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STATIC CONCRETE CONSTITUTIVE RELATIONS BASED ON CUBICAL SPECIMENS. VOLUME II. ADDITIONAL TESTING OF CUBICAL SPECIMENS

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STATIC CONCRETE CONSTITUTIVE RELATIONS BASED ON CUBICAL SPECIMENS

Volume II

Additional Testing of Cubical Specimens

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New Mexico State University

TECHNICAL REPORT NO. AFWL-TR-72-59, Vol. II

December 1972

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
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13. ABSTRACT
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Uniaxial, biaxial, and triaxial compressive tests were conducted on cubical test specimens cast and brought to small dimensional tolerances by Terra Tek, Inc. The primary purpose of the tests was to determine if the test-to-test variation could be reduced by using the carefully prepared test cubes. The test-to-test variation was reduced using the specially prepared cubes. The results obtained from these tests were compared to the results obtained in the primary testing program. The initial tangent modulus from the uniaxial tests of this program was used in the computer solution to the model. The computer predicted results compared favoriably in the uniaxial and biaxial cases, but not in the triaxial case.

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I-C

FOREWORD

This report was prepared by the New Mexico State University, Las Cruces, New Mexico, under Contract F29601-71-C-0007. The research was performed under Program Element 61102H, Project 5710, Subtask SC157, and was funded by the Defense Nuclear Agency (DNA).

Inclusive dates of research were September 1970 through August 1972. The report was submitted 7 November 1972 by the Air Force Weapons Laboratory Project Officer, Captain Philip G. Stowell (DEV-S).

This technical report has been reviewed and is approved.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

1.1 INTRODUCTION

The information presented in this report is related to an extension of a contract awarded to New Mexico State University in September, 1970. The concrete cubical test specimens used in this testing program were produced under a separate contract awarded to Terra Tek, Inc. The Terra Tek, Inc. Final Report "CONCRETE CUBE TEST SPECIMENS" by S. W. Butters and S. J. Green was incorporated into this report. It was edited to provide continuity and is mostly contained in Section II of this report.

1.2 TESTING PROGRAM

Twenty-seven cubical test specimens were produced by Terra Tek, Inc.

Five of the cubes were tested uniaxially to determine the test-to-test variation in strength and strain at the peak stress values. In the above tests, the same testing procedures were used as reported in Reference 1. Three additional uniaxial tests were conducted but without the use of friction reducing pads. One cube was later tested uniaxially in a direction perpendicular to the casting direction.

Twelve cubes were tested biaxially to determine test-to-test variation in strength and strains at the peak stress values. Biaxial tests were conducted using the proportional loadings listed below:

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Number of Tests	σ_1	σ_2
4	5	5
3	5	4
3	5	2
2	5	1

Six cubes were tested triaxially. The loading proportions were as follows:

Number of Specimens	σ_1	σ_2	σ_3
2	10	1	1
2	10	5	1
2	10	10	1

SECTION II

CONCRETE CUBE TEST SPECIMENS

2.1 INTRODUCTION

Concrete cubes, 3 inches on a side, were fabricated by Terra Tek for multiaxial stress tests by New Mexico State University. Mix ratios and mixing and casting procedures were similar to those used by Terra Tek for the triaxial stress tests in Reference 2. The aggregate and cement were from the same batches as previously used.

An unconfined compressive stress strain curve on a 2.7-inch diameter by 6.0-inch long solid cylinder and the unconfined compressive strength of a 3-inch cube (without end lubrication) are included for comparison with tests performed by New Mexico State University.

2.2 MIX AND CASTING

The concrete mix for the cubes was a water/cement/aggregate ratio of 0.6/1/6.3 using 3/8 inch maximum aggregate size and Portland Type I cement, with the mix and casting procedure as presented in detail in Reference 2. The mix was poured into a 24 inch square container and vibrated for approximately 1 minute. After casting the concrete was stored in a constant temperature (72°F) constant humidity chamber (80 percent relative humidity) with a fine water spray over the container. The metal container was cut and removed from the large block of concrete after 4 days.

2.3 SPECIMEN FABRICATION

After removal of the container, the block was cut with a wire saw into seven slabs, each about 3-1/2 inches thick, and then six of the slabs were returned to the humidity chamber. The seventh slab was placed upright and four 2.7-inch diameter by 6.0-inch length cores were taken to be tested for 28 days unconfined compressive strength.

The slabs were diamond-saw cut into cubes (about 3-1/8 inches on a side) at 85 days, with the cube marked as to casting direction. The cubes were cut so as not to be closer than about 3 inches to the surface or edge of the larger block, thereby eliminating any casting edge effects. The cubes were then lapped to final dimensions, measured and weighed (to determine density).

2.4 TOLERANCES

The tolerances of the cubes were maintained at 3.000 ± 0.001 inches parallel and perpendicular to ± 0.0005 inches. The sides (faces not loaded) of the cubes for uniaxial stress and biaxial stress tests were not lapped to the ± 0.0005 inches tolerances, but were maintained at 3.000 ± 0.002 inches.

2.5 VERIFICATION TESTS

Unconfined compression tests were conducted on 2.7-inch diameter by 6.0-inch long solid cylinders taken from two of the slabs, after aging 28 days and 133 days. The stress-strain response for the 133 day aged unconfined compression tests are shown in Figure 1.

Also investigated was the effect of the length to diameter ratio. The maximum unconfined compressive strength versus the specimen length

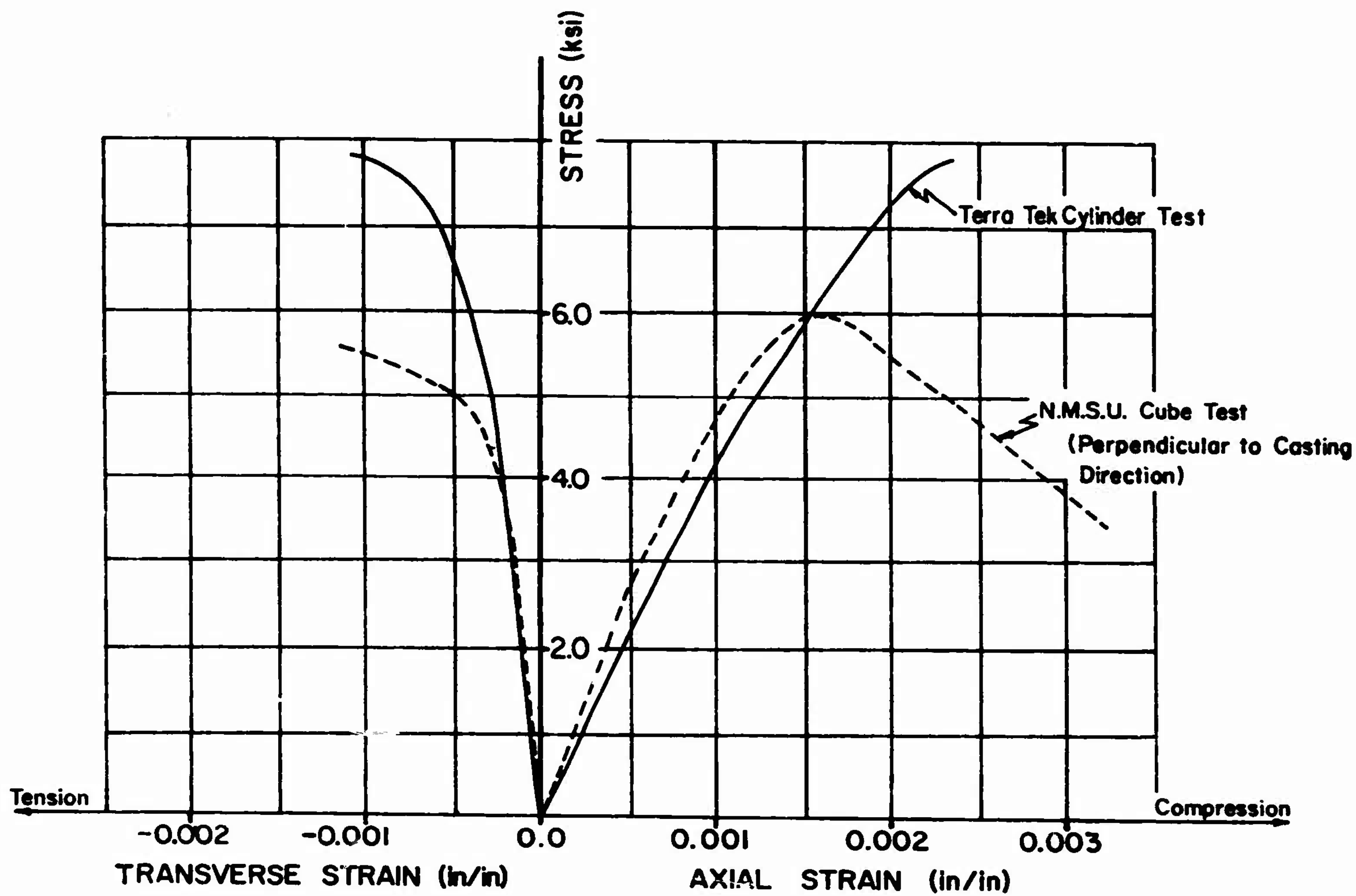

Figure 1. Uniaxial Stress-Strain Curves

(at a similar length-to-diameter ratio as shown in Reference 2) is shown in Figure 2. A concrete cylinder and a cube were used for the two test points, and agree very well with the specimen length effect of concrete as presented in Reference 2.

