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Bond Between Concrete and Steel Reinforcement at Temperatures to 149° C (300° F)

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ABSTRACT

Oak Ridge National Laboratory conducted a series of bond pull-out tests to determine the effect of elevated temperatures [ranging from 24 to 149°C (75 to 300°F)] on the bond strength between concrete and deformed steel reinforcement. This report summarizes the findings of the study, describes the tests and results, and offers recommendations for incorporating these results into the design of structures that must operate within the prescribed range of elevated temperatures.

1. INTRODUCTION

A series of bond pull-out tests was conducted at Oak Ridge National Laboratory to provide a measure of the possible detrimental effects of elevated temperatures on reinforced concrete structures, particularly with respect to the loss of bond strength and slip resistance of embedded steel reinforcing bars. For the tests, three sets of ASTM-standard bond pull-out specimens [15.2-cm (6-in.) concrete cubes with a No. 6 deformed reinforcing bar extending through the cubes] were cast using a 27.6-MPa (4000-psi) limestone aggregate concrete and moist cured for 90 days prior to heating. Two sets of three specimens each were then heated at the rate of 17°C (30°F) per hour to temperatures of 66 and 149°C (150 and 300°F), respectively. They were permitted to soak at the specified temperature for 14 days and then transferred while still hot to a universal testing machine and tested according to ASTM designation C 234-71. Two sets of three 10.2-cm (4-in.) by 20.3-cm (8-in.) unconfined compression cylinders were also tested to determine concrete strength at 149 and 24°C (300 and 75°F). Results of the compression and bond pull-out tests (Fig. 1) indicated little difference in bond strength between 24 and 149°C (75 and 300°F); however, the bond strengths at 66°C (150°F) were consistently below the comparable 24°C (75°F) value. In Fig. 1, the highest, lowest, and mean values are shown for the sets of

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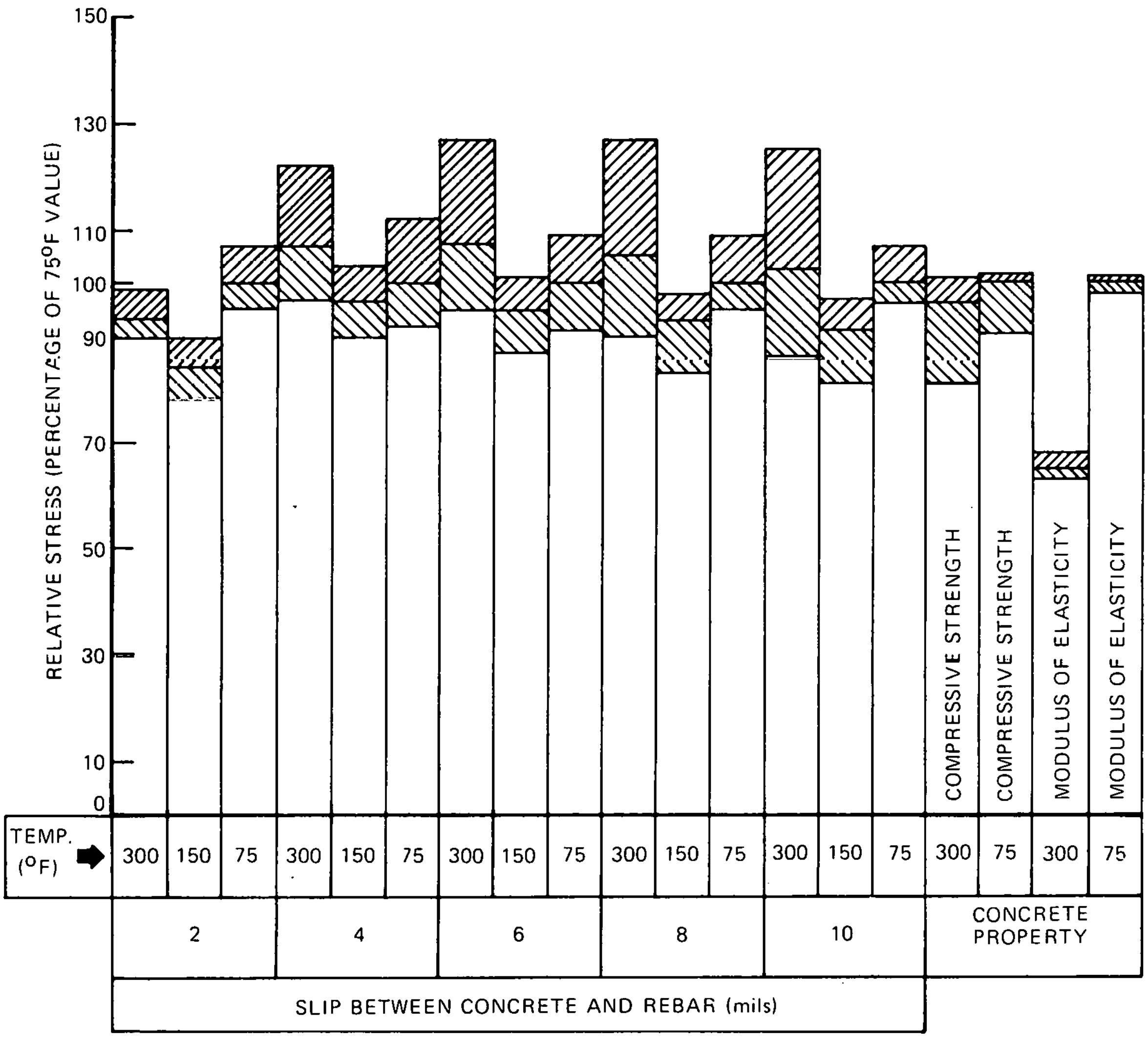

Fig. 1. Results of bond slip and unconfined compression tests (1 mil = 0.001 in. = 0.0254 mm; 300°F = 149°C; 150°F = 66°C; 75°F = 24°C).

three specimens by cross-hatching. The bond stresses are shown for the five slip values recommended by ASTM C 234-71.

For purposes of design, the lower limit to the bond strength for 149 and 24°C (300 and 75°F) appears to agree to within 3%; however, the value for 66°C (150°F) was approximately 10% below the comparable 24°C (75°F) value. Thus for design purposes, a conservative value for bond strength would be 85% of the equivalent 24°C (75°F) value for temperatures up to a maximum of 149°C (300°F). This value also agrees with the 89% decrease in lower-bound compressive strength of concrete at 149°C

(300°F). The basis for this recommendation is strength at 105 days, while design is normally based on a significantly lower 28-day strength value. The modulus of elasticity of concrete heated to 149°C (300°F) was found to be only 63% of the room-temperature value.

The following sections provide a more detailed description of the testing procedures and the results.

2. TEST PROCEDURE

The tests were conducted to determine nominal bond stress at five specified amounts of slip between a concrete cube and an embedded reinforcing bar in order to identify the effects of temperatures up to 149°C (300°F) on the bond between concrete and deformed reinforcement. These data were developed to establish a reasonable bond strength for use in the design of reinforced concrete structures.

3. DESCRIPTION OF SPECIMENS

The basic test specimen consisted of a 15.2-cm (6-in.) cube with a single No. 6 reinforcing bar embedded through the center of two parallel faces. The nine specimens listed in Table 1, together with six 10.2-cm

Table 1. Test specimens

Specimen		Soaking temperature [°C (°F)]
Cube	Cylinder	
75-1	75-1	24 (75)
75-2	75-2	24 (75)
75-3	75-3	24 (75)
150-1		66 (150)
150-2		66 (150)
150-3		66 (150)
300-1	300-1	149 (300)
300-2	300-2	149 (300)
300-3	300-3	149 (300)

(4-in.) by 20.3-cm (8-in.) unconfined compression test cylinders, were cast from a single concrete batch that used a crushed 1.9-cm (3/4-in.) maximum size Tennessee limestone aggregate and had a 28-day design strength of 27.6 MPa (4000 psi). The mixture [as weight per 0.76-m^3 (1-yd^3) batch, water/cement ratio = 0.75] was proportioned as follows:

Component	Weight [kg (lb)]
Water	153 (337)
Cement	213 (470)
Sand	693 (1528)
Gravel	696 (1534)

The specimens were cured by submerging them in water for 90 days. At the end of this curing period, they were heated at the rate of 17°C (30°F) per hr until they reached the temperatures specified in Table 1; they were then maintained at the prescribed temperatures for 14 days. At the end of this heat-soaking period, they were removed one at a time from the oven, placed in position in the universal testing machine, and tested as quickly as possible to prevent excessive cooling. One of the 300-series specimens was permitted to cool prior to testing, but no significant difference in behavior was apparent as a result of this cooling.

