MISCELLANEOUS PAPER NO. 6-934

DEVELOPMENT OF MATERIAL FOR MODELING ROCK

by

K. L. Saucier

October 1967

Sponsored by

Defense Atomic Support Agency

Conducted by

U. S. Army Engineer Waterways Experiment Station
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ARMY-MRC VICKSBURG, MISS

FOREWORD

This research was part of Nuclear Weapons Effects Research (NWER) Subtask 13.191, Rock Mechanics Research Relating to Deep Underground Protective Construction. This subtask was sponsored by the Defense Atomic Support Agency and directed by the Office, Chief of Engineers, U. S. Army.

This work was conducted during the period January through December 1966 by personnel of the Concrete Division of the U. S. Army Engineer Waterways Experiment Station under the direction of Messrs. Bryant Mather, James M. Polatty, and William O. Tynes. Staff members actively concerned with the work included Messrs. Kenneth L. Saucier, Billy R. Sullivan, Frank S. Stewart, and Dale Glass. This report was prepared by Mr. Saucier.

Director of the Waterways Experiment Station during the conduct of this investigation and the preparation of this report was COL John R. Oswalt, Jr., CE, and Technical Director was Mr. J. B. Tiffany.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
microinches per inch	0.001	microns per millimeter
pounds per square inch	0.070307	kilograms per square centimeter
pounds per cubic foot	16.0185	kilograms per cubic meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.16$.

SUMMARY

Successful modeling of structures and explosive effects indicates that modeling of rock by the use of equivalent material could likewise prove fruitful. The purpose of this investigation was to develop mixtures of practical materials to model geological formations. The similitude principles utilized are: (a) similar and similarly oriented Mohr's envelopes (from triaxial tests) of model and structural materials, and (b) coefficients of elasticity in the same relation. A literature review revealed that the most promising model material was probably a mixture of gypsum cement (plaster), fillers, and water. Tensile, compressive, and triaxial strength tests and stress-strain tests were conducted on combinations of plasters, sands, and other filler materials. Results indicated that brittle rocklike material could be easily formulated to secure a wide range of physical properties. With regard to the above-mentioned principles, the stress-strain curves are linear over a wide range, but the triaxial stress condition is restricted by low ϕ angles, approximately 30 degrees compared to 40 degrees and above for most rocks.

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DEVELOPMENT OF MATERIAL FOR MODELING ROCK

PART I: INTRODUCTION

Background

1. The goal of Nuclear Weapons Effects Research Subtask 13.191 is to provide criteria for designing protective structures in rock. It is assumed that the shelters will be exposed to various threats from nuclear explosions. There are many facets to this complex problem. Basically, the response of a given structure (or system) to the disturbance must be determined. This would involve knowledge of fundamental nuclear explosion phenomena, energy coupling, wave propagation, structure-media interaction, stress analysis, dynamic properties of materials, kinetics, etc. Because of the very nature of natural rock masses and geologic formations it is not possible to solve all the problems analytically; thus resort must be made to experimental methods for some of the answers. Since models have been used successfully for study of explosion effects under a myriad of test conditions, it would seem fruitful to use the modeling approach in rock mechanics research.

2. Modeling of structures has long been a useful tool for structural research. Modeling as applied to rock mechanics and explosive phenomena research is less common; however, such application offers the advantages of reduced cost, time, and physical area required. Tests on scale models are based on the criteria of changing the scales of length, time, and force without changing the equations describing the mechanics phenomenon. There are two methods of maintaining these relations: (a) conservation of material, often employed in structural modeling where mass consideration is not important, and (b) equivalent material, whereby a much "softer" material replaces the prototype in such a manner as to satisfy the equations of similitude. Models of bridges, buildings, structural members, etc., utilizing the conservation of material principle are common structural design tools. However, because of mass considerations an equivalent material, "microconcrete," is often employed in

modeling concrete structures. Modeling of geological structure also requires effective utilization of equivalent material.

Purpose and Approach

3. The purpose of this investigation was to develop mixtures of practical materials to model geological formations. The approach was based on the similitude principles established and successfully used for brittle materials at the Mining Institute of the Czechoslovak Academy of Sciences.[1] Essentially, the similitude principles are: (a) similar and similarly oriented Mohr's envelopes of model and structural materials, (b) coefficients of elasticity in the same relation as the Mohr's envelopes, and (c) density relation accounted for in the selection of stress-length ratios. Since, in practice, ratio of model and prototype density cannot deviate far from unity, the stresses in the model must be much smaller than those in the structure. The following specific criteria were established for this study. An unconfined compressive strength of 200 to 1000 psi* was selected as a practical range for modeling rock with strengths in the range of 15,000 to 30,000 psi (see fig. 1). In addition, the ratio of the Poisson's ratios of the structure and the model should be unity. In rock, a triaxial stress condition exists and therefore the intrinsic (inherent) strength relations must be maintained as in fig. 2. Furthermore, if there are large

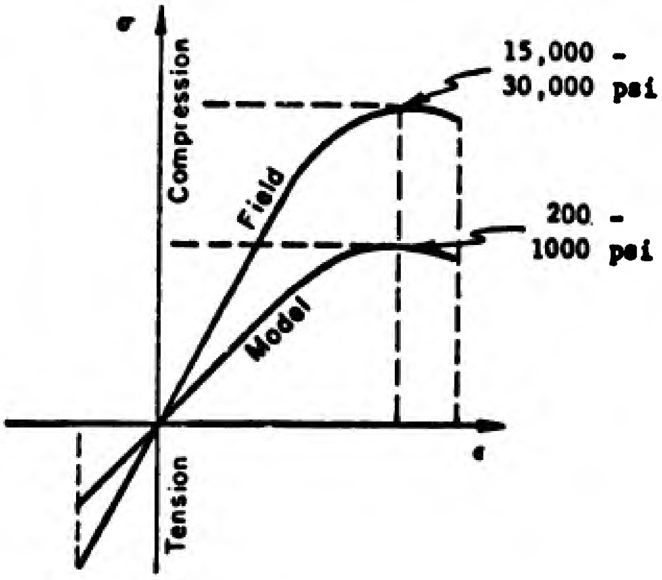

Fig. 1. Field and model stress-strain curves

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* A table of factors for converting British units of measurement to metric units is presented on page vii.

