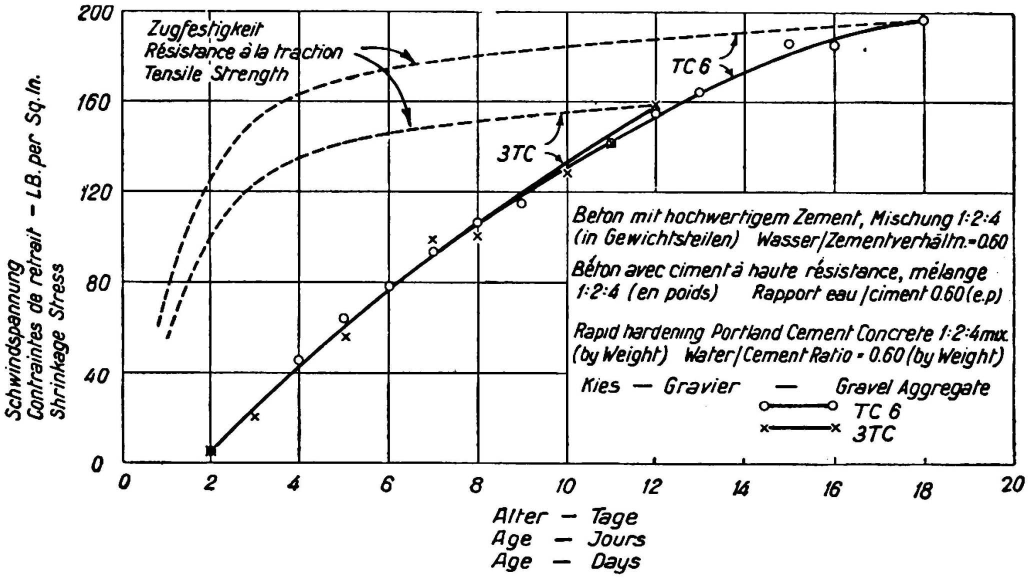

Fig. 3.

Resistance to cracking of completely restrained Rapid Hardening Portland Cement Concrete.

Strain Cracking.

In this section will be considered only the condition where the tensile forces producing cracking are the result of directly applied loading, as in the case of tests in bending or tension. In all tests on reinforced concrete members now being made at the Building Research Station the widths of cracks are measured and it is hoped that at a later date a complete analysis of these measurements will provide considerable information on strain cracking. Certain general results are already available and a few of the tests in which crack measurements have been made are described below.

In one test the beam was rectangular in section, 4 in. wide and $8^1/_4$ in. deep and 7 ft. long. The tensile reinforcement consisted of two mild steel bars of $^3/_8$ in. diameter at an effective depth of 7 in., and suitable stirrup reinforcement was provided to resist shear. The beam was loaded at third points on a 6 ft. span. The appearance and progress of cracks up the side of the beam were carefully observed and the widths of each crack near the bottom of the beam and at the level of the steel were measured for every increment of load.

The load was first increased steadily to the calculated working load and this load was maintained for 21 hours. After this period the load was gradually removed. The results of the crack measurements are shown in Fig. 5. It will be seen from this Figure that the total crack width (i. e. the sum of the widths of all cracks) increases to some extent during the period under sustained load, and that on removal of the load there is a partial recovery in crack width. It is interesting that on reducing the load slightly from the working value the total crack width increased somewhat, and one or two cracks increased slightly in length.

The recovery in crack width on removal of the load is what *Probst* calls the "elastic width" of the crack. In the present test the "elastic width" was on the average just over one-half of the actual width of crack. However, the term "elastic" must be used with caution for it is seen from Fig. 5 that the recovery does not take place uniformly on reduction of the load, but the crack width remains practically constant during the early stages of unloading. It is clear that