Densities were 2.39 gm/cc for the specimens tested at 28 days, and 2.34 gm/cc for the specimens tested at 133 days.

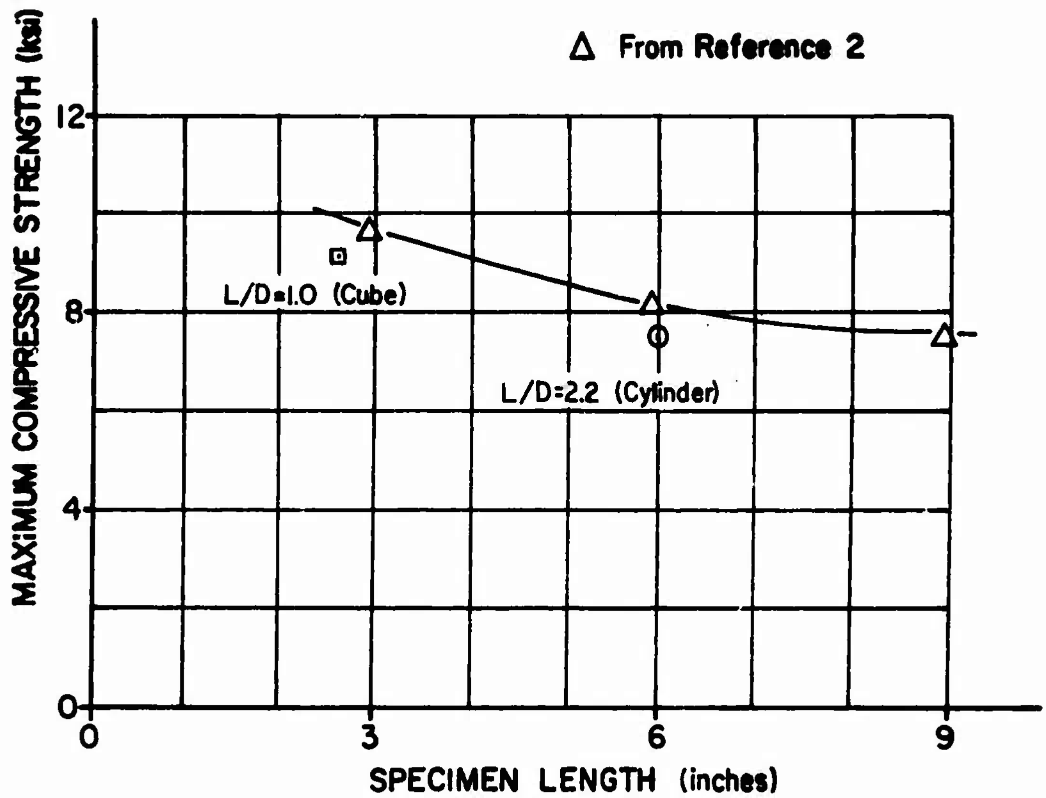

Figure 2. Unconfined Compression Strength versus Specimen Length

SECTION III

TEST RESULTS

3.1 UNIAXIAL TESTS

Five of the concrete cubes prepared by Terra Tek were tested in uniaxial compression to determine the reproducibility of the test results. The stress-strain curves for the five cubes are shown in Figure 3. The largest strength obtained was 6660 psi and the smallest was 6230 psi. The average strength of the five tests was 6470 psi. The extreme variation in the strength (difference between the largest and smallest strength) was 430 psi, which is 6.6 percent of the average strength. The largest variation from the average strength was 3.6 percent. The average variation in the uniaxial strengths obtained from cubes cast at New Mexico State University and whose dimensional tolerances were considerably greater than those prepared by Terra Tek, was 10.5 percent with an extreme variation of 29.6 percent.

The value of the strains at the peak stresses can also be considered from Figure 3. These strains will be referred to as failure strains. The failure strains ranged from 1930 to 1550 micro-inches per inch. The average was 1670 micro-inches per inch. The extreme variation from the average was 22.7 percent. The extreme variation in the failure strains from tests specimens cast at New Mexico State University averaged 37.7 percent.

Considering the stress-strains curves for uniaxial compressive tests, it appears that the reproducibility of test results can be

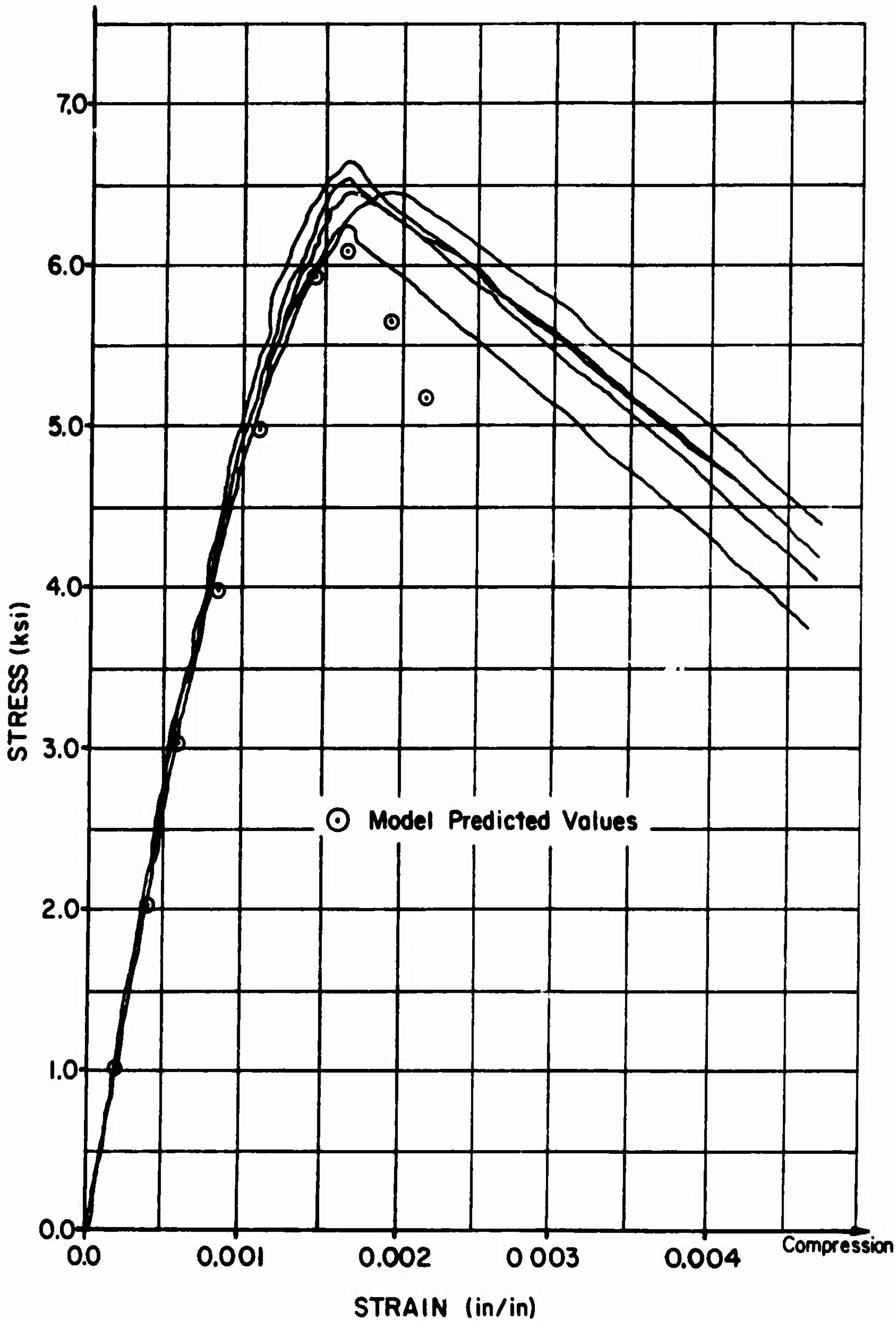

Figure 3. Uniaxial Stress-Strain Curves

improved by strictly controlling the cube dimensional tolerances.

The five cube tests whose stress-strain curves are shown in Figure 3 were conducted using friction reducing pads as described in Reference 2. Three uniaxial compressive tests were conducted without the use of friction reducing pads. The results of these tests are shown in Figure 4. For comparison, the two extreme stress-strain curves for the uniaxial case of Figure 3 are also shown in Figure 4. The results obtained without the use of friction reducing pads show higher strengths and display a more ductile behavior than the results obtained with the use of friction reducing pads. Higher strength and a more ductile behavior are characteristic of concrete subjected to multi-axial loading; hence, friction apparently adds a restraint that produces a multi-axial state of stress. A conical type cracking mode which is similar to that obtained in cylinder tests occurs in tests without the use of friction reducing pads. The cubes split into columns whose long axes are parallel to the loaded direction whenever friction reducing pads are used.