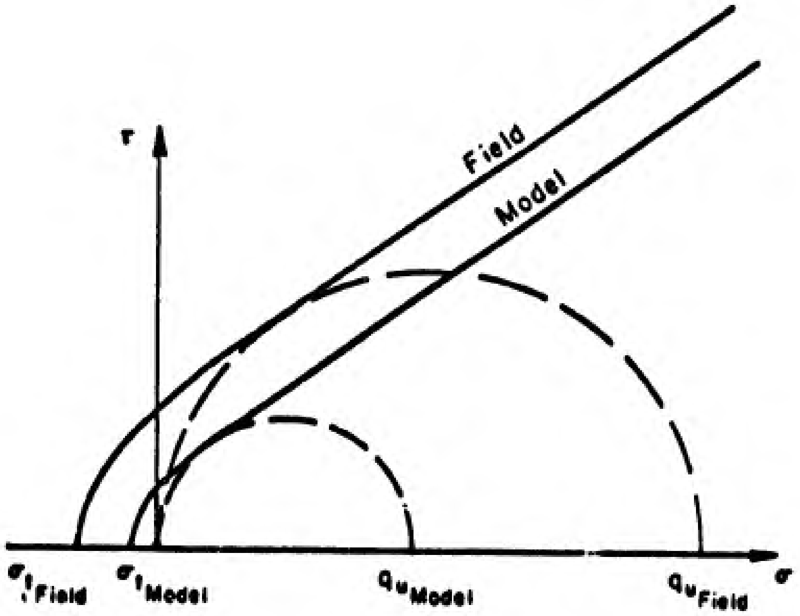

Fig. 2. Field and model Mohr failure envelopes

deformations, the equivalent material must satisfy the supplementary condition that the ratio of Young's moduli must equal the ratio of the intrinsic curves.

Scope

4. It is not the intent of this paper to discuss modeling theory and scaling laws; they are well documented in the literature.[2,3,4] However, once the quantities to be scaled are determined, the development of a practical modeling material is often difficult. For example, Hubbert has shown[5] that a model material for a granite formation 20 kilometers square for a length ratio of 10^{-5} and a density ratio of 1.0 must be a brittle substance that would crush under a stress of 0.29 psi. This is probably an extreme illustration, but it serves to point out the difficulty of securing the proper materials for modeling of geological structures. If practical model materials could be developed to model the appropriate parameters, the modeling of massive structures would be greatly advanced.

PART II: LITERATURE REVIEW

5. It was apparent from the beginning of the literature review that many materials and combinations of materials have been used for various types of modeling work. They may be roughly divided into two general types of materials--ductile and brittle. The ductile materials are of little consequence to this program and will be mentioned only briefly.

6. The most complete list of ductile materials used for modeling work was found in the general report to the second session of the RILEM (The International Union of Testing and Research Laboratories for Materials and Structures) Symposium on Models of Structures in June 1959.[6] The author, C. Benito, noted use of the following materials: compressed cork, rubber, plastics, gelatin, metal, and fine sand in vaseline, among others. Plastics may be fabricated in such a way that they will be brittle, but they have an appreciable tensile strength, are costly, are temperature-sensitive, and have a relatively high Poisson's ratio. Nevertheless, alkathene, perspex, celluloid, and resins have been used to a limited degree in modeling geologic structures[7] for determination of thermal stresses[8] and gravitational stresses.[9] Gelatins have been used extensively in the United States[10] and abroad[11] for photoelastic studies of gravity structures and geologic cross sections. Farquharson and Hennes[12] used gelatin to study stress concentrations around tunnels. Work with photoelastic gelatins could supplement modeling with brittle materials by providing information on maximum stresses and strains, stress concentrations, etc.

7. Two materials stand out upon initial consideration of establishment of a brittle material for modeling of rock: portland-cement mortar and gypsum-cement (plaster) mortar. For structural modeling, portland-cement mortars or microconcrete has been used extensively. Space does not permit enumeration of the many articles dealing with this aspect of modeling. Rather, attention should be directed to work which may be considered geologic modeling. Everling[13] used portland-cement mortar for model tests of the interaction of ground and roof supports around roadways in a layered medium. J. B. Johnson[14] concluded that craters produced by a fraction of a gram of high explosive in portland-cement mortar blocks are similar in

shape to craters produced in rock by much larger explosive charges. Material properties, particularly shear strength and density, were found to have a very large influence on the sizes and shapes of craters formed by small explosions in portland-cement mortar blocks.[15] Fumagalli[16] used calcareous sand, diatom sand, and pumice stone in a highly deformable cement mortar to produce stress-strain and multiaxial properties much like those specified in the criteria of this study. Other brittle materials which possibly could be considered include: ice,[17] fly ash-sodium silicate mixtures,[18] polyvinyl acetate mortars,[19] thermally stabilized clay soil,[20] and calcium-aluminate cement mortars.

8. Plaster or gypsum-cement mixtures are the most frequently used mixtures for modeling work. Outstanding work in modeling of arch dams and dam foundations has been accomplished both in the United States[21,22] and abroad.[7,23] Jones and McCutchen[24] successfully modeled a large-scale explosive blast in sandstone. Hesselbacher and others[25] attempted, with some success, to model explosive blasts in granite by use of gypsum-cement mixtures. Martin[26] defined certain physical properties that must be well established for prediction of fracture phenomena by use of plaster models. Hobbs[27] used plaster models to study strata movement around openings in a simulated rock mass. Barron and Laroque[28] developed a model for study of mine structure. Krsmanovic and Milic[29] performed model tests to determine stress and strain distribution and the behavior of a large rock mass under load. Patton[30] made an extensive study on simulated rock surfaces by use of plaster of paris models and correlated the results with results of tests of actual rock. He concluded that the multiple modes of shear failure postulated for the plaster could be extended to cover rock.

PART III: MATERIALS AND MIXTURES

9. To determine which materials and mixtures would merit consideration for modeling of brittle rock, trial mixtures of the following combinations were proportioned: gypsum cement-pumice mortars, gypsum cement-diatomite mortars, portland-cement mortars, fly ash-lime mortars, calcium-aluminate-cement mortars, wax, and vaseline with sand. In response to a suggestion that the best model for rock might indeed be rock per se, samples of a locally abundant weak sandstone were brought into the laboratory, cored, and tested.