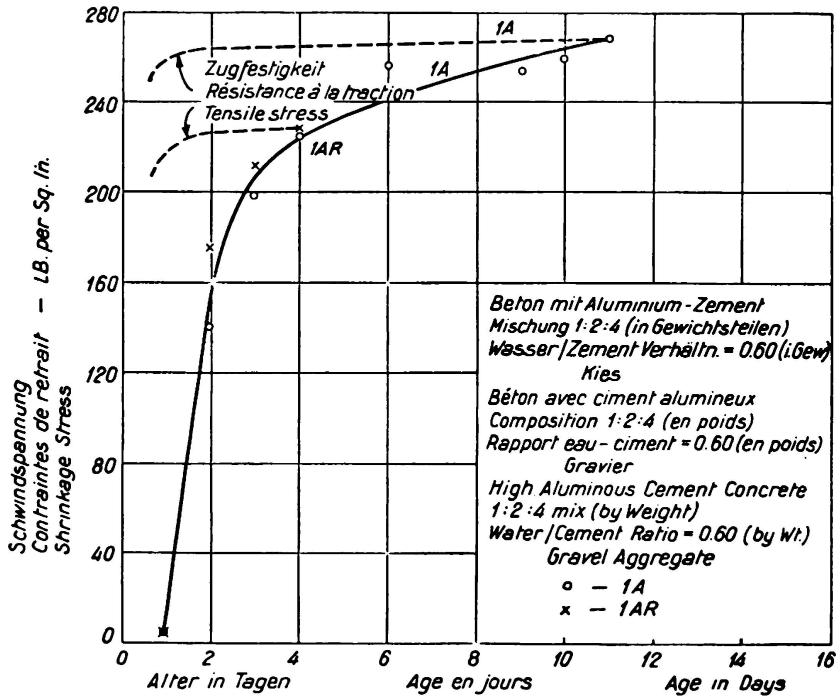

Fig. 4.

Resistance to cracking of completely restrained High Aluminous Cement Concrete.

before recovery can take place the slip mechanism at the steel has to be reversed and this reversal requires a substantial load change.

The beam was left without load only for sufficient time to measure the crack widths, and was then steadily loaded to a value of $1^1/_2$ times the working load. This load was sustained for 44 hours, during which period very little increase of cracking occurred. The load was then increased until failure of the beam resulted from yield of the steel.

In Fig. 6 the maximum crack width at the level of the steel has been compared with the steel stress, computed from the usual straight line-no tension theory. In this Figure the effects on removing the load have not, however, been included. It will be seen that there is a rough linear relationship between the crack width and the steel stress, and that the crack width is inappreciable on first loading until a stress of about 12,000 lb. per sq. in. The relationship is of the form expected from a simple analysis of the mechanics of cracking.[1]

The yield of the steel is shown in Fig. 6 by the very sharp bend in the curve at a stress of 47,000 lb. per sq. in. The deflection of the beam also increased rapidly at this load, but in cases where more than one layer of tensile reinforce-

[1] *Thomas, F. G.* „Cracking in Reinforced Concrete". Struct. Eng. 1936, 14 (7), 298—320.

ment is used it has been found that the crack widths are a much better guide to the yield point of the steel than the deflection. This point was shown up well in some recent tests at the Building Research Station on two-span continuous beams. The results for one test are shown in Fig. 7. From the crack width diagrams it is seen that the yield point loads at both the central support and in the span are quite clearly defined, but there is no definite indication of the value of these loads from the deflection curve. It is seen, therefore, that in such tests the measurement of the crack widths will help materially in the analysis of the test.