The strength of a cube tested by Terra Tek without friction reducing pads was approximately 9200 psi (Figure 2). The strength obtained at New Mexico State University for cubes without friction reducing pads was 8200 psi (neglecting the one test results). The compression platens used in these tests were 2.75 inches square whereas the cube nominal dimensions were 3 inches. It had been determined (Reference 2) that the strength was reduced approximately 12.3 percent due to the smaller platen. Multiplying 8200 psi by the

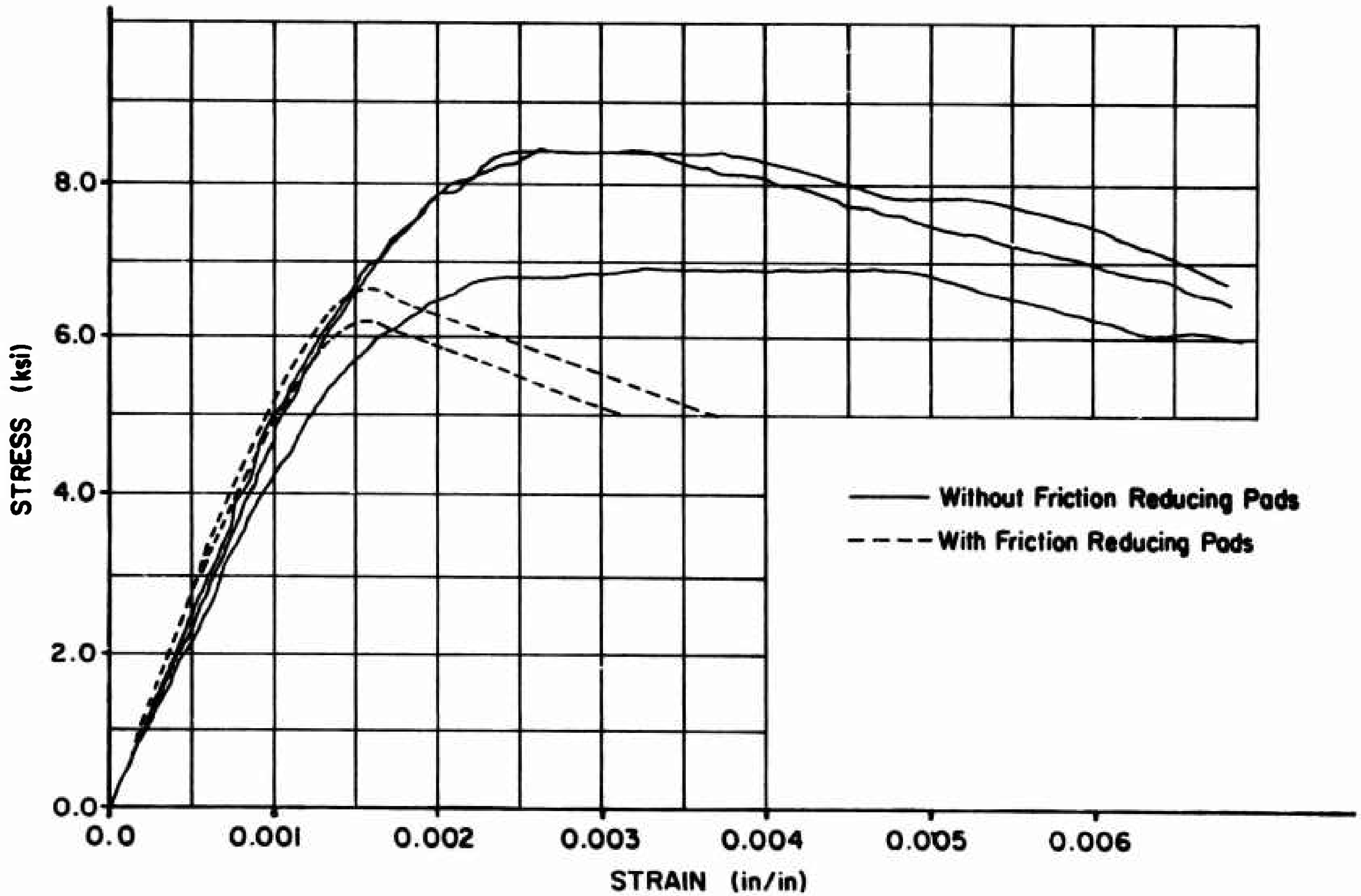

Figure 4. Uniaxial Stress-Strain Curves

correction factor of 1.123 yields a value of approximately 9200 psi. It appears that the uniaxial test results regarding maximum strength are comparable.

The factor of 1.123 is simply the cube strength (100 percent) plus the strength reduction from above (12.3 percent) due to the smaller platens. The total of 1.123 then yields the factor by which strengths obtained from testing using platens smaller than the specimen size must be multiplied in order to compare test results obtained with full-size platens. It is not known if the value of 1.123 holds for different concrete strengths.

An average value for the initial slope to the uniaxial compressive stress-strain curves of Figure 3 was obtained and used as input to the computer program for the model. Poisson's ratio was not changed. The initial slope as obtained from the Terra Tek produced cube specimens was approximately 5.50×10^6 psi. A value of 3.60×10^6 psi had been used in the model development. The model predicted results (using an initial slope of 5.50×10^6 psi) are also shown in Figure 3. As can be seen, the model predicted results yield a slightly lower strength, but otherwise compares favorably with the test results.

In Figure 1, two uniaxial compressive stress-strain curves are shown along with the stress-lateral strain curves. One stress-strain curve is reproduced from the Terra Tek report "Concrete Cube Test Specimens" and the second one was obtained from a uniaxial test on a Terra Tek produced cube, but loaded perpendicular to the casting direction. The lateral strains for the two tests are also shown. The Terra Tek stress-strain curve was obtained from a cylinder test. At the lower stress levels, the lateral strains compare favorably; however, the axial strains do not. The cube indicates a stiffer material than does the cylinder. In addition, the strain at the peak stress is considerably different in the two uniaxial tests. The strain at the peak stress from the Terra Tek test is approximately 0.0024 in/in, whereas it is approximately 0.0016 in/in from the New Mexico State University test. In addition, the Terra Tek cylinder test indicated a strength of approximately 7800 psi and the indicated strength of the New Mexico State University cube test was approximately 6000 psi. These curves point out that the testing procedure and type of test specimen can greatly affect the test results.

Concrete strength values obtained from cylinder and cube tests are presented in Table I. The cylinder strengths and the corresponding cube strengths were obtained from specimens cast from the same concrete batch. The ratios of cube strengths to cylinder strengths are also indicated in Table I. The strength ratios varied from 0.82 to 0.94 with an average of 0.89. The ratio of the New Mexico State University cube test to the Terra Tek cylinder test was 0.77 (6000/7800). This value (0.77) lies below the range of ratios given in Table I. This indicates that either the Terra Tek test results are low, the New Mexico State University test results are high, or the ratio is dependent upon the concrete properties. The cause of the difference is not known.

TABLE I

CONCRETE CYLINDER AND CUBE TEST COMPARISONS

Date Cast	Date Tested	Avg. Cylinder Strength (psi)	Avg. Cube Strength (psi)	Cube Strength / Cylinder Strength
5-6-71	5-24-72	4880	4370	0.90
5-10-71	5-24-72	5170	4260	0.82
5-12-71	5-24-72	5290	4470	0.84
5-3-71	5-31-71	5000	4270	0.94
4-29-71	5-27-71	5200	4890	0.94
4-28-71	5-26-71	4140	3680	0.89
	AVERAGE	4950	4400	0.89

3.2 BIAXIAL TEST

Figures 5 through 8 show the results of the biaxial tests on the Terra Tek produced cubes. Generally the reproducibility from test to test was good; however, on one test the result was considerably different for a loading proportion of 5:2 (Figure 7). The difference in this case cannot be explained.

An average value for the initial slope to the uniaxial compression stress-strain curves was obtained and used as input to the computer program for the model. The model predicted results are shown for each load ratio in Figures 5 through 8. The predicted results compare quite favorably for the initial portion of the curves but depart somewhat in the region of the maximum stresses. The model appears to predict relatively higher results as the intermediate principal stress is increased with respect to the other two principal stresses.