The basic procedure used in this study conformed to ASTM designation C 234-71, "Standard Method of Test for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel."

The bond-test setup is shown in Fig. 2. The 15.2-cm (6-in.) concrete cubes were supported above the upper crossarm of a universal testing machine on spherically seated steel bearing blocks and a steel disk which was slotted to permit free movement of a crosspiece. This crosspiece was attached to the reinforcing bar, which passed through holes in the disks and the upper crossarm of the testing machine and was gripped by the lower crossarm of the testing machine. Relative movement of the reinforcing bar and concrete cube was recorded by three dial gages, two of which are shown in Fig. 2. Another dial gage identical to

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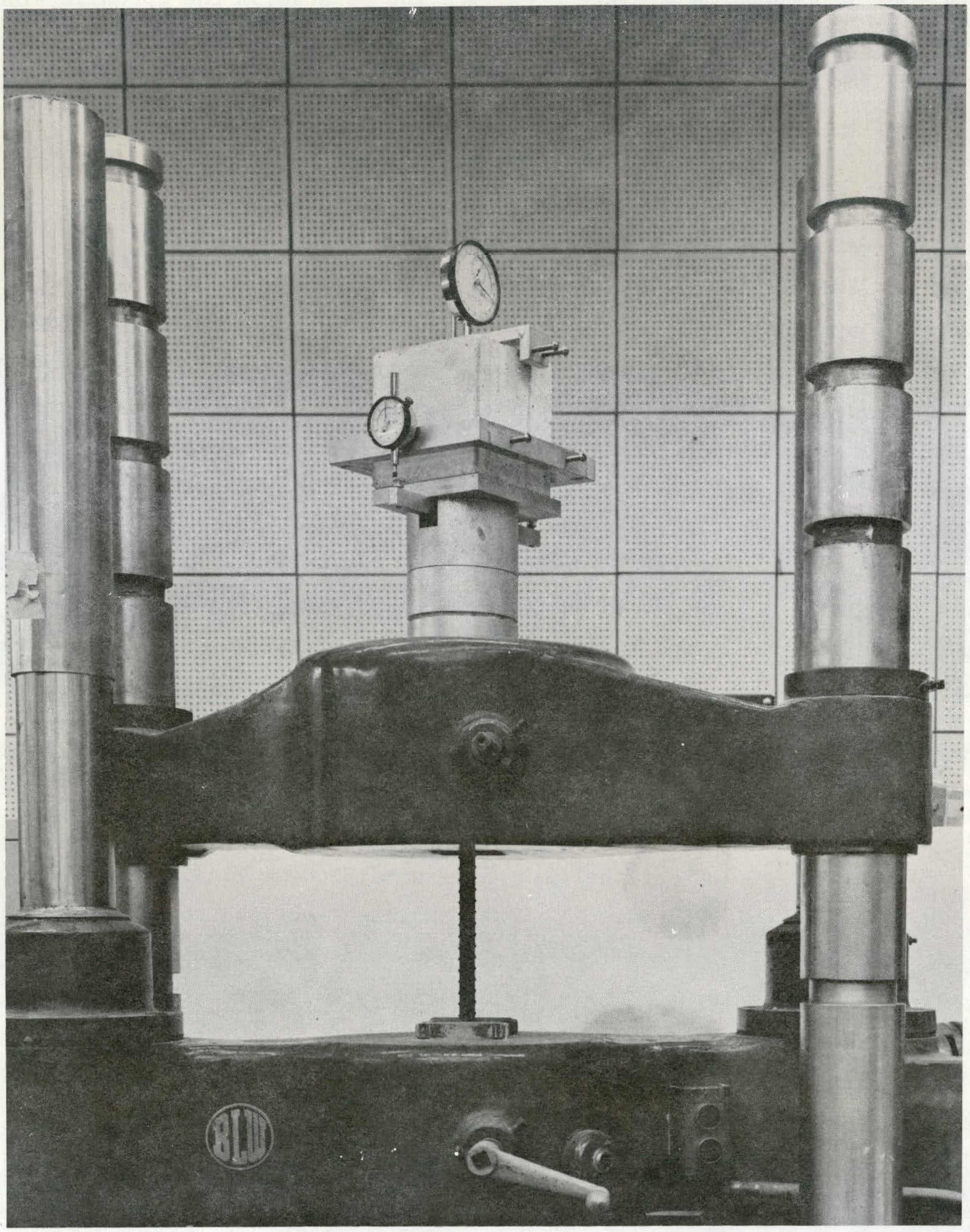

Fig. 2. Setup for bond test.

the one shown bearing on the crosspiece was located on the opposite side of the cube. These two gages measured the slip of the rebar relative to the loaded face of the cube, and the top dial gage measured the relative slip of the unloaded end of the rebar.

The 10.2-cm (4-in.) by 20.4-cm (8-in.) concrete cylinders were tested according to ASTM C 469-65 using a compressometer to obtain concrete strains. The 75-series specimens were also instrumented with 5.1-cm (2-in.) electrical resistance strain gages to provide verification of strains obtained using the compressometer.

Three No. 6 reinforcing bars were instrumented with 2.54-cm (1-in.) strain gages and tested to determine the modulus of elasticity, yield stress, and tensile strength of the rebar. The reinforcing steel conformed to ASTM A615 grade 60 requirements for "Deformed Billet-Steel Bars for Concrete Reinforcement."

During the bond test, the dial gages were read and recorded at 2.2-kN (500-lb) load increments until failure occurred. The concrete compression cylinders were loaded in 11.1-kN (2500-lb) increments, and after each increment, compressometer and strain gage readings were recorded until the ultimate strength was reached.

4. RESULTS AND RECOMMENDATIONS

Relative results of the tests are summarized in Fig. 1 based on the equivalent 24°C (75°F) value. Crossed-hatched sections represent the spread of results between lowest, average, and highest values for each set of three specimens. These results consistently show that the 150-series specimens have the lowest values in every case, although there is some question as to the statistical significance of these data. Four of the series-300 data points had a single relatively high value (specimen 300-2) and tended to bring up the averages for this series. When the results for this one high specimen are taken into consideration, the general trend shows little, if any, difference between bond strengths of 75- and 300-series specimens, while the 150-series specimens are consistently lower. There is no obvious explanation for this observation, and considerably more testing would be required to determine whether there is a basic difference in behavior between the 150- and 300-series specimens.

However, a realistic and conservative design value can be derived from this limited amount of data. It would appear that a bond strength equal to 85% of the room-temperature value should be used in designing a foundation which would operate under temperatures ranging from 24°C to 149°C (75 to 300°F). The recommended design procedure, which is consistent with development length determinations for deformed bars[1] and which will satisfactorily account for elevated concrete temperatures of 149°C (300°F), is to increase the development length (ℓ_d) of deformed bars by 15%. This recommendation is also consistent with the ultimate strength of the concrete at 149°C (300°F), which was 89% of the 24°C (75°F) value. The effect of heating on the modulus of elasticity proved much more significant; the 149°C (300°F) value was 63% of the value at 24°C (75°F).