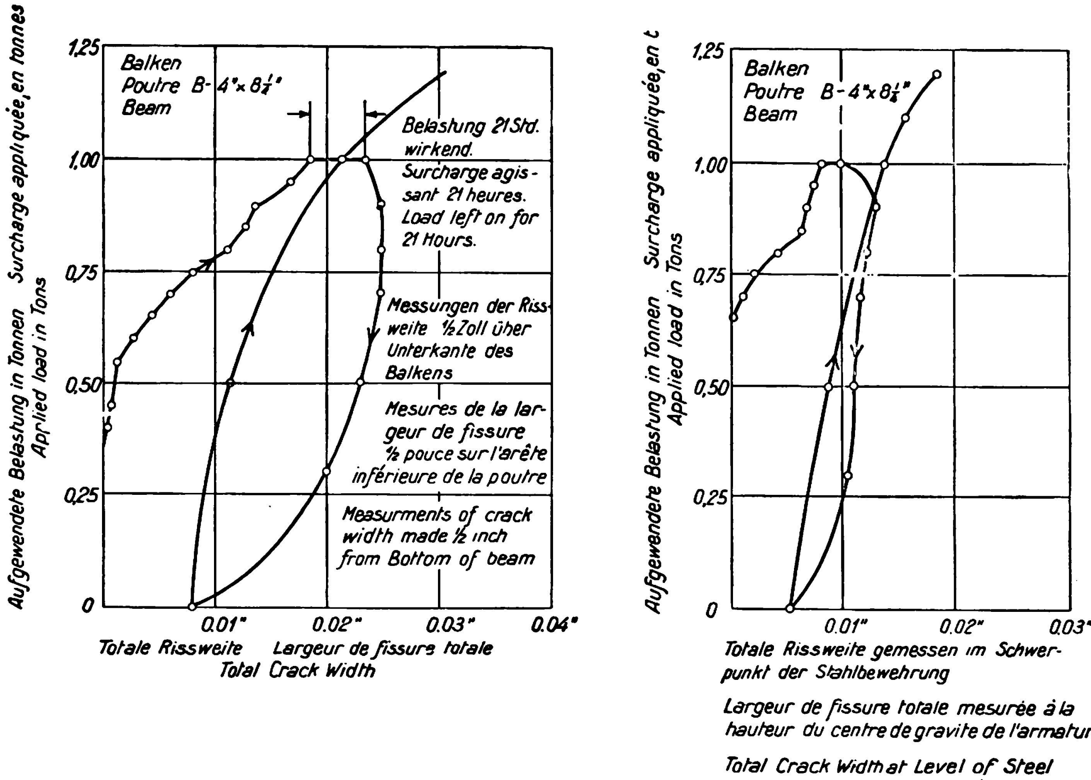

Fig. 5.

Recovery of cracks.

The effect of the percentage of the steel on the crack width when the bar size is kept constant was investigated in some tests on a high tensile steel. Ten beams were tested, all of length 9 ft. 6 in. and overall depth $10^5/_8$ in. Five different widths were used varying from $6^1/_4$ in. to $14^1/_2$ in., two beams of each width being tested. The tension reinforcement consisted in all cases of two compound bars, each of which was made up of two $^1/_2$ in. diameter round bars twisted together helically; the percentage of steel varied, therefore, from about 0.6 to 1.4.

The beams were tested by loading at two points symmetrically 2 ft. 6 in. apart on a span of 9 ft. The results of the measurements of the crack widths in the parts of the beams under constant bending moment (no shear) were as follows:

1) The relationship between steel stress and crack width is not wholly linear. The probable reason for this is that the slope of the stress-strain curve for steel is not constant for the high tensile steel tested but decreases at high stresses.

2) In general, if the crack width-steel stress curve is produced to cut the steel stress axis, the extrapolated stress for zero crack width increases as the percentage of steel decreases. The values for this stress were:

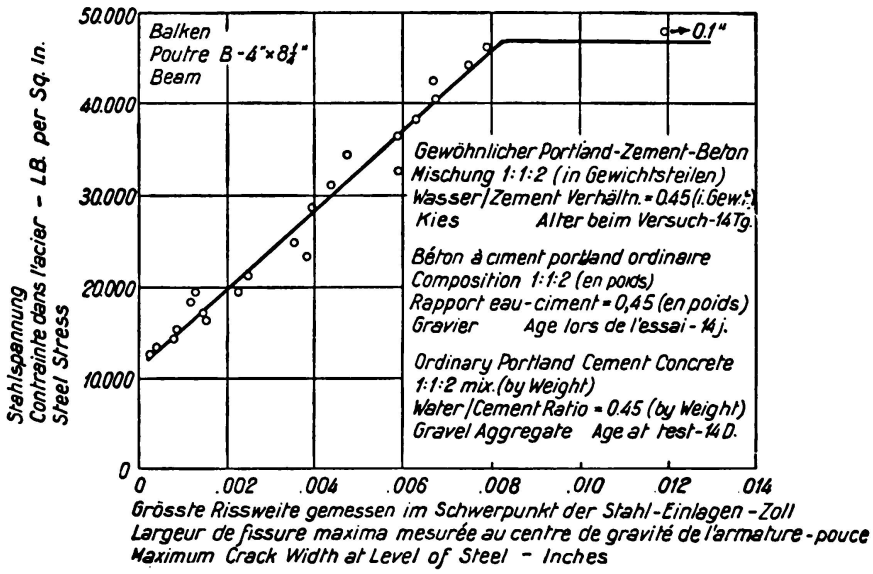

Fig. 6.

Dependence of maximum crack with on steel stress.

Percentage of steel	1.38	1.19	0.98	0.78	0.59
Steel stress for zero crack width — lb. per sq. in.	5,900	4,600	8,900	10,000	13,500.

