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Solid Mechanics, Plasticity, and Limit Analysis

STRESS-STRAIN RELATIONS
FOR RANDOM WIRE
REINFORCED CONCRETE

by

J. L. Carson
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Fritz Engineering Laboratory Report No. 370.1
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STRESS-STRAIN RELATIONS FOR RANDOM WIRE REINFORCED CONCRETE

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National Science Foundation Grants
GY-7459 and GK-14274 to Lehigh University

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ABSTRACT

In recent years it has been brought to light that random wire reinforcement presents an effective crack arrest mechanism in concrete materials. By preventing the propagation of cracks, the tensile strength of the material is greatly improved.

This experiment was designed to measure the effect of the length of the random wire fibers, the percentage by volume of reinforcement, and the age and curing conditions of the concrete on the tensile strength and ductility.

To obtain this information, standard cylinders were tested in direct compression and indirect tension in a set-up designed to obtain the entire stress-strain curves for the material.

Increases in tensile strength on the order of 60 percent, and increases of about one to two hundred percent were measured in the ductility of the reinforced material over the unreinforced material.
1. INTRODUCTION

The use of concrete as a structural material is somewhat limited because of its limited tensile strength. By increasing the tensile strength through the use of random fiber reinforcement, concrete and mortar could have more significant applications in the design of structures. By virtue of its increased strength, the composite material could be used in key bearing points such as the areas surrounding button heads in post or pretensioned prestressed concrete, bearing points of beams, and in the construction of shell structures. The increased ductility of the material could also aid in the design of concrete slabs and shells. Research is being conducted at the present time relating the increase of ductility to bearing capacity in fiber reinforced concrete and mortar.

The idea of using random fibrous reinforcement to increase the tensile strength of materials is by no means a recent one. Many primative societies have applied the principles of this concept almost intuitively. Reeds and grass have been used to reinforce adobe like bricks in many societies, and early American settlers used the same principles to make caulking using animal hair and pastes. However, the application of this concept to concrete has not emerged until fairly recent times.
To date nearly all of the testing and investigations performed on fibrous reinforced concrete have been accomplished through the testing of beams \((2,6,7,8)\). This experiment was initiated in order to determine the influence of length and amount of randomly oriented fibrous reinforcement on the strength and ductility of concrete materials through testing in indirect (split) tension and uniaxial compression. These tests, performed on standard cylinders, were chosen to obtain information of a more fundamental nature.

2. PREVIOUS WORK

As pioneers in the testing of fibrous reinforced concretes, Romualdi and his co-workers \((6,7,8)\), have tested large numbers of beams under static, dynamic, and fatigue loading situations. Romualdi and Mandel \((8)\) have found that the tensile strength of concrete is strongly dependent upon the average spacing of the fiber lengths used as reinforcement. They have shown that substantial increases in tensile strength occur when the average spacing of the fibers is less than 0.5 inches. This average spacing was determined assuming that 41 percent of the fibers would be effective in preventing crack propagation \((8)\). This led to a formula which was proposed for determining the average spacing in inches:

\[
S = 13.8 \frac{d}{\sqrt{1/p}}
\]  

(1)
where $S$ is the average spacing, $d$ is the fiber diameter, and $p$ is the percentage by volume of steel reinforcement.  

This formula is presented here since the comparison of tests under indirect tension to those performed by Romualdi on beams in bending is to be presented in accordance with this spacing formula.

3. SCOPE OF THE EXPERIMENT

Parameters of most importance for this experiment were the length of the short fibers, percentages by volume of fiber reinforcement, and age as well as curing conditions for the concrete and mortar. The diameter of the wire used was maintained as a constant. Black, annealed, 26 gage wire was used throughout the experiment. The percentages by volume used for reinforcement were 0.25, 0.75, 1.50, 2.00 percent. These values were chosen primarily because surround the critical spacing values as observed by Romualdi and Mandel (8). Specimens were tested at 14 and 28 days with 7 and 14 days in curing respectively.

Specimens were made such that for every given length and percentage of reinforcement there were 4 specimens, 2 for tensile testing and 2 for compressive testing. A total of 144 specimens were cast and tested during the course of the experiment.
4. TESTING PROGRAM

4.1 Preparation of specimens

During the experiment, both mortar and concrete specimens were tested. The mix for the mortar consisted of 1 cement (Portland light) to 3 sand to 0.52 water by weight. The concrete consisted of 1 cement to 1.6 sand to 1.5 crushed aggregate (grade 1b, nominal diameter 1/2 inch) to 0.41 water by weight.

All mixings were done in a small rotary mixer. Materials, except for the wire, were first dry mixed, then the water was added. After the mixture had come to uniformity, the wire fibers were added slowly to prevent bundling of the wires and to insure random distribution. The resulting mixture was then molded into standard 6 inch diameter, 12 inch high cylinders according to ASTM specification C192.