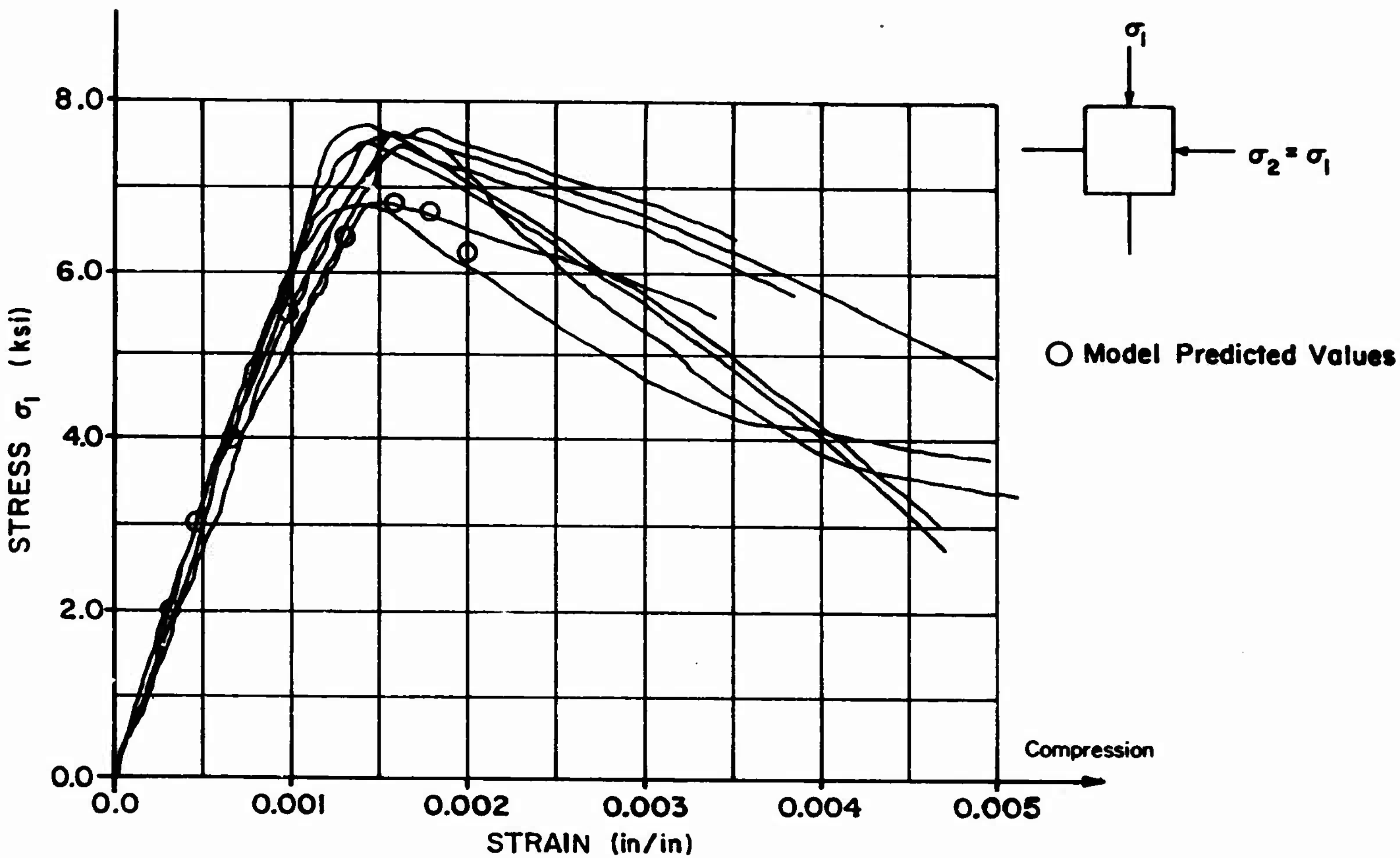

Figure 5. Biaxial Stress-Strain Curves

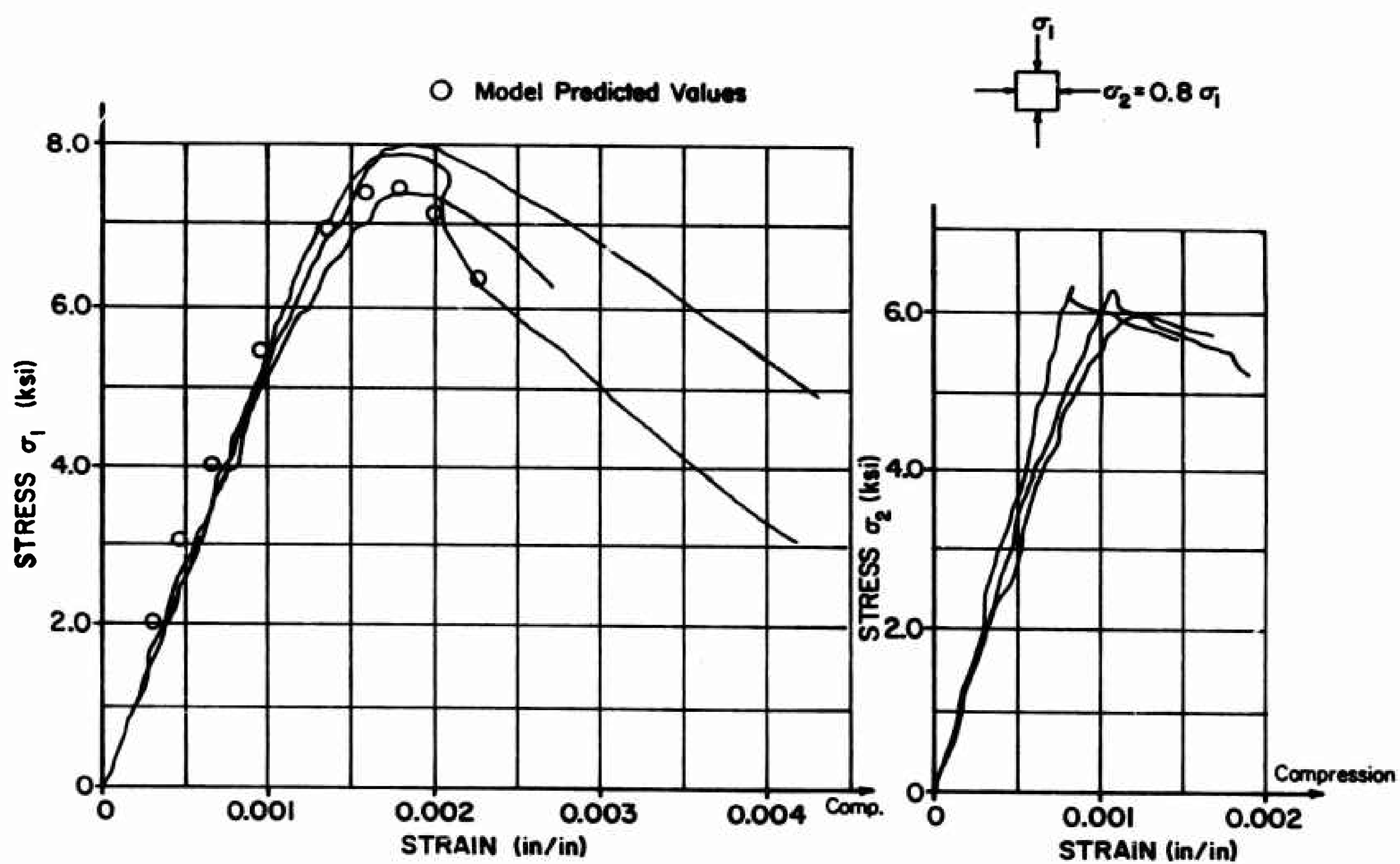

Figure 6. Biaxial Stress-Strain Curves

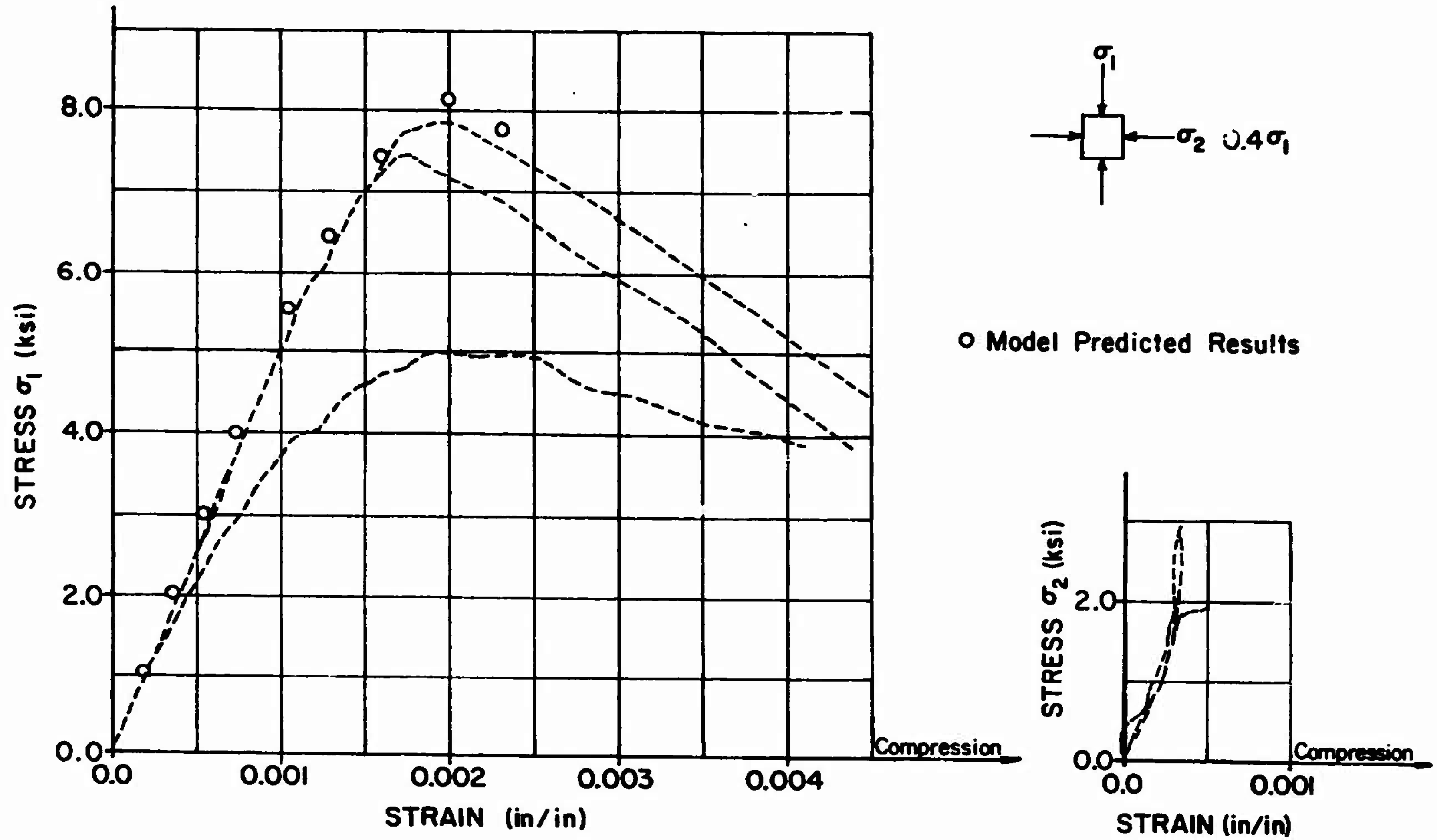

Figure 7. Biaxial Stress-Strain Curves

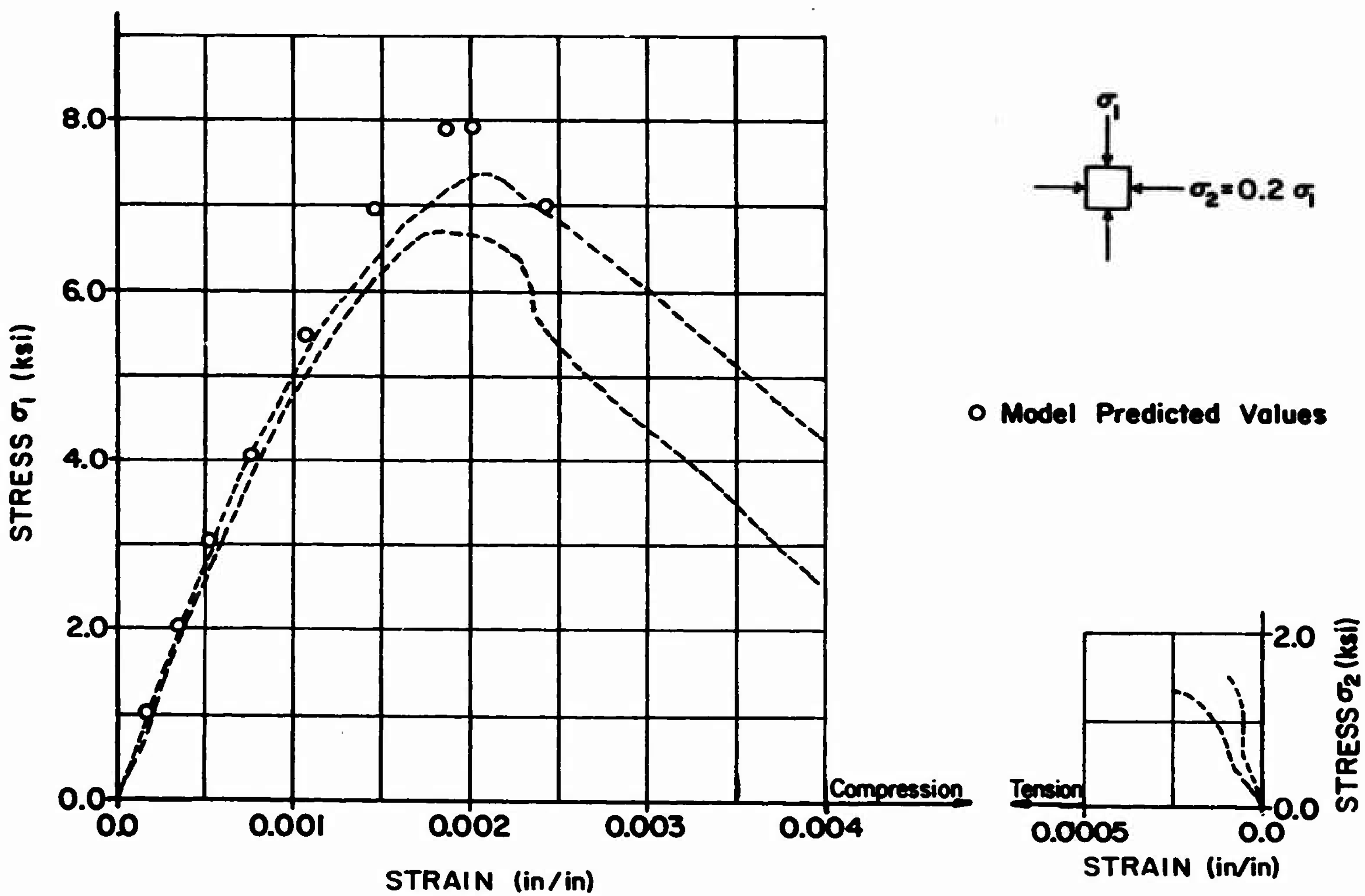

Figure 8. Biaxial Stress-Strain Curves

Four biaxial tests with loading ratios of 1:1 were conducted to determine reproducibility of testing from test to test. There is a slight difference in the maximum loads on the two loaded axes. For each axis, the following maximum stresses and strains at peak stresses were obtained.

Maximum Stress		Peak Strain (μ in/in)	
σ_1 (psi)	σ_2 (psi)	ε_1	ε_2
7590	7470	1510	1610
6740	6810	1380	1400
7700	7760	1380	1510
7500	7550	1430	1650

Note that the strains on the two loaded axes were generally not the same. This is due to the anisotropic effect resulting from casting of the cubes. The concrete material has a different stiffness in the two directions. One of the loads was applied in the direction of casting and the other perpendicular to the direction of casting. One of the tests yielded lower results than the remaining tests.

For the biaxial case reproducibility was somewhat better than in the original testing program. The largest strength variation was 13 percent and the strain variation was 16 percent. Considering only the three best tests the strength variation was less than 3 percent. For the dimensionally uncontrolled test specimens used in the initial test program where a loading ratio of 1:1 was used, the average strength variation observed was 17 percent and the average strain variation was 37 percent. Thus the improvement in strain variation was much greater than the improvement in strength variation.

The results of a biaxial test based on maximum strength observed during the test are presented in Table II. The data is also normalized based on a uniaxial unconfined compression strength, σ_r = 6,466 psi.