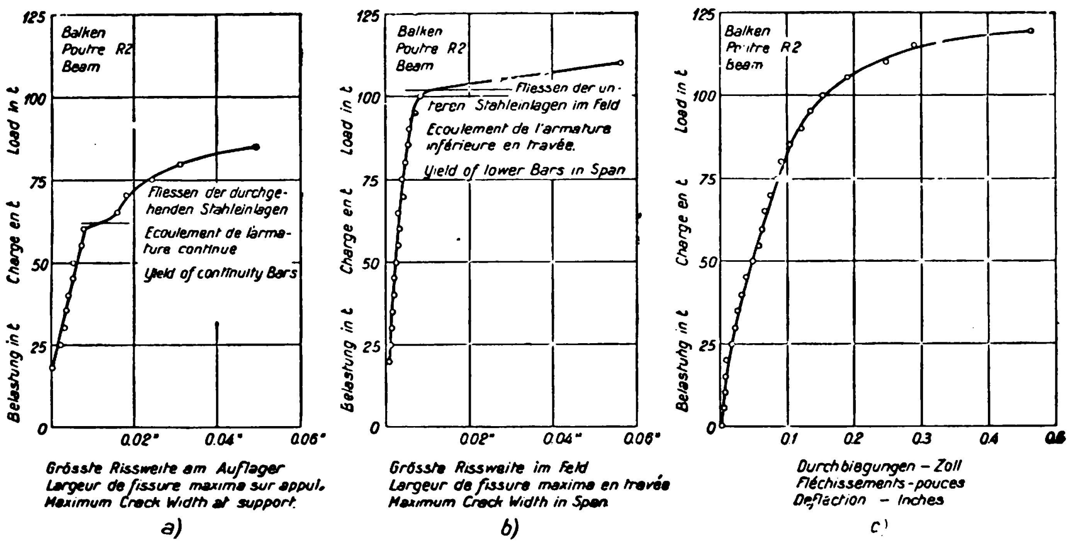

Fig. 7.

Maximum cracks width as guide to steel yield.

This effect tends to keep the cracks small at working stresses for low percentages of steel.

3) The rate of increase of crack width with stress is greater for low percentages of steel. The increases in crack width between 18,000 and 40,000 lb. per sq. in. were:

Percentage of steel . . .	1.38	1.19	0.98	0.78	0.59
Increase in crack width — in. $\times 10^{-3}$	3.9	5.2	6.4	7.3	8.1.

This effect tends to make the cracks bigger for low percentages of steel, particularly when the stresses are increased beyond the values now used in design. If, therefore, for high tensile steel higher steel stresses are allowed leading to decreased percentages, the cracking may be increased as a result of both the increased stress and the decreased percentage if the bar size is unaltered. It should be remembered at the same time that the percentage increase of cracking is decidedly greater than the percentage increase in working stress in the steel.

Effect of Prolonged Loading on Cracking.

An increase with time of the widths of cracks may result from two effects; first, the increase in steel stress due to a continuous breakdown of the concrete in tension and to the creep of the concrete; and second, a creep in bond causing increased slip of the concrete along the steel away from the crack.

Measurements have been made at the Building Research Station of the increase of cracking in reinforced concrete beams, and in one series of tests four beams were maintained under prolonged loading. High tensile steel was used for two of the beams and ordinary mild steel used in the others. At an age of 12—13 days the beams were loaded so that the theoretical maximum steel stress was 20,000 lb. per sq. in. for the plain bars and 27,000 lb. per sq. in. for the high tensile bars. The load was maintained for 6 weeks and was then altered so that the theoretical steel stresses were increased by 50 per cent. This load was sustained for a further period of 6 weeks before the beams were tested to destruction. It was found that the crack widths increased by about 50 per cent. during the early stages of the test when the cracks were extending up the sides of the beams and the concrete creep was comparatively large; and that at a later age, even at the higher steel stresses. the change in crack width with time was small.

Pretensioning of the Reinforcement as a Preventative of Cracking.

The possibility of preventing cracking at working loads by artificially obtaining an initial concrete compression has frequently been advocated, notably by *Freyssinet.* The method is sometimes applied in the case of precast concrete floor slabs. The tension reinforcement is stressed to a high percentage of its yield strength by means of springs or levers before the concrete is cast. The pretensioning apparatus is left in position until the concrete has sufficiently hardened to take the stresses induced in it when the forces in the reinforcing bars are allowed to be taken up by adhesion between concrete and steel.