10. Gypsum cement is available with slight difference in properties under many names in this country, e.g. plaster of paris, Cal-Seal, Hydrostone, all of which are basically calcined gypsum consisting of two hemihydrates. The differences in many types of commercial plasters are largely due to the relative amounts of the hemihydrates. The properties of plaster are well documented in the literature.[22,28] Diatomite or diatomaceous earth is made from fossil deposits of microscopic marine plants. It is extremely fine, having a surface area of approximately 20,000 sq cm per g, and is an excellent filler material. Pumice, also used as a filler, is a volcanic product, but is not nearly as fine (7000 sq cm per g) as diatomite. Portland cement is, of course, the primary cementitious material used for construction and needs no description here. Fly ash is a by-product of coal-burning furnaces which possesses cementitious properties in the presence of lime. Calcium-aluminate cement is an extremely rapid hardening cement used primarily in Europe. Wax and vaseline were considered only as a result of favorable comment on their use by Benito.[6]

11. From the literature and work with the trial mixtures, the gypsum-cement mortars appeared to offer the best possibilities for modeling the several properties of brittle rock. Both plaster and portland cement are ceramic-type materials, but portland cement requires more time for stabilization than plaster. Also, plaster should require less heat for an accelerated cure. Fly ash-lime mortars are more time-dependent than portland cement and hardly as practical. The mixtures with calcium-aluminate cement yielded strengths too high (3000 psi) to be commensurate with the criteria

of this study. Mixtures of vaseline and several gradations of sand, fine and coarse, proved impractical to mix, handle, and form. The wax, a paraffin-rosin mixture, yielded a pronounced curvilinear stress-strain curve and consequently was discarded. Specimens drilled from the sandstone samples and tested in compression resulted in a wide variation in ultimate strengths, and use of this stone was also abandoned. Consideration was given to using a consolidated clay with and without a heat treatment, but it was believed that such a procedure would require excessive care and control and would also result in wide variations in physical properties.

12. Four basic combinations are possible with the materials used in the gypsum-cement mortars:

	Materials			
Combination	Plaster	Filler	Sand	Water
1	X			X
2	X	X		X
3	X		X	X
4	X	X	X	X

Two different plasters (plaster of paris and Hydrostone), two fillers (diatomite and pumice), and several types and gradations of sand were used. Mixtures involving only plaster and water (combination 1) are very easy to mix and use, but the range of usable mixtures is limited by the amount of water which can be effectively combined with plaster. Excess water accumulates on the tops of cast specimens as bleed water, and the specimen thus is reduced in solid volume or shrinks. Addition of the filler materials (combination 2) greatly extends the range of possible mixtures because the fillers require the use of additional water. The use of sand (combination 3) requires some additional water but results in harsh mixtures in the low stress ranges and entrapment of large and numerous air voids. When plaster, filler, sand, and water are utilized (combination 4) and properly proportioned, the result is a workable, uniform, economical mixture which can be pumped or molded into almost any form or shape required. Proportions of the 21 mixtures investigated in this study are given in table 1. One of the plasters was a commercial casting plaster and the other a high-strength molding plaster, Hydrostone. Sands used include Ottawa (several gradings), limestone, traprock, silica, and silica flour, a very fine silica sand. The various sand gradings are given in table 2. Mixing was accomplished in a mechanical mixer of the epicyclic type which imparts both planetary and revolving motion to the mixer paddle.[31] The water and filler were added first as the mixer operated at reduced speed. The plaster and sand, if required, were then added, and the speed of the mixer was increased. After all materials were in the mixer, mixing was continued for 2 min. All mixtures appeared well mixed, with little evident segregation of the sand or bleeding of excess mixing water.

PART IV: TESTS AND RESULTS

Tests

13. As indicated in table 1 the following tests were made on the unhardened mortars: consistency, pot life, setting time, and bleeding and shrinkage. The consistency test, made to determine a relative degree of fluidity and workability for the various mixtures, was patterned after the slump test for concrete.[31] The slump cone, shown in fig 3, is placed on a flat glass surface, filled to the top with mortar, and the excess material is struck off with a straightedge. The cone is then lifted vertically, and the diameter of the material which spreads out radially is measured. The increase in diameter over the base diameter of the cone (3 in.) is a measure of the consistency of the mixture, i.e. the larger the consistency measurement, the more workable the mixture. Naturally, the fluidity decreases as the mixture begins to set; therefore, the consistency test is made immediately after mixing is completed. Mixtures with consistency measurements of 5 in. or more could be pumped into final position of placement; mixtures with less consistency would require molding or placement by gravity pour.

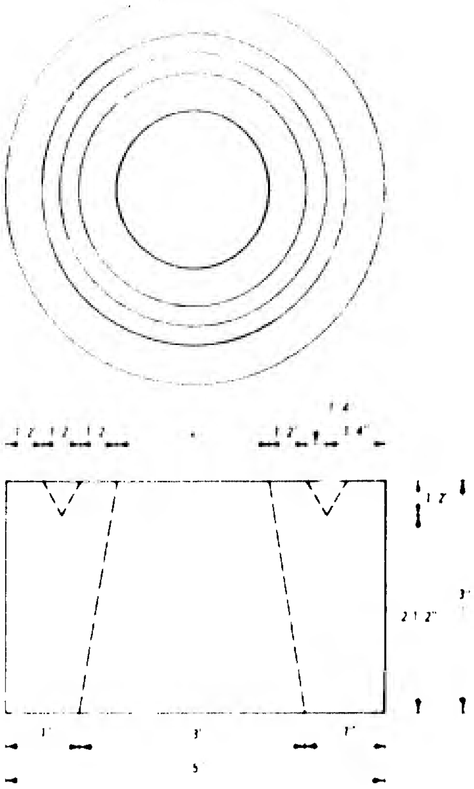

Fig. 3. Slump cone

14. The pot life and setting time are dependent on the presence and amount of retarding agent in the plaster and the water-plaster ratio used for the particular mixture. Many commercial plasters have retarders added during manufacture, but it is not difficult to extend the setting time if desired.[22,28] Pot life or initial setting time is a measure of the length

of time a mixture remains in the plastic, fluid state. Between the pot life time and setting time indicated in table 1, the material could be molded or made to change shape, but resistance to change of physical shape was present. At the time indicated as setting time, final stiffening had been attained and any further effort to mold or change a shaped specimen would have resulted in physical damage to the specimen. With care, specimens can be stripped from molds soon after the setting time is reached. Bleeding and shrinkage were determined on a 500-ml sample of the respective mixtures allowed to stand until final set had been achieved. The bleed water that accumulated at the top above the solid surface of the sample was converted to percent by volume and given in table 1. This percentage is also the shrinkage since the top of the solid specimen is the lower level of the accumulated bleed water.