To compare the strength results with those obtained during the initial tests, the normalized data from both test series are presented in Figure 9. A comparison of normalized strengths is best here since different strength concretes were used in each case. For the case of equal biaxial compression, the average normalized strength from both testing programs is the same. An average strength increase of approximately 15 percent was observed. For all other ratios of σ_1/σ_2 the results using the Terra Tek cubes fall below the average biaxial strength curve determined using the New Mexico State University cubes. There could be several reasons for the difference in the shape of the two curves.

It was reported by Vile (Reference 4) that there are several parameters which determine the shape of the biaxial compression strength envelope. The main parameters which determine the different classes of behavior are a limiting maximum aggregate size of about 1/4 inch and the volume concentration of coarse aggregate in the mix above the 1/4 inch size. Mortars and lightweight concrete exhibit a square strength envelope. Normal aggregate concrete exhibits a very rounded convex envelope.

Table III has the average values tabulated for each type of test based on the nominal ratios of σ_1/σ_2. The maximum difference from the average strength is also shown in Table III. The reproducibility

TABLE II

BIAXIAL COMPRESSION STRENGTH DATA

Cube No.	Nominal Ratio σ_1/σ_2	σ_1 (psi)	σ_2 (psi)	$\frac{\sigma_1}{\sigma_r}$	$\frac{\sigma_2}{\sigma_r}$
4-3		6460	0		
4-19		6470	0		
4-7	1/0	6230	0		
4-15		6660	0		
6-8		6510	0		
4-18		7590	7470	1.174	1.155
6-11	5/5	6810	6740	1.053	1.042
4-12		7700	7660	1.191	1.185
6-12		7550	7500	1.168	1.160
6-4		8000	6400	1.237	0.990
4-22	5/4	7900	6360	1.222	0.984
4-14		7400	5900	1.144	0.902
*2-8		5000	1000	0.773	0.155
6-10	5/2	7400	3000	1.144	0.464
6-2		7800	3200	1.206	0.495
6-8	5/1	6700	1380	1.036	0.213
6-5		7300	1500	1.128	0.232

*Bad data not included in average values.

σ_r = 6,466 psi.