There are, however, certain difficulties. Immediately the steel load is transferred from the pretensioning apparatus to the concrete section there is a compressive strain in the concrete resulting in a release of tensile load in the steel. At the same time there will be slip at the ends of the bars over the distance required to develop the maximum steel stress, and it would be wise, therefore, to delay the removal of the pretensioning device until the bond strength is sufficient to reduce this distance to a fraction of the whole length of the slab.

Further, between the time of removing the pretensioning apparatus and applying the working load the concrete continues to deform as a result of the creep of the concrete under the action of the internal load, and also through the normal shrinkage of the concrete. Since shrinkage tends to decrease the strain capacity of all air cured concrete this factor does not enter into a comparison between members with and without pretensioning, but in calculating the pretension necessary to prevent cracking under a given bending moment the effect of shrinkage must certainly be considered.

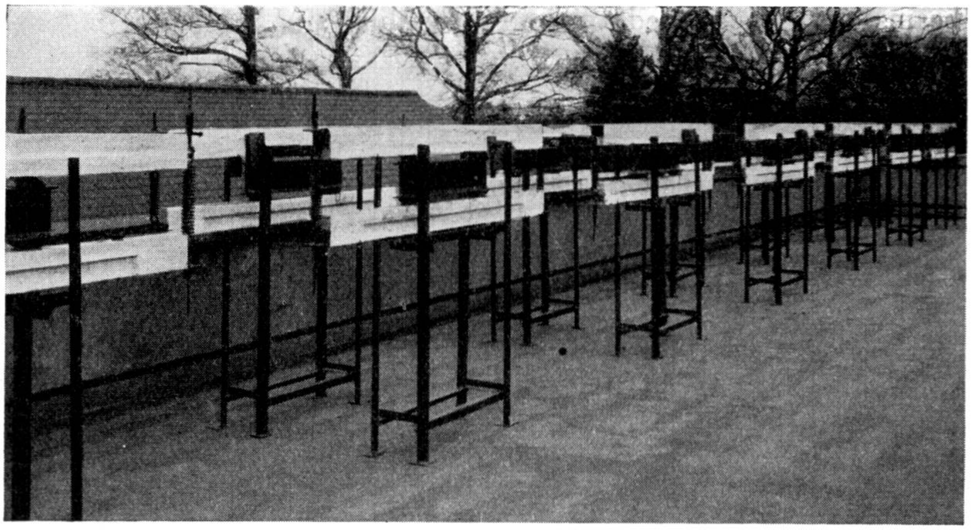

Fig. 8.
Exposure Tests on Reinforced Concrete Beams.

The results of tests at the Building Research Station to determine the effect of pretensioning the tension reinforcement of beams made with foamed slag concrete are given below. The beams were 6 ft. long and of rectangular section, $4^1/_4$ in. wide by $6^1/_2$ in. deep, with two $^1/_4$ in. diameter high tensile steel bars as tension reinforcement and two $^1/_4$ in. diameter mild steel bars as compression reinforcement. The concretes used were:

Beams PT 1 and PT 2. Rapid-hardening Portland cement concrete, $1:1^1/_4:1^3/_4$ by volume, 1:0.55:0.54 by weight, water/cement ratio 0.53 by weight with foamed slag aggregate of maximum size $^3/_{16}$ in.

Beams PT 3 and PT 4. As above, except that the proportions were $1:2^1/_2:3^1/_2$ by volume, 1:1.10:1.09 by weight, water/cement ratio 0.80 by weight.

The tension bars of beams PT 1 and PT 4 only were stressed to an initial tension of 40,000 lb. per sq. in. before placing the concrete, and the pretensioning apparatus was left in position until an age of 14 days. All specimens were stored under damp sacks for 4 days and subsequently in air at 64^0 F. and 64 per cent. relative humidity. At an age of 14 days the pretensioning device was removed from the two beams so that the steel load was transferred to the concrete. All beams were tested at an age of 28 days by loading at third points on a 5 ft. span. A very high tensile steel was used, the failing strength being 120,000 lb. per sq. in. (based on original area); there was no clearly defined yield point but the stress corresponding to a permanent deformation of 0.2 per cent. was 100,000 lb. per sq. in.