15. The following physical tests were conducted on 3- by 6-in. cylindrical specimens of the 21 mixtures: unit weight, tensile, unconfined compressive, and triaxial strengths, Young's modulus, and Poisson's ratio (see table 3). All tests except the unit weight and triaxial tests were conducted on specimens fabricated from a single batch of each of the respective mixtures. Tests at various ages for tensile strengths (by the tensile splitting method) and compressive strengths provided information on the strength gain with time. All specimens were cured at 73 ± 3 F and 55 ± 5 percent relative humidity. It was discovered that the specimens could not be capped with a plaster cap for compressive testing due to the formation of a weak area beneath the caps when wet plaster was applied to the dry specimens. Subsequently, all compressive strength specimens were capped with a sulfur-silica compound and all triaxial specimens were struck off plane and parallel on the ends with a straightedge immediately after set. Two diametrically opposed axial electrical resistance strain gages applied at midheight to the 28-day compressive strength specimens yielded strain data for stress-strain curves (plates 1 through 21) and determination of Young's modulus. Young's modulus was computed as the slope of the tangent to the stress-strain curve at one-half of the ultimate strength. Diametrically opposed circumferential gages, also mounted at midheight, provided strain data for computation of Poisson's ratio. Specimens were

cast from a second round of the respective mixtures for triaxial tests. Daily weight measurements of the specimens indicated that five days storage at 100 ± 3 F effected the complete cure for the plaster. This agreed substantially with Raphael[22] and the U. S. Bureau of Reclamation* practice for construction of plaster models of dams. Unit weight determinations were made prior to triaxial testing from the final weights and physical measurements of the specimens. Triaxial tests were conducted according to conventional procedure[31] at relatively low confining pressures (< 800 psi) on selected mixtures. The Mohr circles plotted from the triaxial tests are given in plates 22 through 31.

Results

16. First to be considered are the factors governing construction of a sound model. Of the two gypsum cements utilized in this study, one (plaster of paris) was relatively fast setting and the other somewhat slower (see table 1). Although the setting time may be extended by the use of retarders, extended plastic life of fluid mixtures increases the bleeding and shrinkage and should be used only if required. The bleeding and shrinkage for the mixtures reported herein are not sufficient to jeopardize the integrity of a model. The use of the various types of sands did not affect the plastic properties significantly.

17. The physical test data in table 3 reveal several significant factors. There is no significant strength gain between 14 and 28 days; therefore, it would feasible to test a model at 14 days after curing at 73 F and 50 to 60 percent humidity. However, the mass of the model must be considered. To determine if large blocks effectively cured throughout, 1-ft cubes were cast from mixture 33, stored at 73 F and 50 to 60 percent humidity, and cored at different ages. The cores, NX size, were tested for compressive strength. Results are given on the following page.

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* Information on use of models by the Bureau of Reclamation was obtained in conversation with Mr. Bill Lockart during visit to USBR laboratory on 21 June 1966.

Age in Days at Which Test Specimens Were Cored and Tested		
Cored	Tested	Compressive Strength, psi
1	3	355
1	7	400
1	28	580
3	3	270
7	7	290
28	28	330

The results clearly reveal that the material in the blocks had not completely cured at 28 days age (330 psi) although the cores taken at 1-day age and cured identically apparently reached optimum strength (580 psi). Many investigators,[22, 28, 32] including the U. S. Bureau of Reclamation, have solved this problem by constructing models of mass structures by fabricating individual blocks, the least dimension of which is usually not more than 6 in., and cementing the blocks together to form the mass. The cemented joints apparently transmit the test loads without affecting the integrity or action of the model as a whole. This appears to be the most effective way to secure a relatively uniform massive structure throughout.

18. The tensile strengths obtained on the mixtures used in this study are relatively high compared with that required to achieve a compressive-tensile ratio comparable to that of most rock (approximately 20:1). It was hoped that the various types and gradations of sand would yield comparatively lower tensile strengths, but they did not. Indeed, it appears that the compressive-tensile ratio is relatively constant over the entire strength range and with either type of filler or any of the sands used. The results of the stress-strain tests indicate that a range of moduli may be secured over one order of magnitude, i.e. 0.20 to 2.00 × 10^6 psi (see table 3). Poisson's ratio for the model material closely approximates that of most rock types and varied only slightly between mixtures, with lower values achieved with certain sands and/or filler materials. An examination of the stress-strain curves, plates 1 through 21, reveals that a relatively linear relation exists up to approximately

80 percent of the ultimate strength for most of the mixtures. The greater strains were attained with the mixtures with the lesser amounts of filler and aggregates (see table 3). The strain at failure was difficult to define on many mixtures, but generally where the stress-strain curve is curving sharply at the top, a more brittle failure developed, and where the curvature is less pronounced, a "softer" type failure occurred. The results of the triaxial tests were disappointing. Results are given in table 3. The envelope for most of the mixtures yielded ø angles of approximately 30 degrees which is somewhat less than the ø angle for most rock types. Other investigators, including Goldstein,[32] da Silveira,* Krsmanovic, Tufo, and Langof,[33] have experienced this limitation. Goldstein and others,[32] however, used rocks (limestone, sandstone, and clay shale) that had ø angles approximately equal to that of the mold material. Krsmanovic[33] devised a unique solution for a particular problem of modeling joints; he utilized several types of irregularities to secure various angles of friction from 40 to 65 degrees. The use of various types and gradings of sand did not result in perceptible changes in the ø angle. Apparently the ø angle is primarily dependent upon the strength of the gypsum-cement mortar and the distance between the sand grains in the hardened material. Since the individual sand grains are not in direct contact and the gypsum paste is appreciably weaker than the aggregates, failure always occurs through the paste. Thus, no increase in ø angle was noted with the addition of fillers or aggregates.

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* Pertinent information contained in a letter from Mr. A. F. da Silveira of the Laboratorio National De Engenharia Civil, undated, subject, "Mechanical Characteristics of Plaster."

PART V: DISCUSSION AND CONCLUSIONS

Discussion

19. To effectively utilize the model material developed in this study, the requirements and uses of the model must be considered. The ratio of unit weights of the prototype and model will likely be approximately 2 for any model system. This is readily resolved in the modeling equations.[2,3,4] Next, however, the modeler must decide which physical quantities need be considered relevant. It is unlikely that he will find optimum properties for all quantities selected to be modeled. For example, if low strength is dictated by limitations of test equipment or other considerations, a low-strength mixture must be selected, e.g. mixture 2, 6, 24, 25, 28, or 33. Next, a high-modulus mixture (mixture 25) or low-modulus mixture (mixture 2) and low strain, brittle failure (mixture 6) or high strain, plastic-flow-type failure (mixture 24 or 28) must be selected. Other factors, such as the state of stress, triaxial and tensile strengths, Poisson's ratio, etc., will probably require consideration.

20. Other factors which various investigators, including Azevedo and Ferreira[7] and the U. S. Bureau of Reclamation, have found relevant to their problems when using gypsum cement include: (a) the use of a waterproofing agent on the cured model to prevent changes in the water content within the model with atmospheric changes, (b) the use of a cutting tool to remove 1/8 to 1/4 in. from the surface of the properly cured model to eliminate a "skin friction" effect (slight hardening of the outside surfaces) which sometimes results on a cast model section and causes erroneous strain readings, and (c) fabrication of massive sections by cementing together individually cast blocks, the least dimension of which is 6 in.