Series 75-, 150-, and 300-specimens are shown after testing in Figs. 3, 4, and 5, respectively. Little, if any, difference can be seen in the appearance of specimens exposed to the three temperatures.

Bond stresses were calculated using a nominal bond area of 90 cm^2 (14.14 $in.^2$) for the reinforcing bars. The slip of the rebars was obtained by averaging the readings of the two side gages and subtracting the calculated elongation of the portion of the bar extending between the gage crosspiece and the loaded face of the concrete cube. Individual curves of bond stress vs slip for each specimen are shown in Figs. 6 to 14; the stress vs strain curves for the concrete compression cylinders are shown in Figs. 15 to 20, and the stress vs strain curves for the rebar specimens are shown in Figs. 21 to 23.

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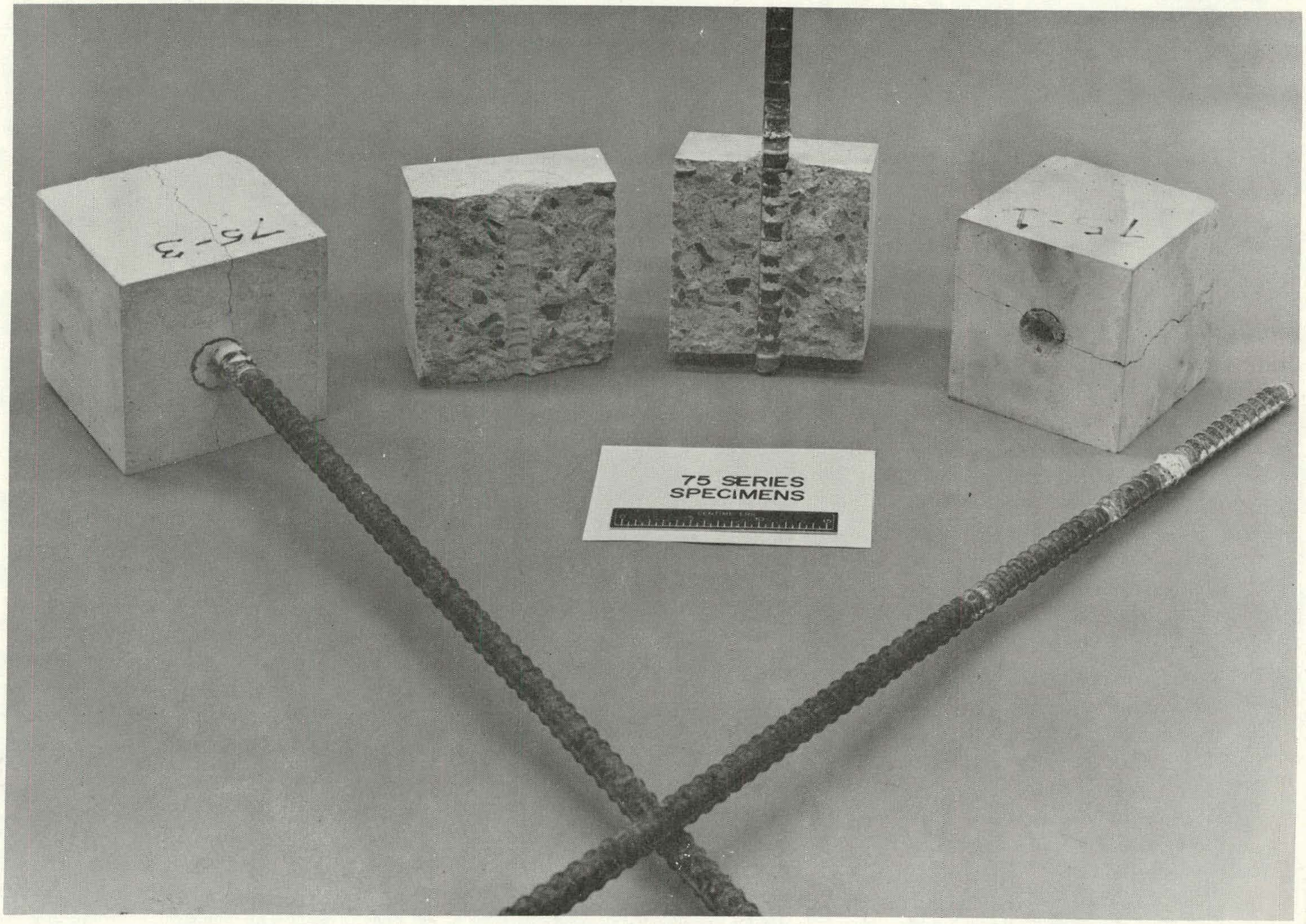

Fig. 3. Series-75 specimens after pull-out testing.

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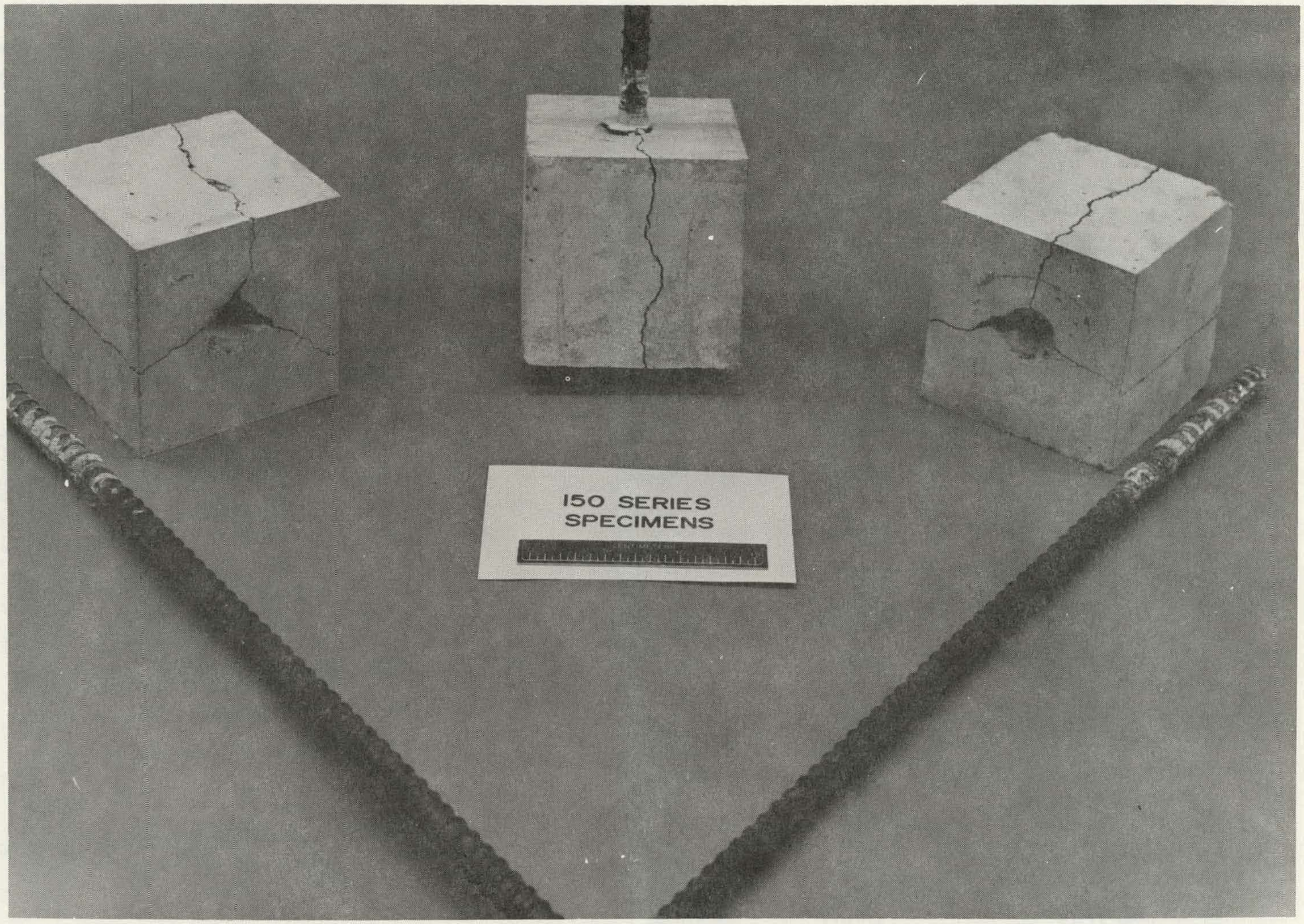

Fig. 4. Series-150 specimens after pull-out testing.