The main results of the tests are given in Table 1. At a steel stress of 25,000 lb. per sq. in., calculated according to the usual no-tension theory, there were no cracks in the pretensioned beams but those in the other beams had reached widths of 0.003 and 0.005 in. The deflection at this stress was reduced as a result of the pretension to $^1/_3$ and $^1/_4$ of the deflection of the beams without pretension. In order to obtain the same deflection and crack widths as those that were in the beams without pretension at a steel stress of 25,000 lb. per sq. in. the pretensioned beams had to be loaded to about twice this value.

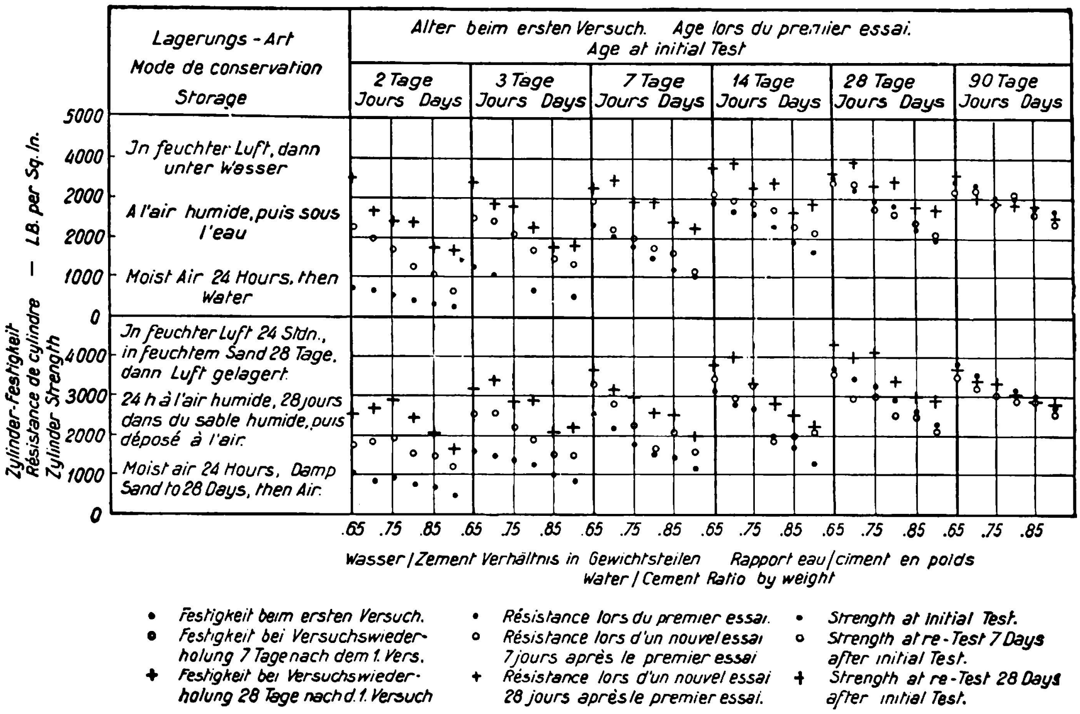

Fig. 9.

Autogenous Healing of concrete.

It is clear, therefore, that pretensioning of the reinforcement is extremely useful in reducing deflection and cracking. It will be noticed, however, that the increase in stress to give the same conditions as in the beams without pretension was about 25,000 lb. per sq. in., and not 40,000 lb. per sq. in., which was the original pretension applied to the steel. Less than two-thirds of the nominal pretension was effective at the time of loading. The reason for this is that the initial strain in the steel is reduced as a result of concrete deformation when the load is transferred from the pretensioning apparatus to the concrete and by subsequent creep of the concrete. The pretensioning had no effect on the failing load of the beams.

TABLE 1.

Effect of Pretensioning Reinforcement of Beams.