Conclusions

21. Of the various materials suggested in the literature and explored in trial mixtures, the most practical and feasible material available to

model brittle rock appears to be mixtures of gypsum cement (plaster) and filler materials. Plaster mixtures: (a) are isotropic and homogeneous, (b) are easily mixed and placed, (c) are economical, (d) have been widely used and therefore many of the properties are well documented, and (e) can be controlled to fit the requirements of the test with regard to strength and elastic properties and setting time. Given below is an estimate of physical properties of the four combinations of the plaster mixtures that may reasonably be expected for materials similar to those used in this study.

Estimated Physical Properties

Combination*	Compressive Strength psi 28 days**	Hardened Unit Wt lb/cu ft	Compressive-Tensile Ratio	Young's Modulus 10^6 psi	Failure Strain μin./in.	Poisson's Ratio	Triaxial Angle of Internal Friction (Ø), deg
1	400 up	70	7:1 to 8:1	0.20 to 0.80	2500	0.25	24
2	500 up	55-65		0.20 to 0.80	2500	0.22	30
3	600 up	100-115		0.80 to 2.00	1000	0.19	30
4	400 up	90-105		0.40 to 1.00	1200	0.17	30

* Combination 1 = plaster and water; combination 2 = plaster, filler, and water; combination 3 = plaster, sand, and water; combination 4 = plaster, filler, sand, and water.

** Figure shown is strength for lowest strength practical mixture that would still exhibit insignificant bleeding and a relatively linear stress-strain curve.

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Table 1

Mixture Proportions and Data on Unhardened Material

Mixture No.	Types and Proportions by Weight of the Material Used in the Mixtures						Consistency in.	Pot Life min	Setting Time min	Bleeding and Shrinkage %	Type of Sand Used
	Gypsum		Filler		Sand	Water					
	Type	Proportion	Type	Proportion							
							Combination 1				
24	P	1.0	--	--	--	1.0	11.5	10	15	0	
23	P	1.5	--	--	--	1.0	7.75	8	15	0	
19	H	1.5	--	--	--	1.0	13.75	15	20	0.4	
							Combination 2				
2	H	0.67	D	0.33	--	1.0	0	30	40	0	
28	P	0.80	D	0.20	--	1.0	3.5	12	20	0	
36	P	1.0	Pu	0.70	--	1.0	5.75	15	20	0	
29	P	1.3	D	0.20	--	1.0	0	5	12	0	
37	P	1.5	Pu	0.20	--	1.0	6.0	12	20	0	
							Combination 3				
31	P	1.0	--	--	2.33	1.0	3.0	15	20	0.8	Standard graded Ottawa sand
40	H	1.0	--	--	2.65	1.0	0	12	20	0	Silica flour
38	H	1.0	--	--	4.41	1.0	0	20	35	0	Silica sand
25	P	1.0	--	--	4.70	1.0	0	10	20	0	20/30 Ottawa sand
32	P	1.5	--	--	3.50	1.0	3.25	10	15	0	Standard graded Ottawa sand
21	H	1.5	--	--	6.00	1.0	5.0	15	25	0.4	20/30 Ottawa sand
22	H	1.5	--	--	6.00	1.0	5.5	20	25	0.4	50% 20/30 Ottawa sand. 50% standard graded Ottawa sand
30	H	1.5	--	--	8.00	1.0	0	15	25	0	Standard graded Ottawa sand
							Combination 4				
6	H	0.46	D	0.23	2.55	1.0	0	30	40	0.2	Standard graded Ottawa sand
33	H	0.60	D	0.10	3.50	1.0	7.5	25	35	0.8	Standard graded Ottawa sand
34	H	0.90	D	0.10	3.50	1.0	7.75	20	30	0.2	Standard graded Ottawa sand
39	H	0.90	D	0.10	3.50	1.0	4.5	20	35	0.4	Traprock sand
41	H	0.90	D	0.10	3.50	1.0	5.5	15	30	0.2	Limestone sand

Note: **P indicates plaster of paris, specific gravity = 2.72.**
H indicates Hydrostone, specific gravity = 2.72.
D indicates diatomaceous earth, specific gravity = 2.10
Pu indicates pumice, specific gravity = 2.35

Table 2

Fine Aggregate Data

	Cumulative Percent Passing						
Sieve Size	20/30 Ottawa	Standard Ottawa	50% Blend 20/30 and Standard	Limestone	Traprock	Silica Sand	Silica Flour
No. 16	100.0	100.0	100.0	100.0			
No. 20	85.0	100.0	92.0	75.4	100.0		
No. 30	5.0	98.0	51.0	48.0	65.0	100.0	
No. 50		28.0	14.0	6.9	18.3	78.5	100.0
No. 100		2.0			1.0	4.7	99.3
No. 200							49.8
Specific gravity	2.65	2.65	2.65	2.67	2.90		

Table 3

Physical Test Data

Mixture No.	Hardened Unit Wt lb/cu ft	Strength, in psi, at Age Shown: Unconfined Compressive, 2 Days	3 Days	7 Days	14 Days	28 Days	Tensile, 3 Days	28 Days	Compressive: Tensile Ratio 28 Days	Young's Modulus 10^6 psi	Failure Strain µin./in.	Poisson's Ratio	Triaxial Angle of Internal Friction (Ø), deg
							Combination 1						
24	66.5	330	360	400	--	400	45	50	8.7:1	0.17	2500	--	24
23	70.1	1020	1050	1110	--	1560	95	185	8.4:1	0.84	2000	0.29	--
19	73.2	770	865	--	--	1600	115	225	7.1:1	0.76	2400	0.25	--
							Combination 2						
2	49.6	250	260	300	--	490	50	60	8.2:1	0.27	2300	0.22	--
28	50.8	--	--	225	440	470	--	65	7.2:1	0.22	2800	0.20	--
36	69.3	--	--	560	1010	970	--	135	7.2:1	0.70	2000	0.25	32
29	67.5	--	--	900	1430	1470	--	200	7.4:1	0.53	3000	0.17	--
37	74.8	--	--	1215	1910	1830	--	235	7.8:1	0.90	2300	0.20	37
							Combination 3						
31	98.1	--	--	360	790	760	--	110	6.9:1	0.76	1100	0.20	--
40	97.9	--	--	430	1080	1200	--	135	8.9:1	1.02	1400	0.14	31
38	110.9	--	--	750	880	870	--	90	9.7:1	1.53	800	0.14	--
25	110.2	245	230	335	--	610	30	85	7.2:1	1.26	600	--	22
32	108.7	--	--	1615	1440	1480	--	175	8.5:1	1.61	1000	0.22	--
21	120.7	830	835	1440	1460	1460	50	155	9.4:1	1.78	900	--	--
22	122.8	1060	1200	1390	--	1340	60	150	8.9:1	1.70	1300	0.14	30
30	119.2	--	--	1030	1200	1120	--	135	8.3:1	2.13	800	0.24	31
							Combination 4						
6	88.8	275	300	350	--	340	20	40	8.5:1	0.31	1400	--	--
33	106.4	--	--	325	485	505	--	55	9.2:1	0.60	1000	0.19	27
34	109.3	--	--	770	920	1120	--	140	8.0:1	1.29	1100	--	--
39	112.6	--	--	550	910	860	--	120	7.2:1	0.82	1200	0.15	35
41	107.3	--	--	500	925	950	--	135	7.0:1	0.96	1200	0.14	26