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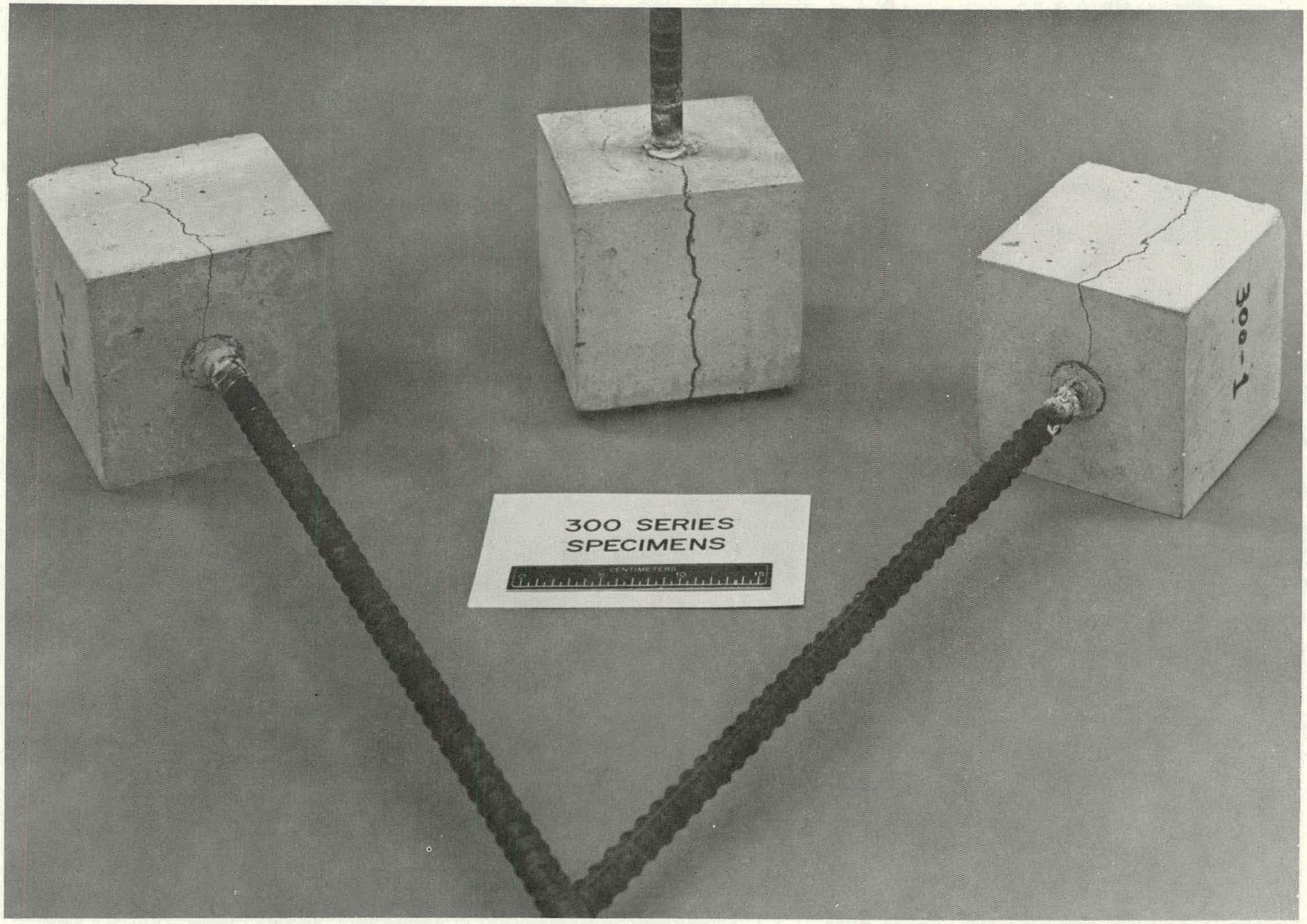

Fig. 5. Series-300 specimens after pull-out testing.

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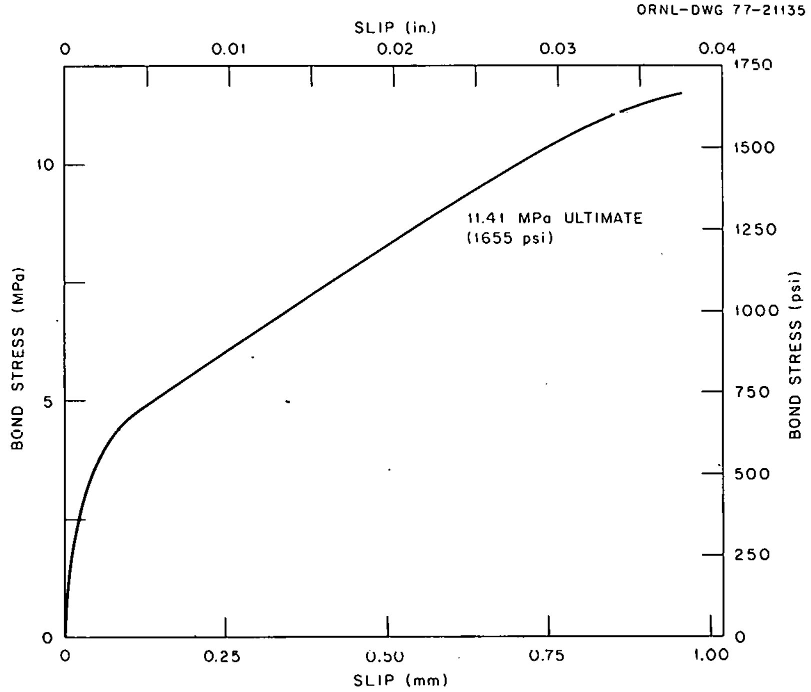

Fig. 6. Bond stress vs slip for 75-1.

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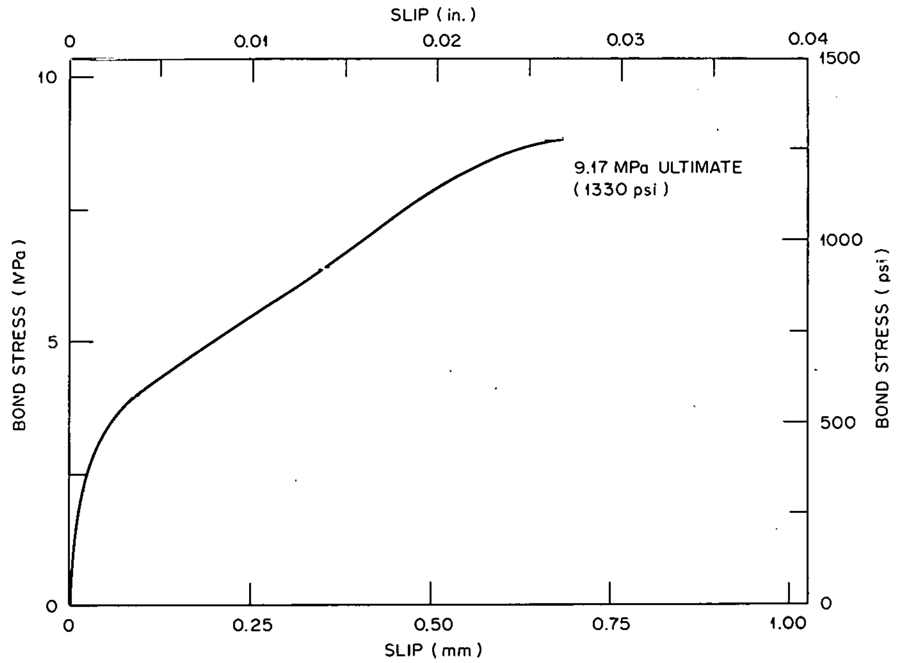

Fig. 7. Bond stress vs slip for 75-2.