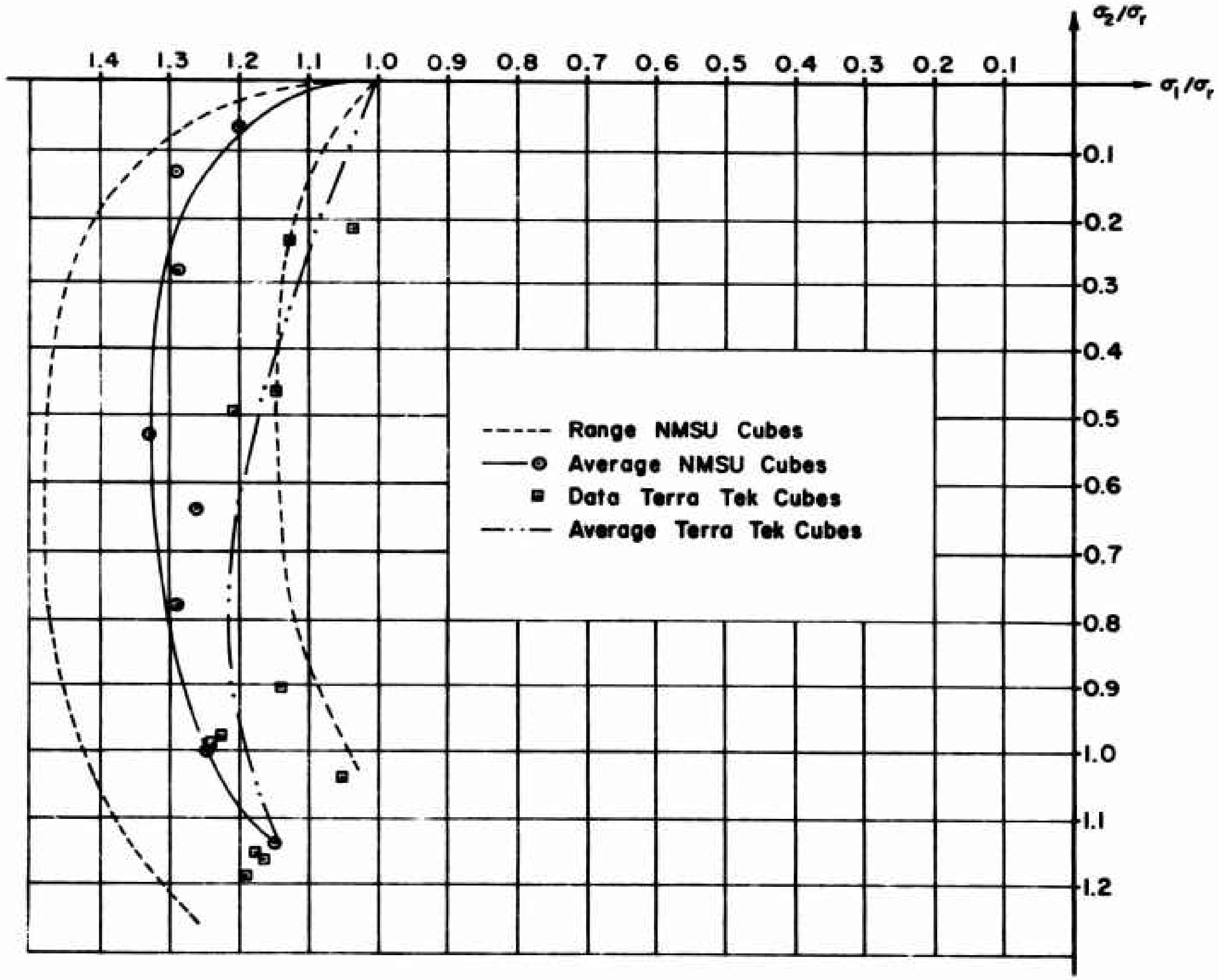

FIGURE 9. BIAXIAL STRENGTH COMPARISON

TABLE III

AVERAGE BIAXIAL COMPRESSION STRENGTH DATA

Nominal Ratio σ_1/σ_2	σ_1 (psi)	σ_2 (psi)	$\frac{\sigma_1}{\sigma_r}$	$\frac{\sigma_2}{\sigma_r}$	Maximum Difference from Average
1/0	6466	0	1.000	0	-3.66%
5/5	7412	7343	1.146	1.136	-7.75%
5/4	7767	6220	1.201	0.962	-4.72%
5/2	7600	3100	1.175	0.479	±2.63%
5/1	7000	1440	1.083	0.223	±4.29%

of the strength obtained for a given type of test is quite good. The maximum difference observed between the strength of the given specimen and the average for the group was - 7.75 percent. The smallest difference observed was ± 2.63 percent. Based on the data obtained using the New Mexico State University cubes in the initial test program, the range of differences observed was + 1.5 percent to + 17 percent. The average difference was approximately 7 percent. Some of the scatter observed using the New Mexico State University cubes was undoubtedly due to a batch to batch variation since the cubes were not all cast in the same batch.

3.3 TRIAXIAL TESTS

The results of the triaxial tests are shown in Figures 10 through 12. A proportional loading was used for each test and the ratio of the load on each axis is indicated in the figures. The stress-strain curve for each axis is shown in each case. The ductile behavior of the concrete is apparent here compared to the brittle behavior observed for the uniaxial and biaxial test.

Duplication of results from test to test is quite good for the portion of the curves with some variation occurring at the higher stress levels. In general the variation was not too large where the loading proportions were held constant. The largest difference observed is in Figure 12 where the loading proportions were not held as closely as in the other tests. The curve for cube number 6-9 is higher than it should be since the ratio σ_3/σ_1 is somewhat higher than intended. This can be