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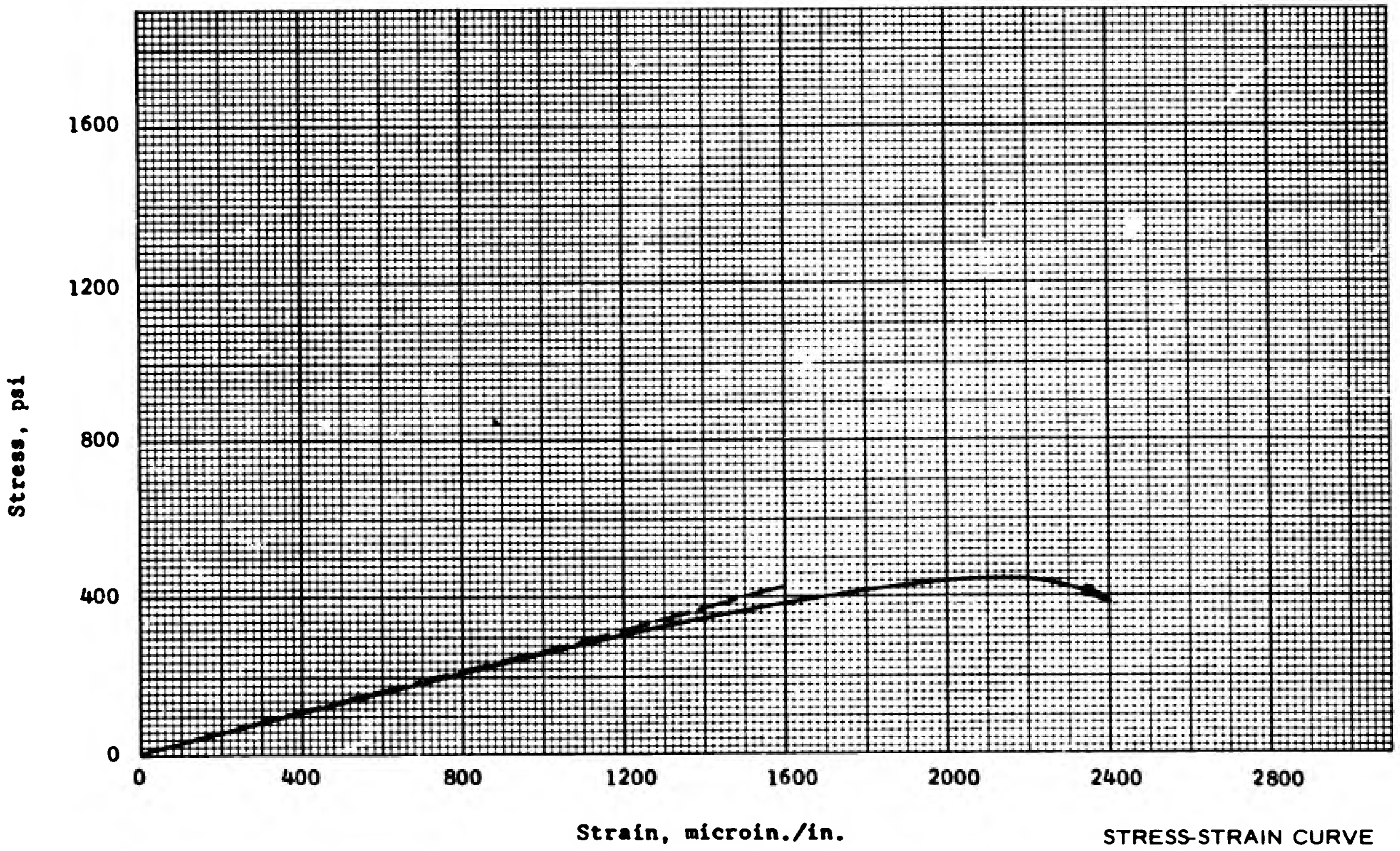
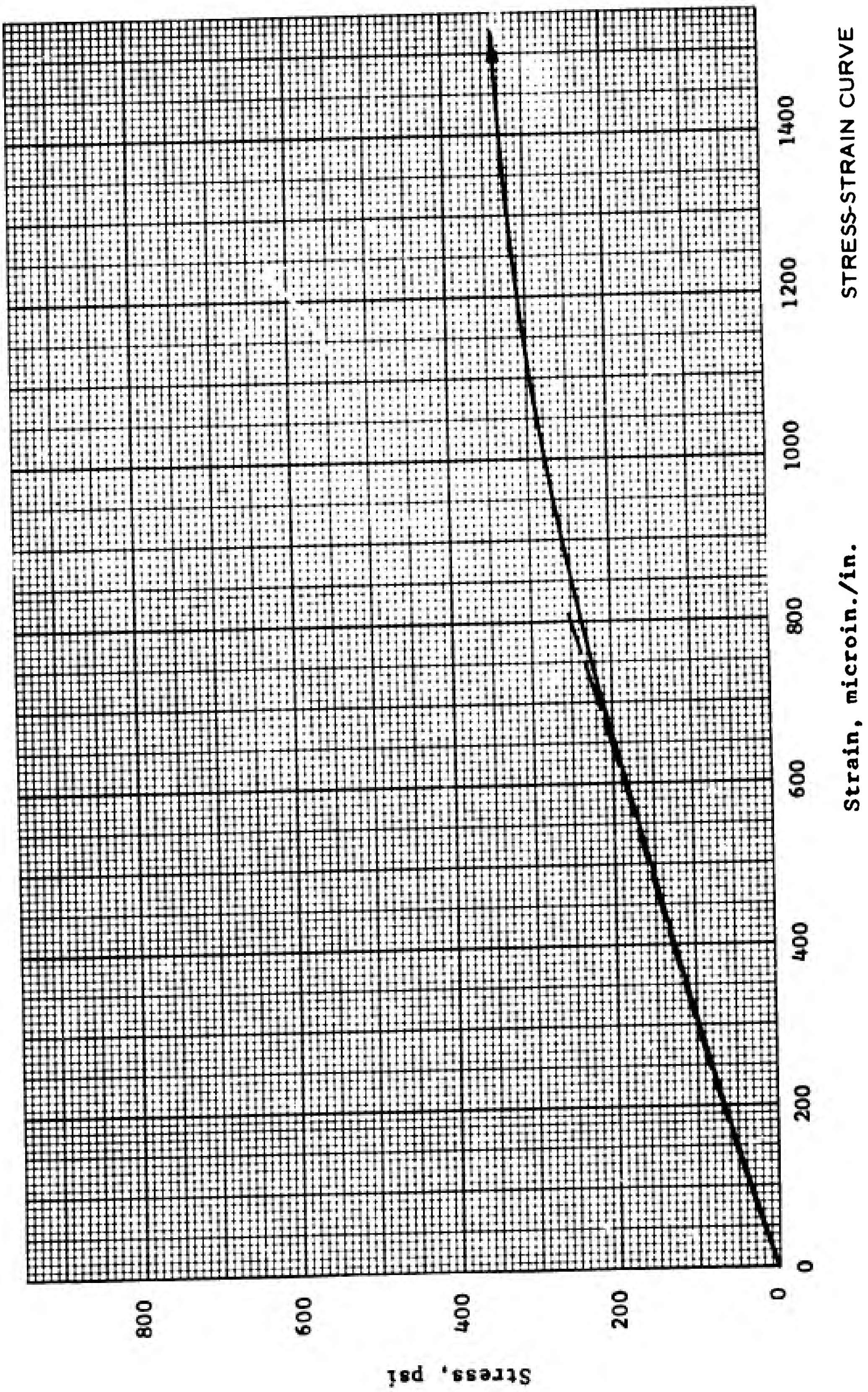