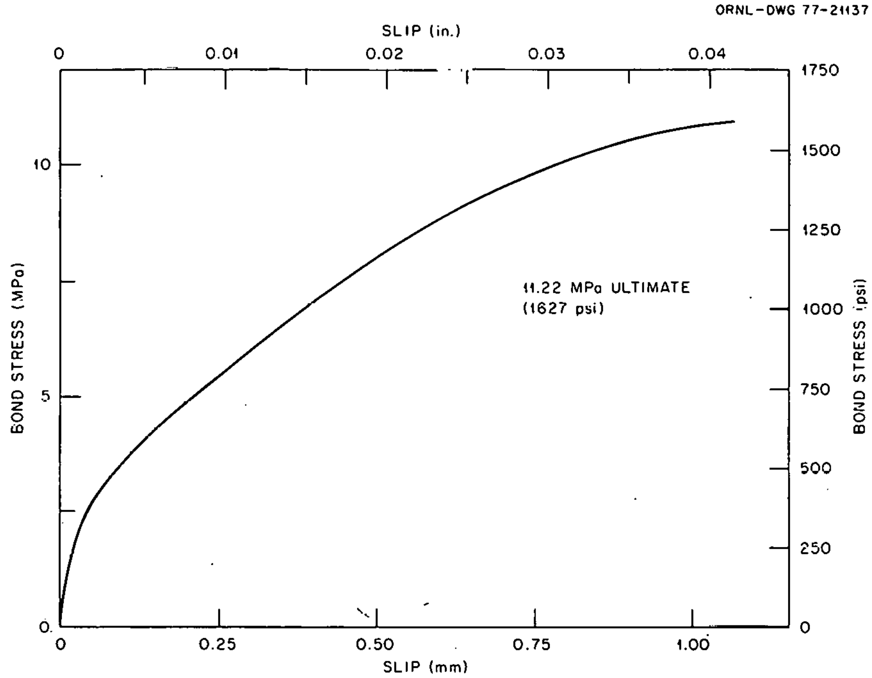

Fig. 8. Bond stress vs slip for 75-3.

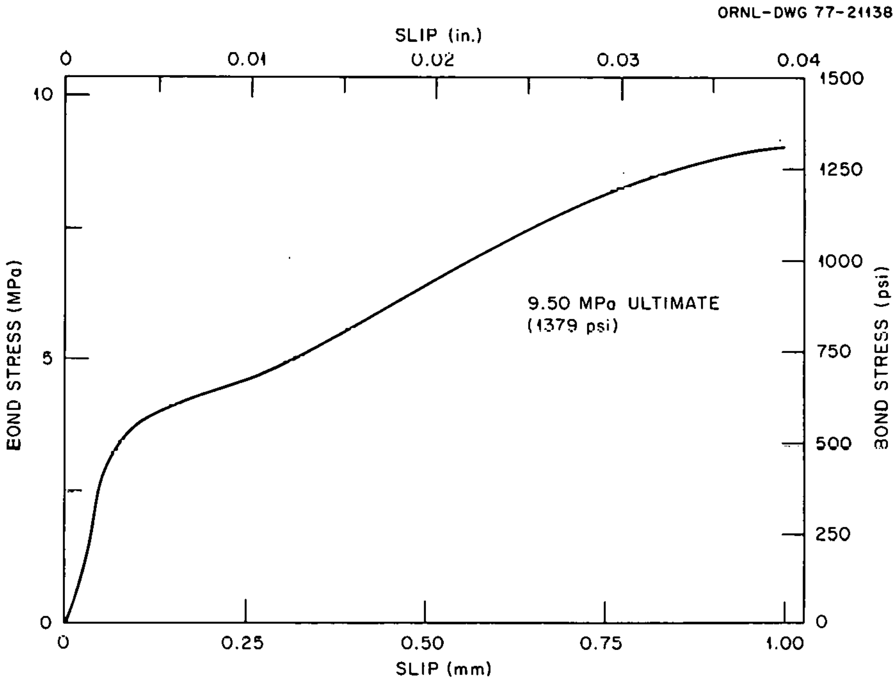

Fig. 9. Bond stress vs slip for 150-1.

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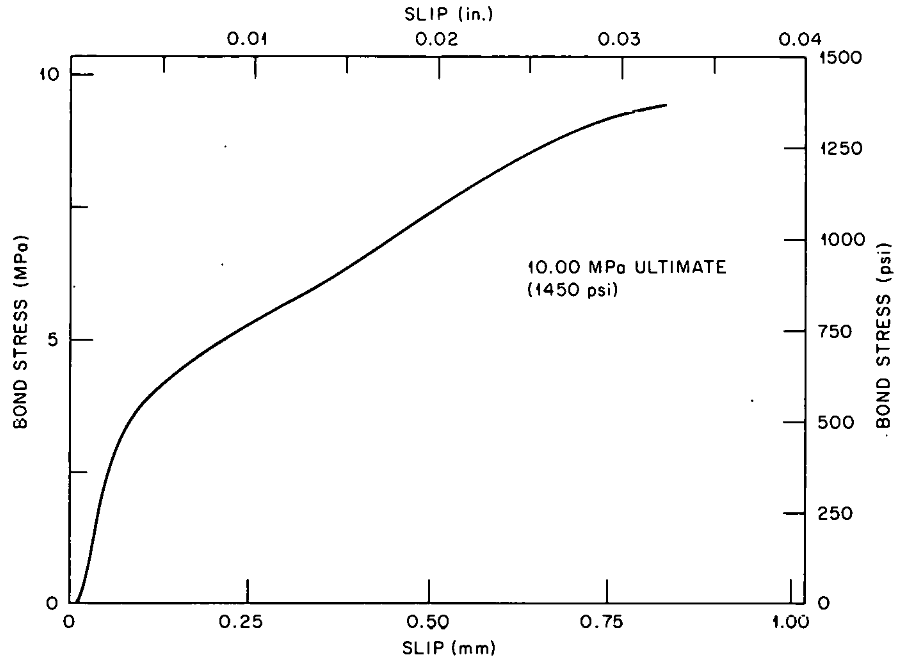

Fig. 10. Bond stress vs slip for 150-2.

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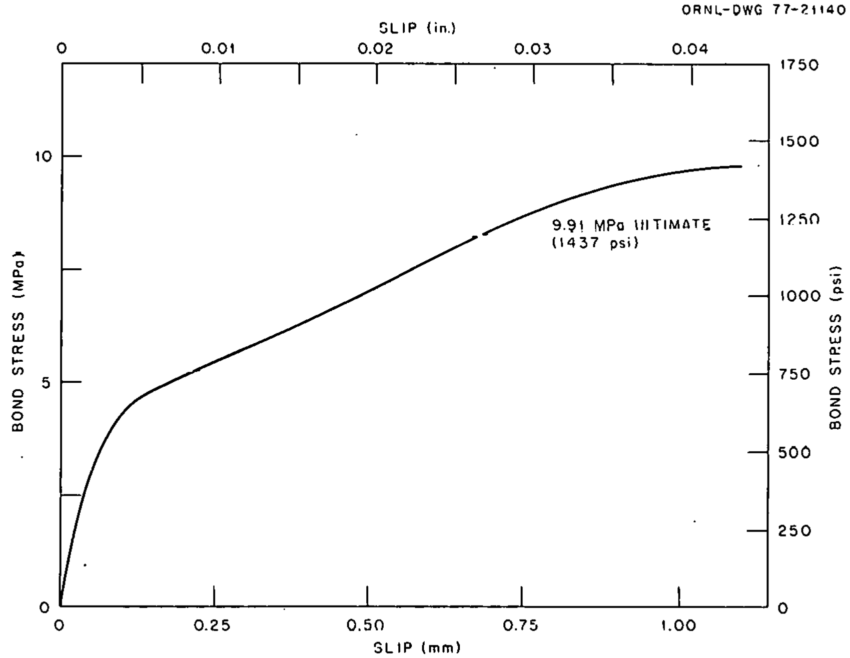

Fig. 11. Bond stress vs slip for 150-3.