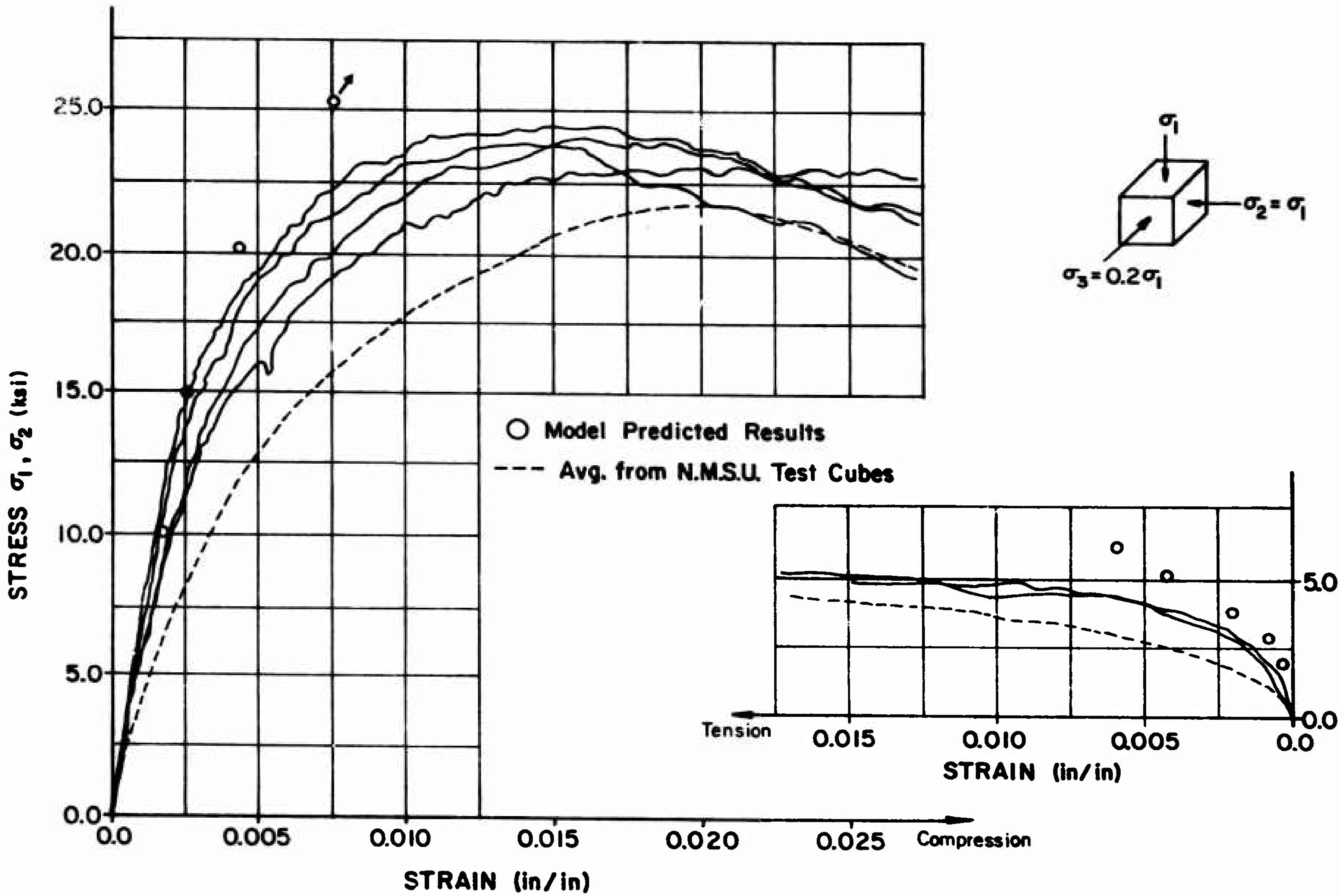

Figure 10. Triaxial Stress-Strain Curves

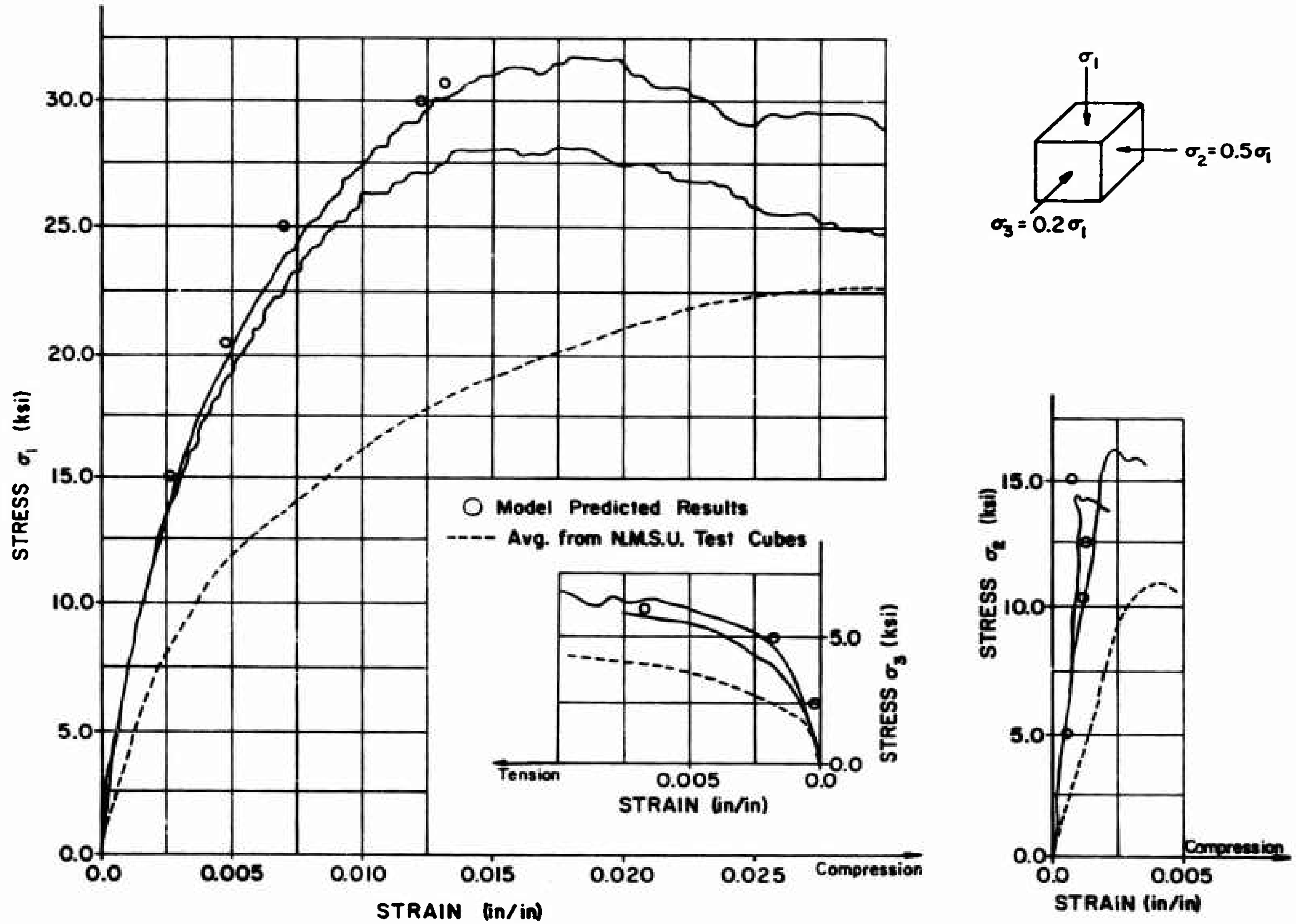

FIGURE 11. TRIAXIAL STRESS-STRAIN CURVES

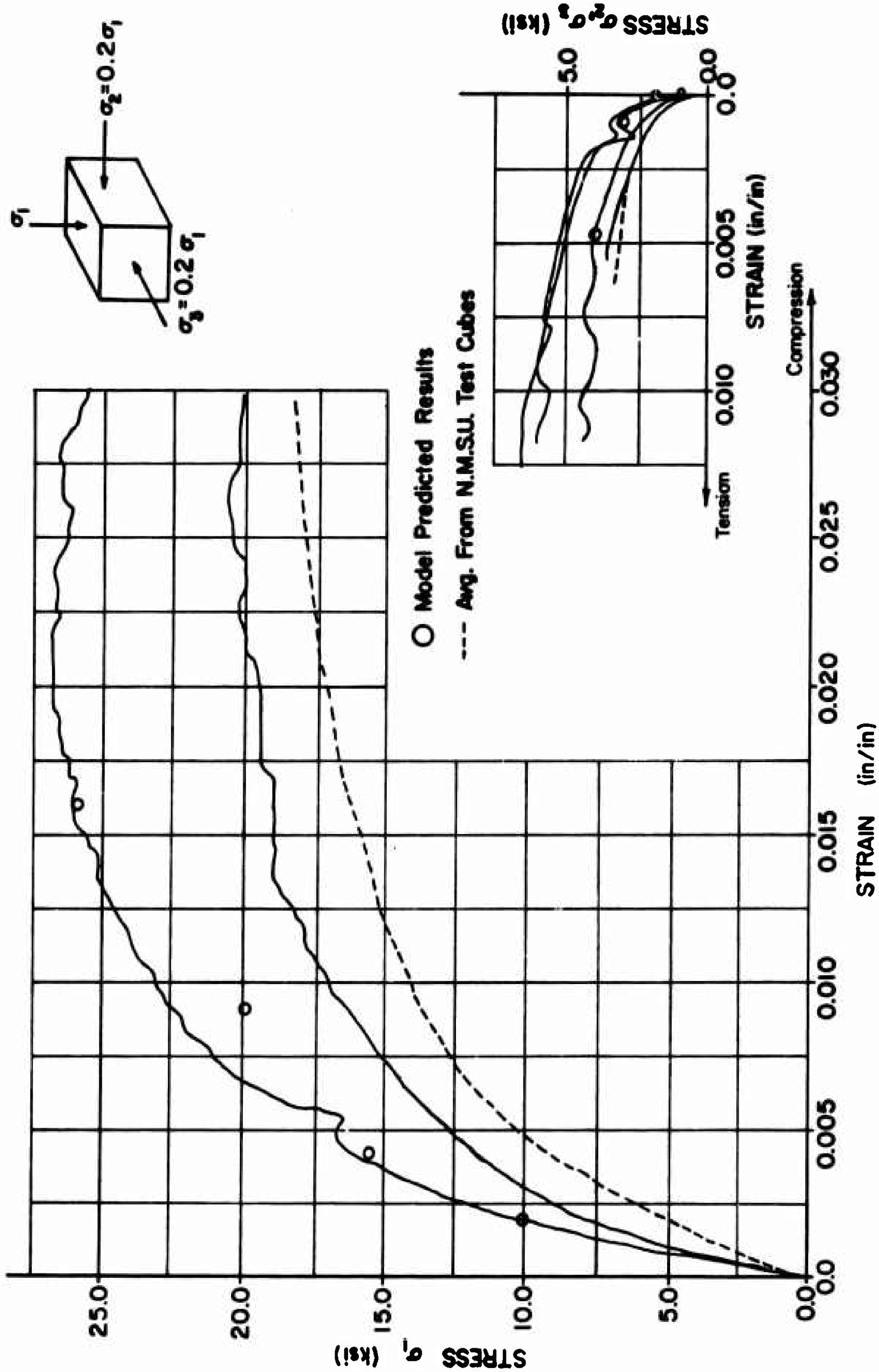

Figure 12. Triaxial Stress-Strain Curves

seen in Table IV which is a tabulation of the maximum strengths observed on each axis during the testing. The tabulation includes the normalized strengths based on a uniaxial unconfined compression strength, σ_r = 6,466 psi. The ratio of σ_3/σ_1 is also shown for each test since this is the most important parameter affecting the triaxial strength.

Figures 10 through 12 also contain the model predicted results based on a change in the initial slope of the stress-strain curve. The model predicted results in this case do not agree very well with the test results. Peak strains are different. This indicates that for a triaxial loading the stress-strain relationship does not depend solely on material properties and a change in the control constants in the model is necessary to adjust for different concrete strengths.

A comparison of the triaxial compression strength obtained for the Terra Tek produced cubes with the cubes produced at New Mexico State University during the initial test program is made in Figures 13 and 14. The comparison is of the compression strength envelope for all data with a ratio of σ_3/σ_1 approximately equal to 0.20. Both plots indicate that the shape of the strength envelope is the same for both test programs. In Figure 13 it can be seen that the Terra Tek produced cubes had a slightly higher triaxial strength than the New Mexico State University produced cubes. When the same comparison is made using normalized results in Figure 14, the curve obtained for the Terra Tek cubes is much lower than that obtained for the New Mexico State University cubes. This points out that although the Terra Tek cubes had a much higher unconfined strength

TABLE IV

TRIAXIAL COMPRESSION STRENGTH DATA

Cube No.	Nominal Ratio	σ_1 (psi)	σ_2 (psi)	σ_3 (psi)	$\frac{\sigma_1}{\sigma_r}$	$\frac{\sigma_2}{\sigma_r}$	$\frac{\sigma_3}{\sigma_r}$	$\frac{\sigma_3}{\sigma_1}$
2-3	5/5/1	24,300	23,800	4,920	3.76	3.68	0.76	0.202
2-13	4/4/1	23,500	23,000	4,700	3.63	3.55	0.73	0.200
6-3	5/2-1/2/1	27,800	14,400	5,520	4.30	2.23	0.85	0.199
4-30	5/2-1/2/1	31,500	16,300	6,100	4.87	2.52	0.94	0.194
6-9	5/1/1	26,600	6,100	5,700	4.11	0.94	0.88	0.214
4-23	5/1/1	20,500	4,300	4,080	3.17	0.66	0.63	0.199