STRESS-STRAIN CURVE
MIXTURE 2

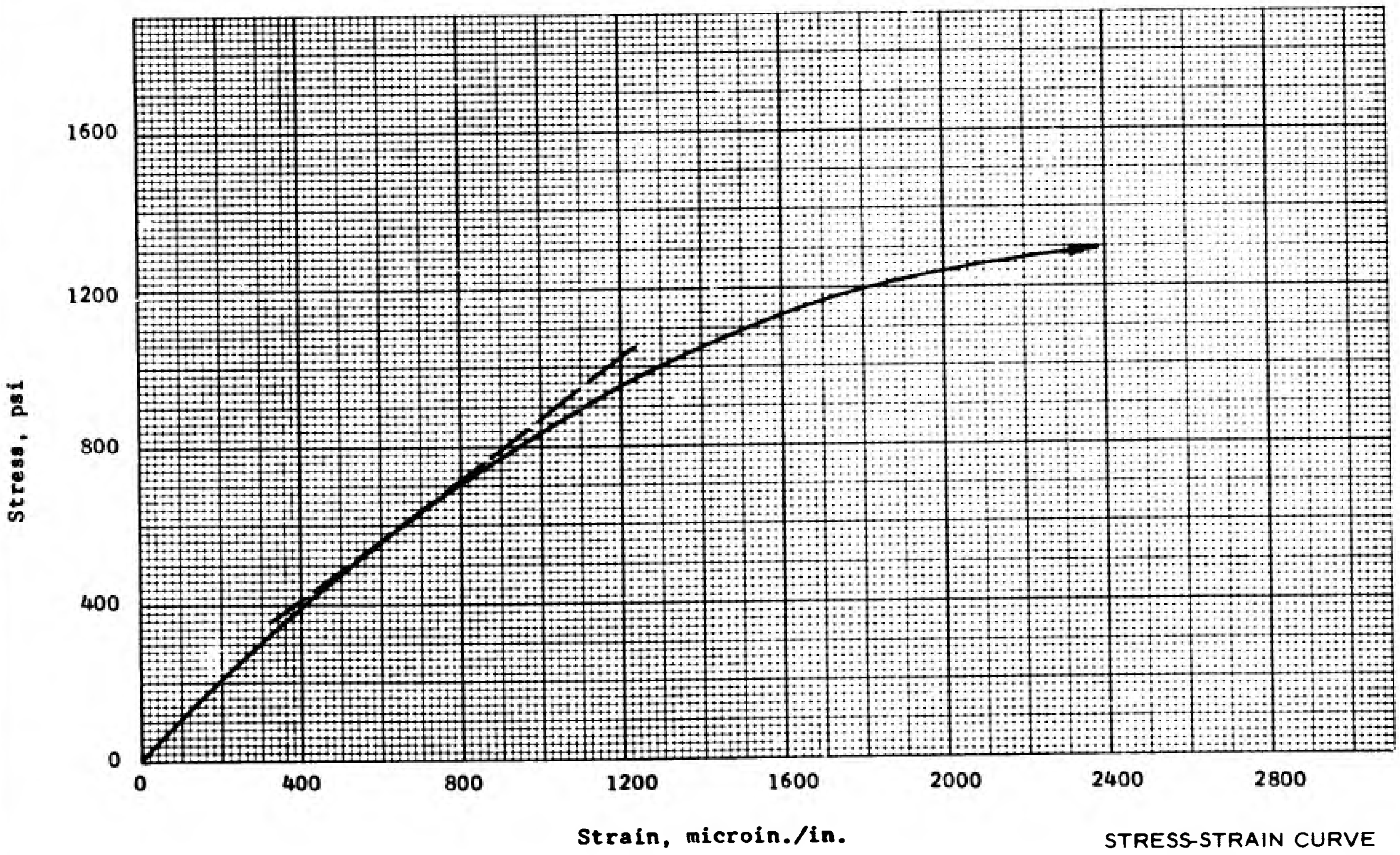
PLATE I



STRESS-STRAIN CURVE

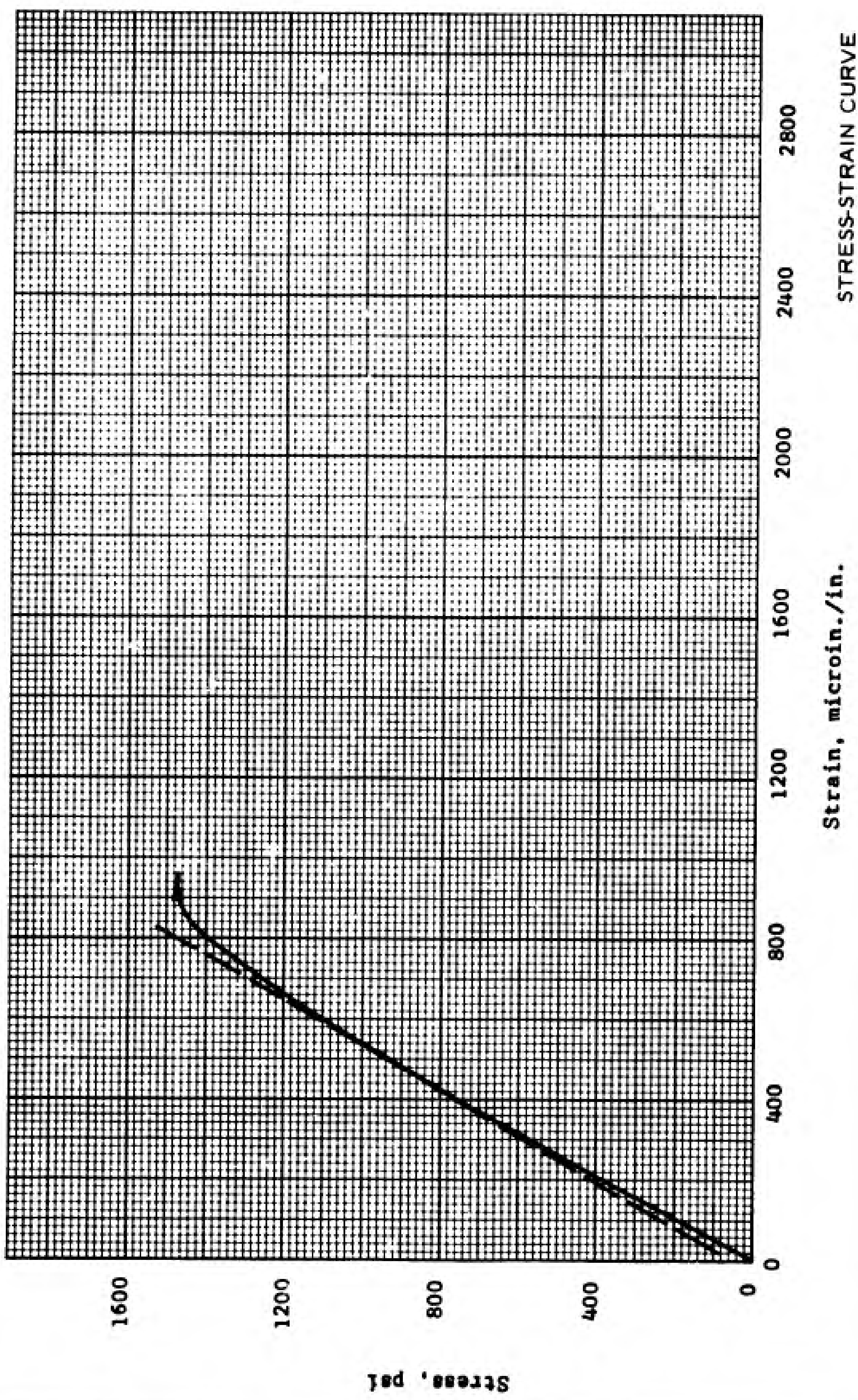
MIXTURE 6

PLATE 2