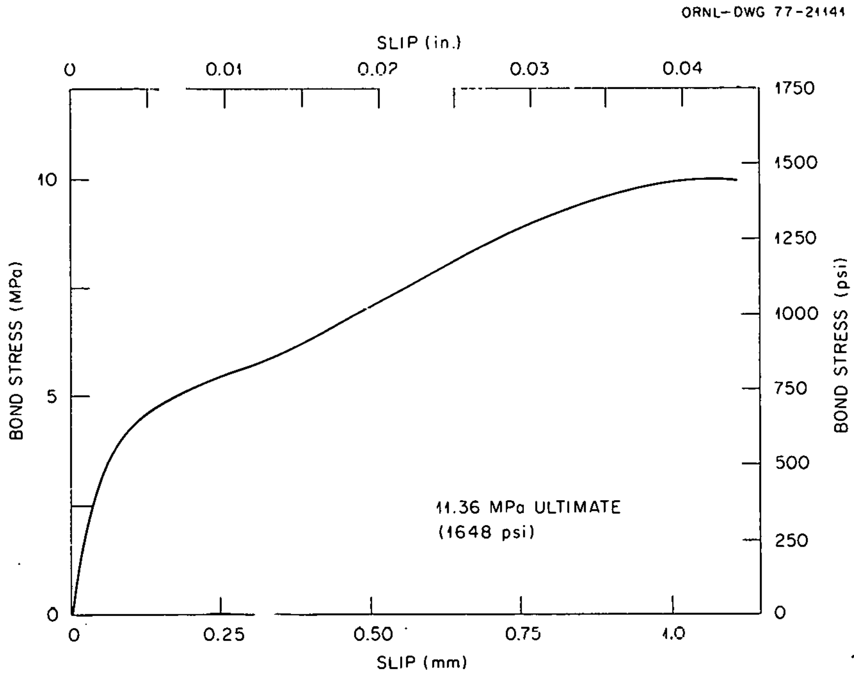

Fig. 12. Bond stress vs slip for 300-1. (Tested cool.)

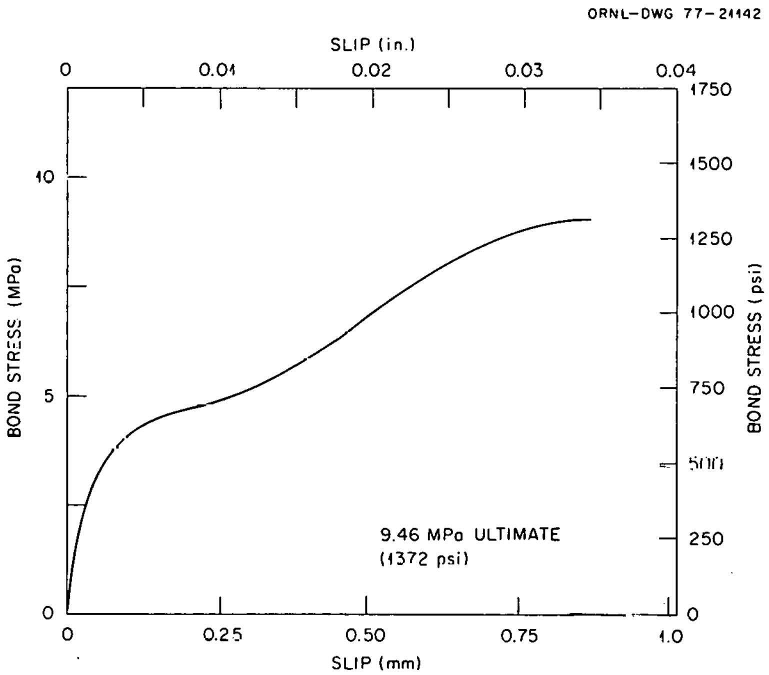

Fig. 13. Bond stress vs slip for 300-2.

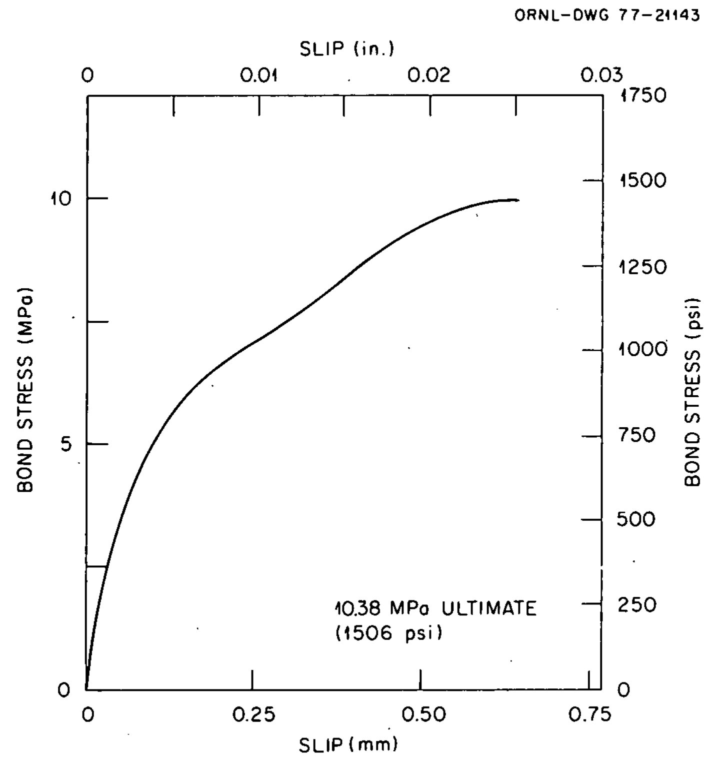

Fig. 14. Bond stress vs slip for 300-3.

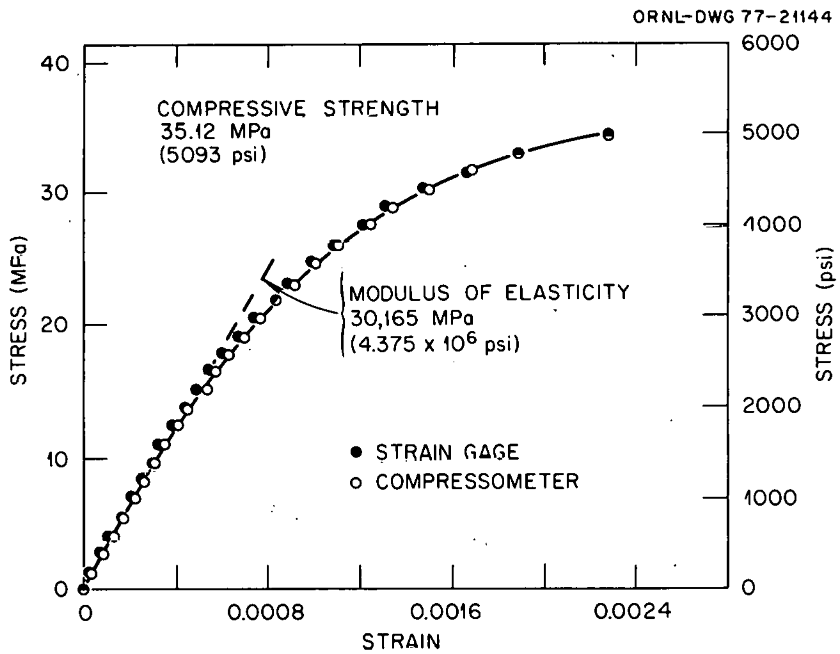

Fig. 15. Stress vs strain for cylinder 75-1.