The specimens were allowed to set during the following 24 hour period, and then the molds were stripped and the specimens placed in a curing room. Specimens were cured at 100% humidity for 7 and 14 days, and then were allowed to air dry for 7 and 14 days respectively. After the specimens had dried sufficiently at room temperature, those specimens which were to be tested in direct compression were capped to insure parallel and smooth surfaces.
It was noted during the mixing process that as the length of the fibers was increased, and as the percentage by volume of reinforcement was increased, the difficulty in mixing also proportionally increased. The mixing of the concrete was at all times more difficult than the mortar. A limit was finally reached at 1.5% by volume of 1.5 inch wire lengths in the concrete. Attempts to mix to higher percentages with the 1.5 inch lengths while maintaining the same water to cement ratio resulted in large amounts of entrapped air and severe balling of the wire lengths. In Figure 1, the 1.5% by volume of 1.5 inch wire reinforced concrete is shown on the right, and the pitted concrete resulting from higher percentages with the 1.5 inch wires is shown on the left.

4.2 Testing Method

In the testing medium and high strength concretes in uniaxial compression and indirect tension the failures are normally sudden and explosive. It is very difficult to obtain the load deformation curve under these conditions.

It was known that this sudden and violent failure could be traced not only to the material, but also to the equipment used for testing (1,5). Mechanical loading devices are not rigid enough to unload the specimen at the required rate, and hydraulic loading machinery can not usually unload rapidly enough to obtain the unloading
portion of the stress-strain or load deformation curves.

It was necessary to devise a mechanism which could be used on standard testing equipment without elaborate changes in the machinery. This could have been accomplished with equipment with accurate strain control, however, equipment of sufficient capacity was not readily available with these controls. Instead, a mechanism was devised whereby a pair of beams acting in series about the specimen were used to load the specimen. (Fig. 2) thus, the hydraulic loading machinery was able to unload at a sufficient rate through the use of the flexural resistance of the beams.

The beam system consisted of a 12 foot section of a 12 WF 120 of A514 steel and a stiffened spreader beam as a base support for the system. Contact between the beam system and the specimen was through a spherical loading head mounted on the lower flange of the upper beam (Fig. 3).

The beam system was calibrated with the use of SR-4 electrical resistance strain gages mounted on the upper beam, and the load being carried by the beam system was monitored via these gages. Careful monitorization of the strain in the upper beam insured that the system was always operating in the elastic range. The system was calibrated before each day of testing, and was found to vary very little.
Strain in the specimens was monitored by a rheostatic extensometer (Fig. 3) which was connected to a direct stress-strain plotter mounted on the testing machine. Electrical gages were also used to measure strain in some of the specimens. Thus, by measuring the strain in the beam system, and subtracting the calculated load being carried by the beam system from the total recorded load, it was possible to obtain the stress-strain curves for the specimens.

Strain as measured by the electrical resistance gages was monitored and recorded through the use of a B & F Multichannel Digital Strain Recorder.

5. TEST RESULTS

The typical trend for both the tensile and compressive stress-strain curves is illustrated by the comparison of two tensile stress-strain curves for the mortar specimens. Stress in the tensile specimens was calculated by the formula:

\[ f_t = \frac{2P}{\pi dl} \]  \hspace{1cm} (2)

where \( f_t \) = the tensile stress, \( P \) = the load, \( d \) = the diameter of the cylinder, and \( l \) = the height of the cylinder. Figure 4 compares two stress-strain curves of unreinforced mortar (M-0-0.5-T1) and for reinforced mortar (M-1.5-0.5-T1). The larger modulus of elasticity, higher ultimate load, and larger strain at ultimate load
for the specimens which were reinforced is to be noted. The entire stress-strain curves for the tensile testing were not obtained because of failure of the electrical resistance gages at the onset of failure in the specimen.

Tables 1 and 2 show the general trend in the measured properties of the mortar and concrete respectively. Columns 1 through 4 give the parameters for each set of specimens. Column 5 gives the tensile strength as measured by the indirect tensile testing. Column 6 represents the compressive strength as measured through direct compressive testing. Strain at maximum load is reported in column 7 rather than the strain at failure because of the proximity of these points in unreinforced concrete of high strength and a lack of comparative data for some tests. Columns 8 and 9 represent the ratio of the tensile and compressive strengths of the reinforced materials to that of the unreinforced control specimens for each set of specimens.

5.1 Length Dependence

The dependence of strength upon the length of the fibrous reinforcement is shown in Fig. 5 for the mortar specimens. In general, the increase in strength as represented by the strength ratio was higher for the 1/2 inch wire lengths than for the 1 or 1.5 inch lengths in reinforced specimens of both mortar and concrete.
Theoretically, the longer wires in a random orientation would present a more effective crack arrest mechanism than the shorter lengths. However, data as shown in Fig. 5 seems to refute this idea. Postulated reasons for the observed behavior include a more truly random distribution and orientation of the shorter fibers as noted in mixing, and possibly the bending of the longer small diameter wires during the mixing process. If in fact the longer wires became bent in the mixing process, then the data as observed conforms with theory. Bending of the 1 inch wires would result in shorter effective lengths. These shorter effective lengths would not give a more random orientation after mixing since their configuration would aid in the knitting together of the wires. This would cause the strength of the specimen of a given percentage of 1 inch wires to have a lower strength ratio than a specimen of corresponding percentage of 1/2 inch wires. The same thinking would apply to the 1.5 inch wire lengths, only here the effective length after bending would be sufficiently greater to cause a slight increase over the 1 inch fiber specimen strength.