σ_r = 6,466 psi

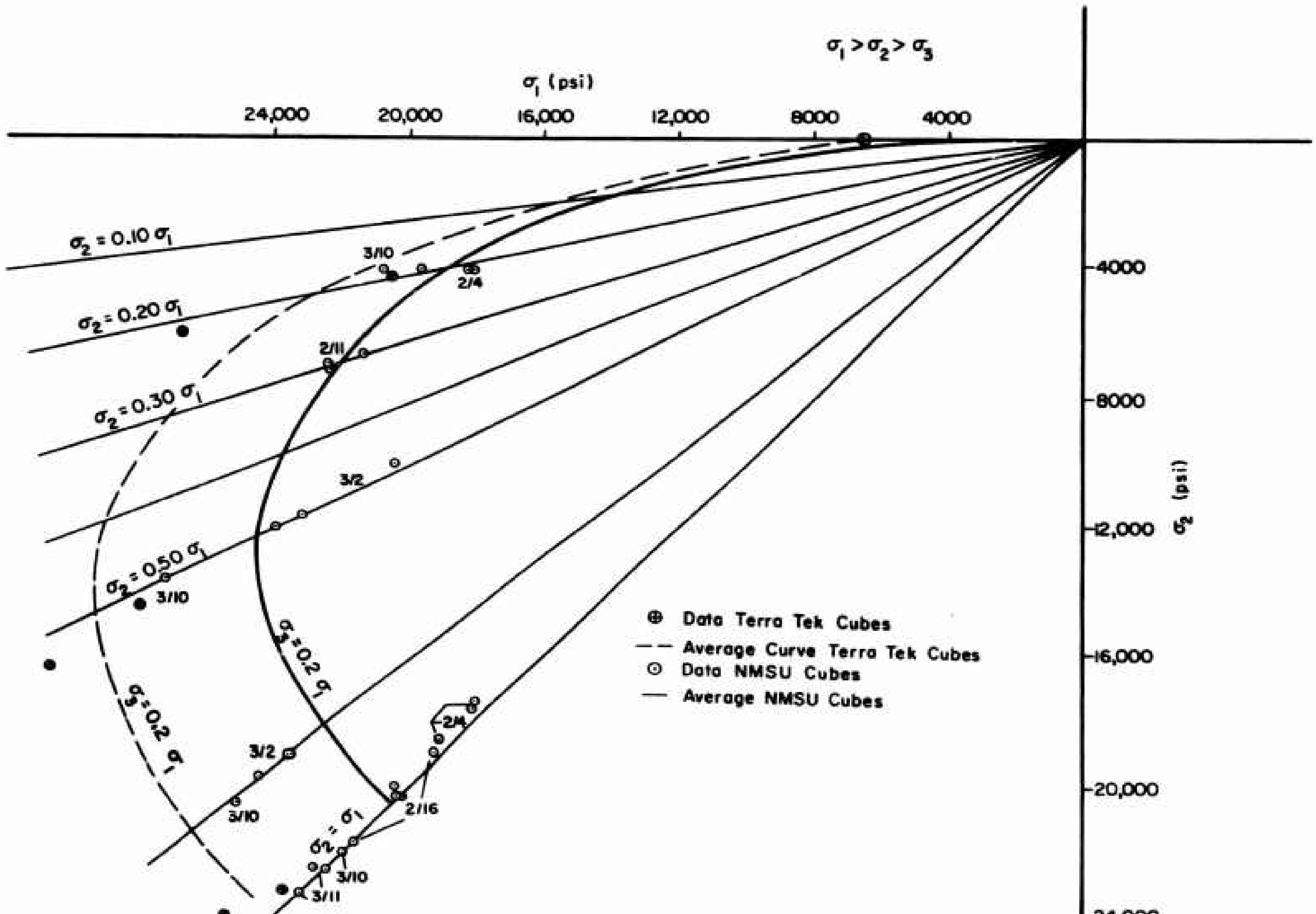

FIGURE 13. TRIAXIAL STRENGTH COMPARISON

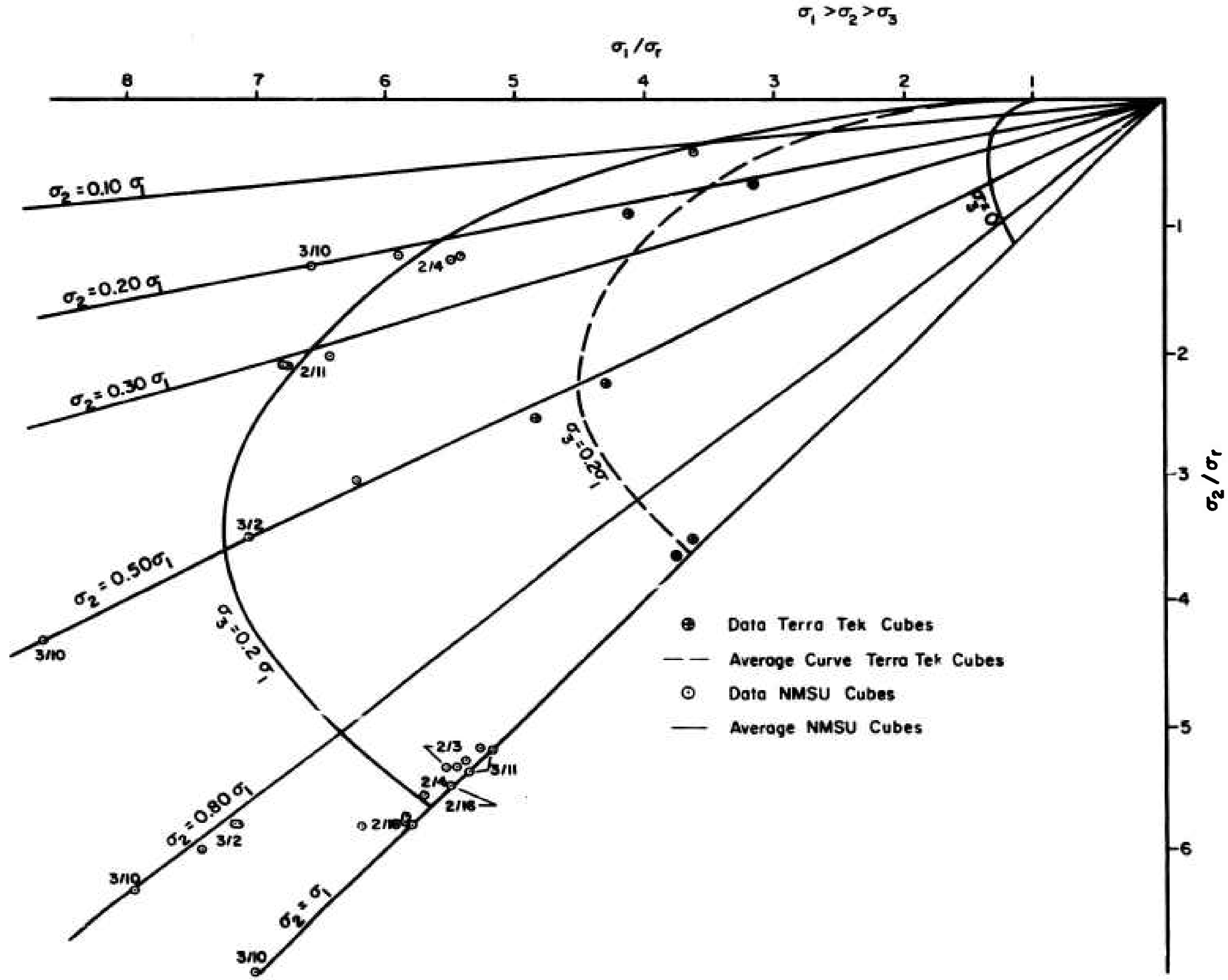

FIGURE 14. NORMALIZED TRIAXIAL STRENGTH COMPARISON

than the New Mexico State University cubes, the triaxial strength increase is not proportional to the unconfined strength increase.

SECTION IV

SUMMARY AND CONCLUSIONS

Twenty-seven concrete cubes were cast and brought to a close dimensional tolerance by Terra Tek, Inc. Great effort was taken to insure that opposite faces of these cubes were plane and parallel.

Five uniaxial tests were conducted to determine the test-to-test variation in the maximum strengths and the strains at maximum stresses. The maximum variation from test to test was compared to that obtained in the primary testing program. For the uniaxial tests, it appeared that the use of dimensionally controlled test cubes decreased the variation from test-to-test.

Two uniaxial tests were conducted without the use of friction reducing pads. The stress-strain curves from these tests displayed a greater strength and a more ductile behavior as compared to tests utilizing friction reducing pads. It was apparent that friction adds a lateral restraint and that actually a triaxial state of stress exists in the presence of friction.

The initial stiffness as obtained from the uniaxial cube tests was used in the computer program for the model. The predicted maximum stress was slightly lower than the experimental; however, the predicted and experimental strains compared favorably.

Biaxial tests were conducted using different loading proportions. Four biaxial tests were conducted to determine test-to-test variation. A comparison of these tests was made with those conducted in the primary part of the testing program. It appeared that the maximum variation from test to test was smaller in the case of the dimensionally controlled test specimens. Equal loads were applied in the two directions for this series of tests.

A comparison of the failure stresses of the biaxial tests with those from the primary part of the testing program indicates in general a fair comparison. The controlled cube test strengths are lower than those from the primary program for the lower principal stress to major stress ratios. Model predicted values were compared to the experimental results. The comparison between the predicted and experimental values was fair. In some cases the predicted values were larger and in some cases they were smaller.

Six cubes were tested triaxially. Three different loading proportions were used. A comparison of the test results with those of the primary testing program indicates differences in strength and in the strains at the peak stress values. The results of the tests of the controlled cubes display less ductility and higher strengths. The model predicted values were much too large in the triaxial case. This indicates that concrete subjected to triaxial loads does not behave in proportion to its uniaxial strength.

It was apparent that the use of dimensionally controlled test cubes reduced the test-to-test variation in the results. The variation reduction was particularly significant in the case of the strains at the peak stress values. There was a reduction in the strength variation, but in view of the cost of dimensionally controlling the test speicmens, it may not be that significant.

The material properties (from a uniaxial test) appeared to mostly account for differences in biaxial behavior between two different concretes; however, they do not completely explain the difference in strengths and strains in the triaxial case. Apparently the concrete material properties (aggregate, sand, etc.) affect the triaxial case. To adjust the model to account for these additional properties will require modification of the control equations of the model. The nature of the concrete properties must be known before the control equations can be modified.

REFERENCES

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