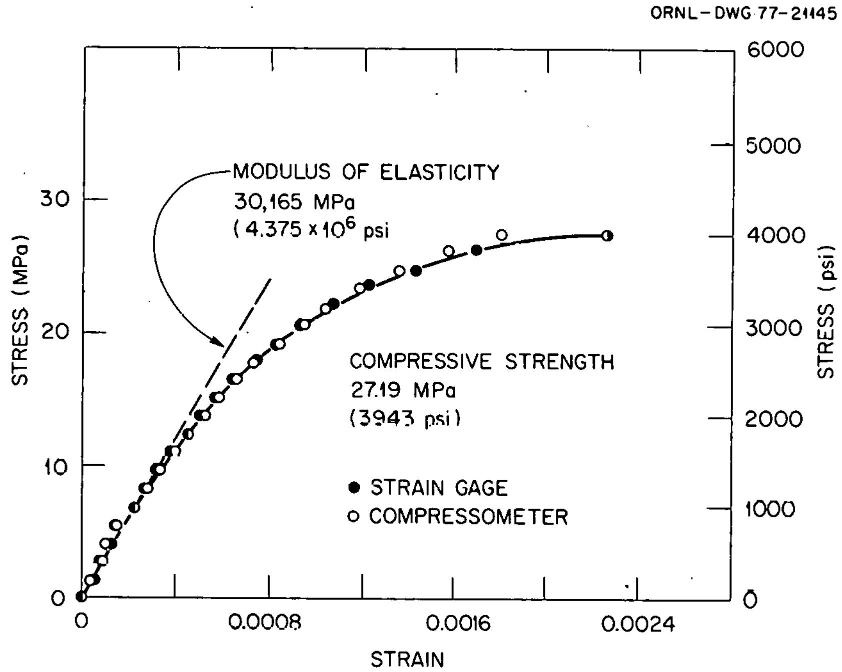

Fig. 16. Stress vs strain for cylinder 75-2.

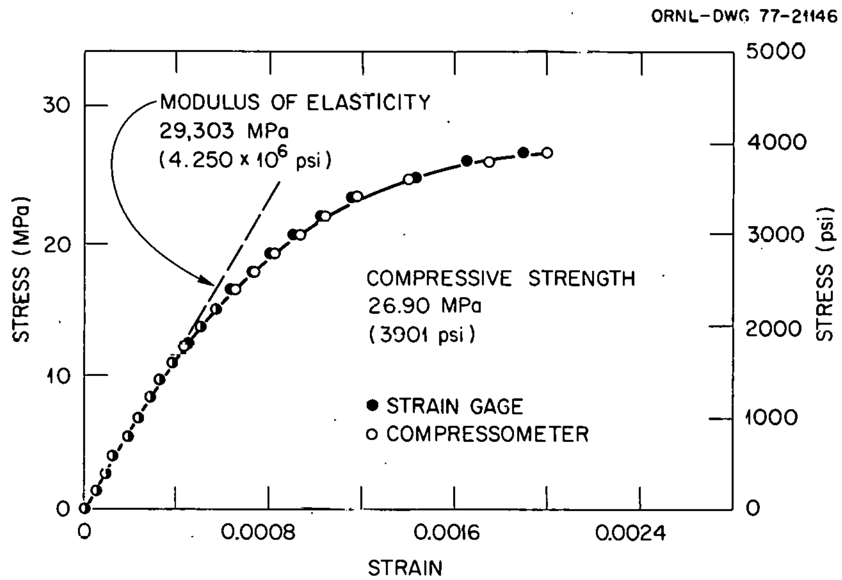

Fig. 17. Stress vs strain for cylinder 75-3.

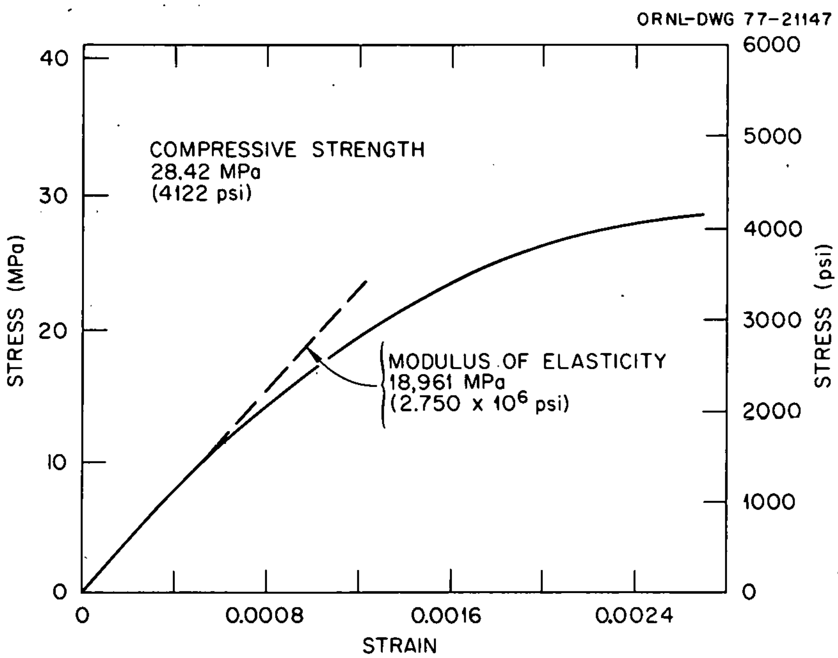

Fig. 18. Stress vs strain for cylinder 300-1.

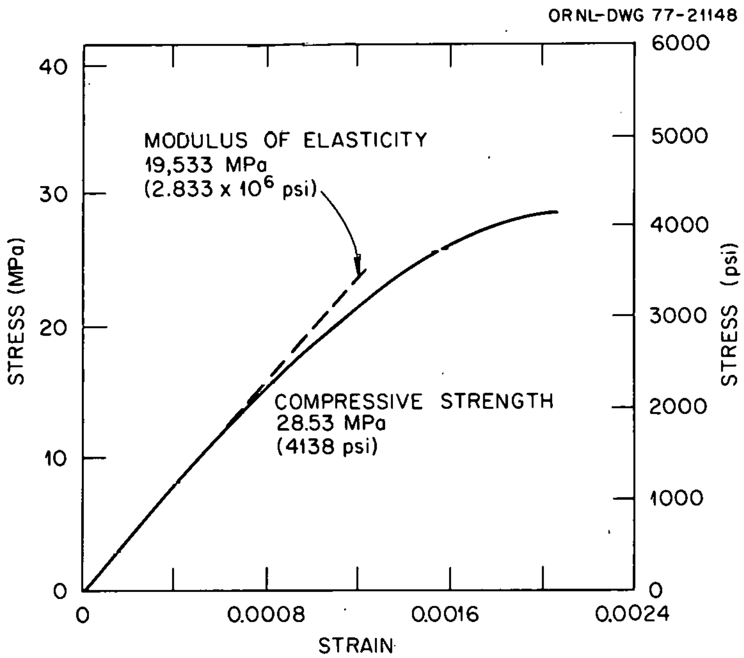

Fig. 19. Stress vs strain for cylinder 300-2.