5.2 Effect of Percentage Reinforcement

A rather unique property of the mortar specimens can be observed by comparing the tensile strength ratio to the percentage reinforcement (Fig. 6). The figure shows
clearly that the optimum percentage and length for mortar strength under the test conditions would be 0.75 percent of the 1/2 inch wire lengths. The longer wire lengths did not exhibit the optimum noted for the 1/2 inch specimens, but again, this could be attributed to bending and knitting of the wires.

The concrete specimens did not exhibit the clear optimum observed in the mortar testing; however, they did exhibit the decrease in tensile strength ratios for the longer wire lengths except at 2.00 percent by volume. The strength of the concrete always increased with the increase in percentage reinforcement, but at a decreasing rate.

By inspection of column 9 of tables 1 and 2, it can be seen that the compressive strength was generally not increased greatly. The greatest increases in strength were in the shorter lengths of reinforcement, and this substantiates the more truly random orientation and distribution of the shorter fibers.

The ductility increased with the increase of percentage reinforcement. A definite measure of the ductility can not be reported here because of a lack of comparative data. However, during testing, the increase in ductility actually became visible in the form of gross deformations of the planer surface under strip loading. Figure 7 shows the gross deformation of an originally plane surface in concrete reinforced to 2.00 percent by volume with 1 inch long wires.
5.3 Types of Failure

The increase in the percentage reinforcement also affected the type of failure in the material. In compressive testing, the failure was always planer along the diagonal; but as the percentage reinforcement was increased, the amount of vertical cracking was reduced. Unreinforced specimens failed in a typically destructive manner with extensive vertical cracking. In both the mortar and the concrete specimens, vertical cracking was eliminated by the 1.5 percent by volume of reinforcement in all lengths of wire used. In tensile testing the type of failure also varied with the increase in the percentage reinforcement. The unreinforced specimens failed in the typical planer mode, characteristic of brittle materials. As the percentage reinforcement increased, the mode of failure progressed toward the conical failure predicted by Chen and Drucker (3) which is characteristic of more ductile materials. (Fig. 8). This type of failure under strip loading is based upon a theory of sufficient deformability of concrete under tension to warrant the application of plastic limit analysis to determine bearing capacity. The observed mode of failure is more evidence of the large increases in the ductility of the composite over that of the plain material.
Figure 9 shows a comparison of the strength ratio to the average spacing computed by Romualdi and Mandel's proposed spacing formula (Eq. 1). As in Romualdi and Mandel's experiment, the difference between the theoretical and observed values increases as the percentage increases and the spacing decreases. This again would point to the probability of balling of the wires and possible bending during the mixing process, particularly at higher percentages.

The difference between the two experimental curves is attributable to the method of testing. Tensile strength as measured by flexural beam testing is usually greater than that measured through indirect tensile testing. Thus, the material conforms with previous experience in the testing of concrete materials.

6. CONCLUSIONS

The use of the beam system shown in figure 2 to obtain the entire stress-strain curve for concrete materials in uniaxial compression and indirect tension is very effective, particularly in tensile testing.

The best length and percentage reinforcement for optimum strength is not always the optimum for ductility. However, the optimum percentage and length for strength is usually the best for strain to maximum load.
Mortar exhibited an optimum strength and its largest strain to maximum load at 0.75 percent of the 1/2 inch wire fibers. The concrete gave its best strength at 2.00 percent of the 1 inch fibers. It must be emphasized that only one size of wire was tested in this experiment, and that mixes were not altered to facilitate mixing. Higher strengths and greater ductilities can be obtained by using different sizes and higher percentages of reinforcement.

The significant increase in the ductility of the material as shown by gross surface deformations and the ductile failure mode in indirect tensile testing seems sufficient to warrant the application of plastic limit analysis as proposed by Chen and Drucker (3).

The trend of change in tensile strength as a function of the spacing as proposed by Romualdi was observed in the simple test data.
7. ACKNOWLEDGEMENT

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8. REFERENCES


Table 1

MORTAR RESULTS

<table>
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<tr>
<th>Material</th>
<th>Age (Days)</th>
<th>Reinforcement</th>
<th>Length in. (cm.)</th>
<th>% By Volume</th>
<th>$f'_t$ (Psi (kgf/cm$^2$))</th>
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<th>$\epsilon_u$</th>
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### Table 2

**CONCRETE RESULTS**

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</tbody>
</table>
Fig. 1 Mixing Limitation, 1.5%, 1.5 in. Fibers (Right Side)

TESTING SETUP

Fig. 2 Beam System
Fig. 3 Specimen Setup

Fig. 4 Tensile Stress-Strain Curves for Mortar
Fig. 5  Strength Dependence Upon Fiber Length

28 DAY MORTAR

Fig. 6  Strength Dependence Upon Percentage Reinforcement
Fig. 7
High Ductility Exhibited by Reinforced Concrete

Fig. 8
Ductile Conical Failure Under Strip Loading
Fig. 9  Strength Compared to Average Spacing and Previous Work