	Beam No.			
	PT_1 [1]	PT_2	PT_4 [1]	PT_3
Crack width at steel stress, due to external load, of 25,000 lb. per sq. in. — inch.	0	0,003	0	0,005
Steel stress at which cracking started — lb./sq. in.	35,000	17,000	35,000	14,000
Steel stress in pretensioned beam to give same crack width as in beam without pretension at 25,000 lb./sq. in. — lb./sq. in.	55,000	—	52,000	—
Deflection at mid span at steel stress of 25,000 lb./sq. in — inch	0.019	0.054	0.018	0.080
Steel stress in pretensioned beam to give same deflection as in beam without pretension at 25,000 lb./sq. in. — lb./sq. in	48,000	—	47,000	—
Weight of concrete per cubic foot. — lb.	115		110	
Concrete strength (4 in. cube) — lb./sq. in.	4900		3800	
Average bond strength obtained with a 1/4 in. high tensile steel bar embedded in concrete cylinder, 3 in. diameter, 6 in. long. — lb./sq. in.	14 days 330 28 days 320		310 350	

[1] With tension steel pretensioned to 40,000 lb. per sq. in. (nominal).

Corrosion.

It has been suggested that there is a limiting width of crack below which corrosion of the reinforcement will not take place. Although this seems reasonable, satisfactory evidence on this point has yet to be obtained. It is felt that the best way to do this is by actual exposure tests on loaded reinforced concrete beams, and such tests have been started at the Building Research Station, measurements being made of the progressive cracking of the beams. A photograph of some of the beams is given in Fig. 8. The usefulness of exposure tests by certain other investigators has been severely restricted owing to the lack of data with regard to the widths of the cracks.

Healing of Cracks.

A few years ago Professor *Duff Abrams*[2] tested a number of concrete cylinders to failure, and retested them after a period of some years; they not only took as much load as they had originally taken but gave values from 167—379 per cent. of the original 28-day strength. *Abrams'* opinion was that the small cracks

[2] *Abrams, D. A.* „Question Box". Am. Conc. Inst. Proc. 1926. 22, 636—9.

which opened up at the time of the original test were actually welded together by the subsequent depositing of the soluble materials from the cement and aggregate. It was actually a healing process and the concrete gained in strength much as it would if it had not been subjected to its original load.

Tests carried out at the Building Research Station have confirmed the results of *Abrams*. The tests were on 8 in. $\times$ 4 in. cylinders which were retested at quite short periods of either water, damp sand or air storage after loading to failure. The cylinders were tested in a hydraulic testing machine and were not shattered under test. The results of a few of the tests which may be regarded as typical are given in Fig. 9. In this Figure, which relates to Portland cement concretes of various consistencies, the strengths obtained on first testing are compared with the strengths on re-testing after a period of 7 days and again at 28 days from the initial test. From this Figure it will be seen that the healing is greater for concrete initially crushed at early ages than for older concrete. In most cases a period of only 7 days is sufficient for the concrete to heal sufficiently to bear at least the load that caused failure originally and only in the case of concrete initially tested at 90 days is the period of 28 days insufficient, and even here the difference in ultimate strengths is not very much.

Similar results were obtained with several batches of cement including aluminous cement. In general it was found that:

a) the leaner and more permeable the mix the greater the amount of healing and b) the wetter the mix the greater the amount of healing.

Summary.

A method has been developed whereby the shrinkage stresses in restrained concrete members can be measured until cracking occurs. It has been shown that there is tendency for the resistance to cracking to decrease as the rapidity of hardening of the cement used increases.

The suggestion put forward by several investigators that cracks are to some extent "elastic" — that is, they recover somewhat when the load is removed — has been confirmed, but it is clear that the term "elastic" is not very satisfactory. The cracks do recover when the load is completely removed but the recovery is not proportional to the reduction in load. In fact, a reduction of one-half of the load may cause no change at all in the crack widths owing to the hysteresis due to the change in direction of the slip mechanism at the steel-concrete interface.

It has been found that for a particular bar size the crack widths increase with steel stress more rapidly for low percentages of steel. The increase in crack width that would result from an increase in the working stresses in the tension steel may proportionately be much greater than the increase in stress, particularly as the percentages of steel normally used would tend to be reduced.

Considerable development of cracking may occur in beams under prolonged loading, though a state of equilibrium is reached after a few weeks from loading.

Tests in which an initial pretension of 40,000 lb. per sq. in. was applied to the tension steel of beams have shown that the effect of the elastic and inelastic movements of the concrete may reduce appreciably the effectiveness of pretensioning. In the particular tests cited, the pretensioning apparatus was removed at an age of 14 days, and the beams were loaded at an age of 28 days. The effective pretension had during the intervening period been reduced by concrete deformation to only about two-thirds of its original value.

A series of tests has been made which indicated that fine cracks in concrete members often heal completely with time. The healing process takes place to some extent in air but is more complete in moist curing conditions.

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