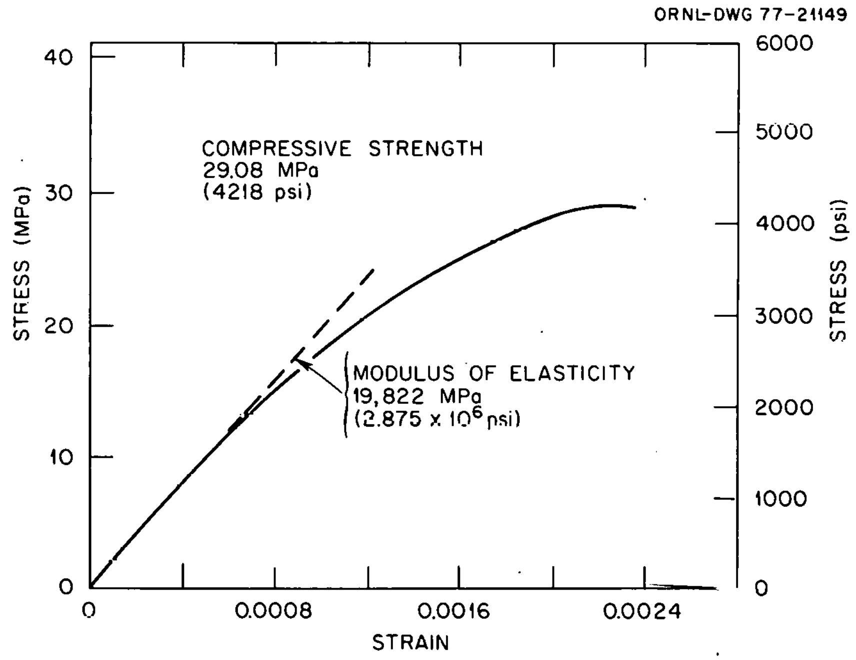

Fig. 20. Stress vs strain for cylinder 300-3.

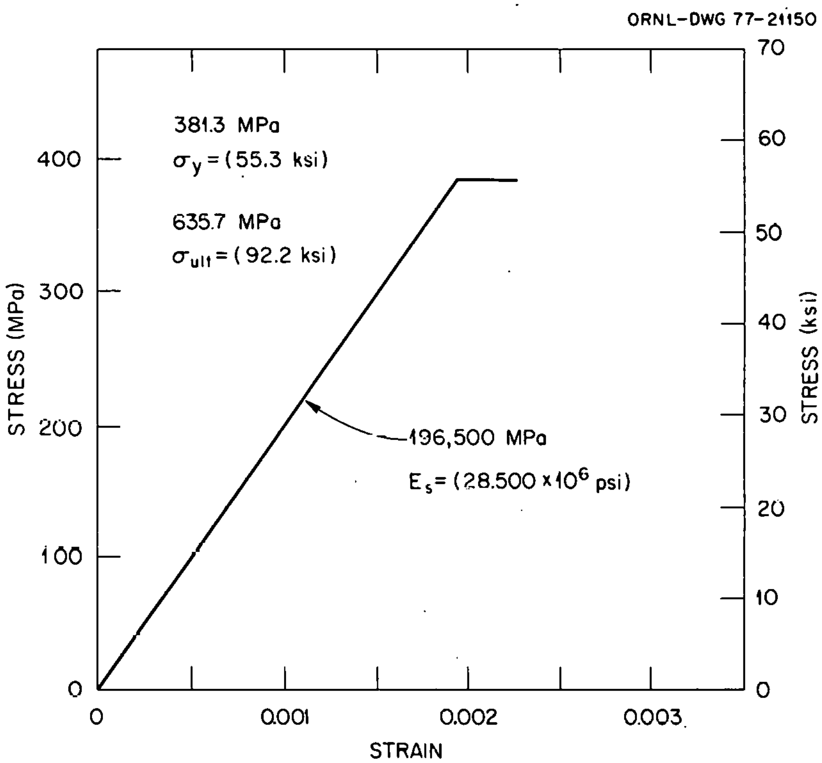

Fig. 21. No. 6 bar stress vs strain (No. 1).

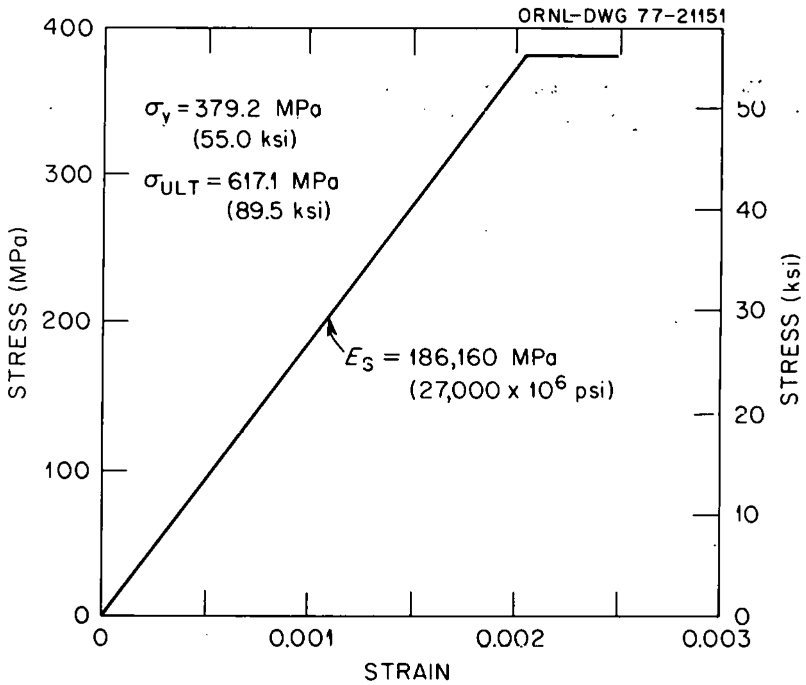

Fig. 22. No. 6 bar stress vs strain (No. 2).

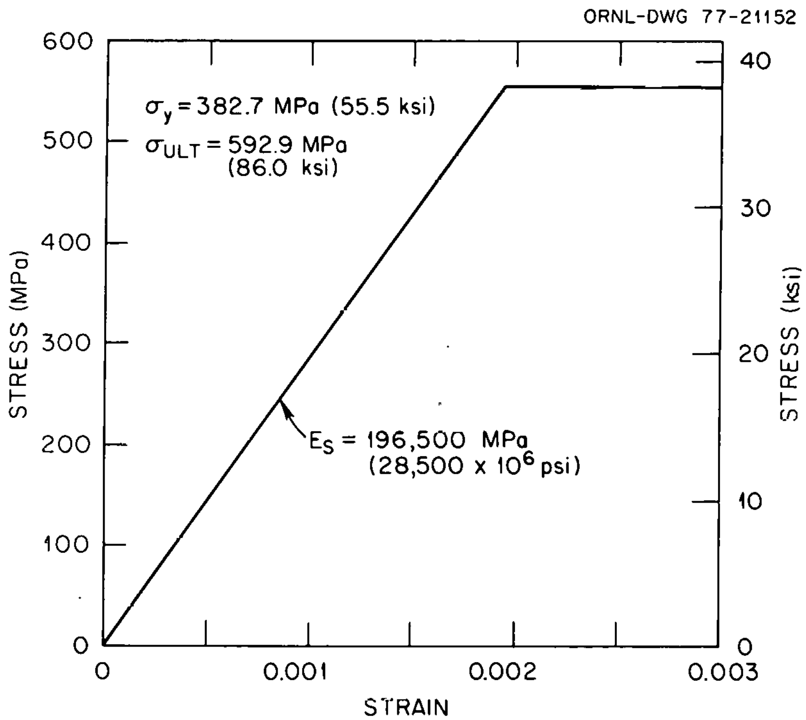

Fig. 23. No. 6 bar stress vs strain (No. 3).

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1. "Development of Reinforcement," Chap. 12 in Building Code Requirements for Reinforced Concrete (ACI 318-71), American Concrete Institute, 1971.

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