STRESS-STRAIN CURVE
MIXTURE 19

PLATE 3



STRESS-STRAIN CURVE
MIXTURE 21

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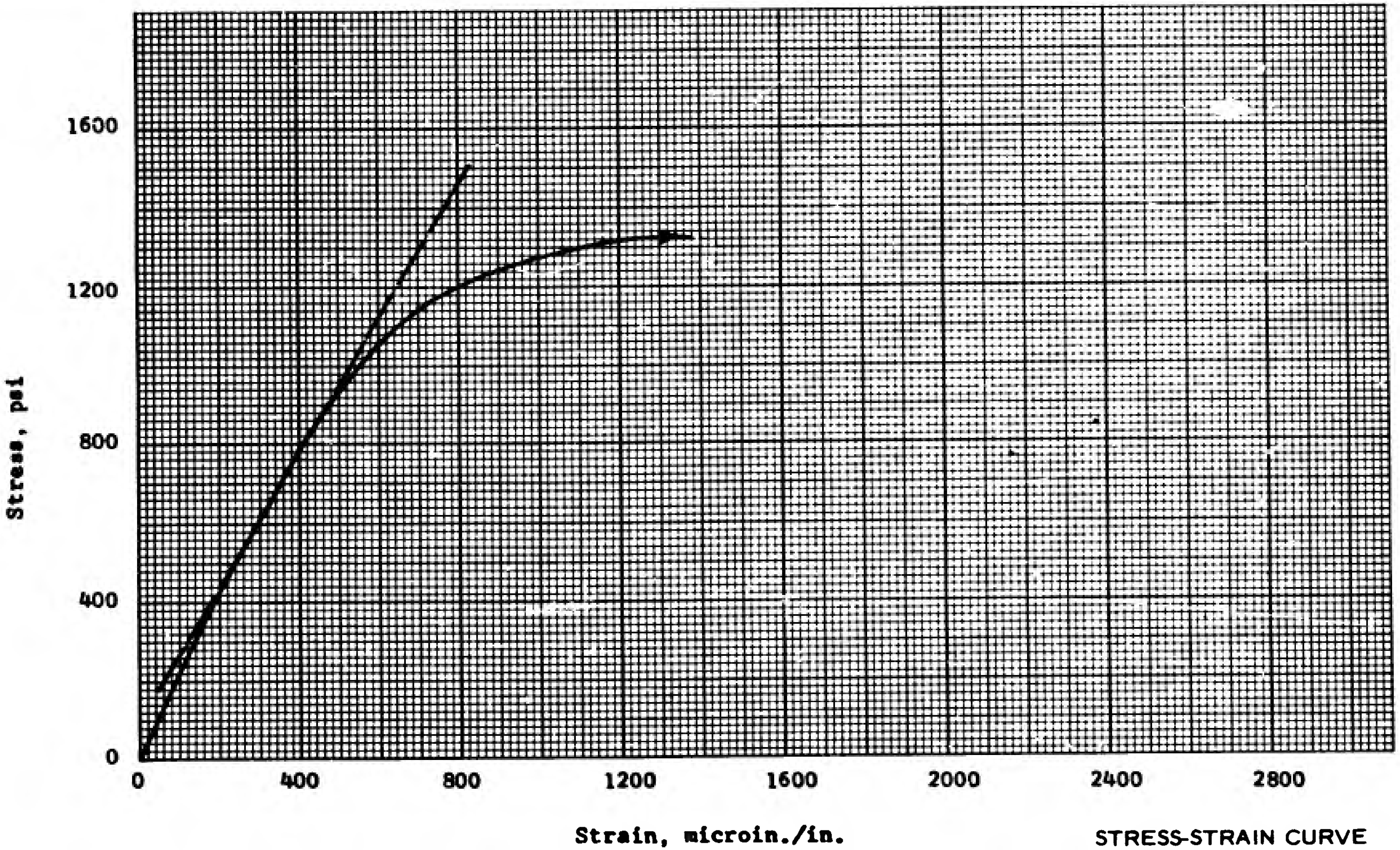
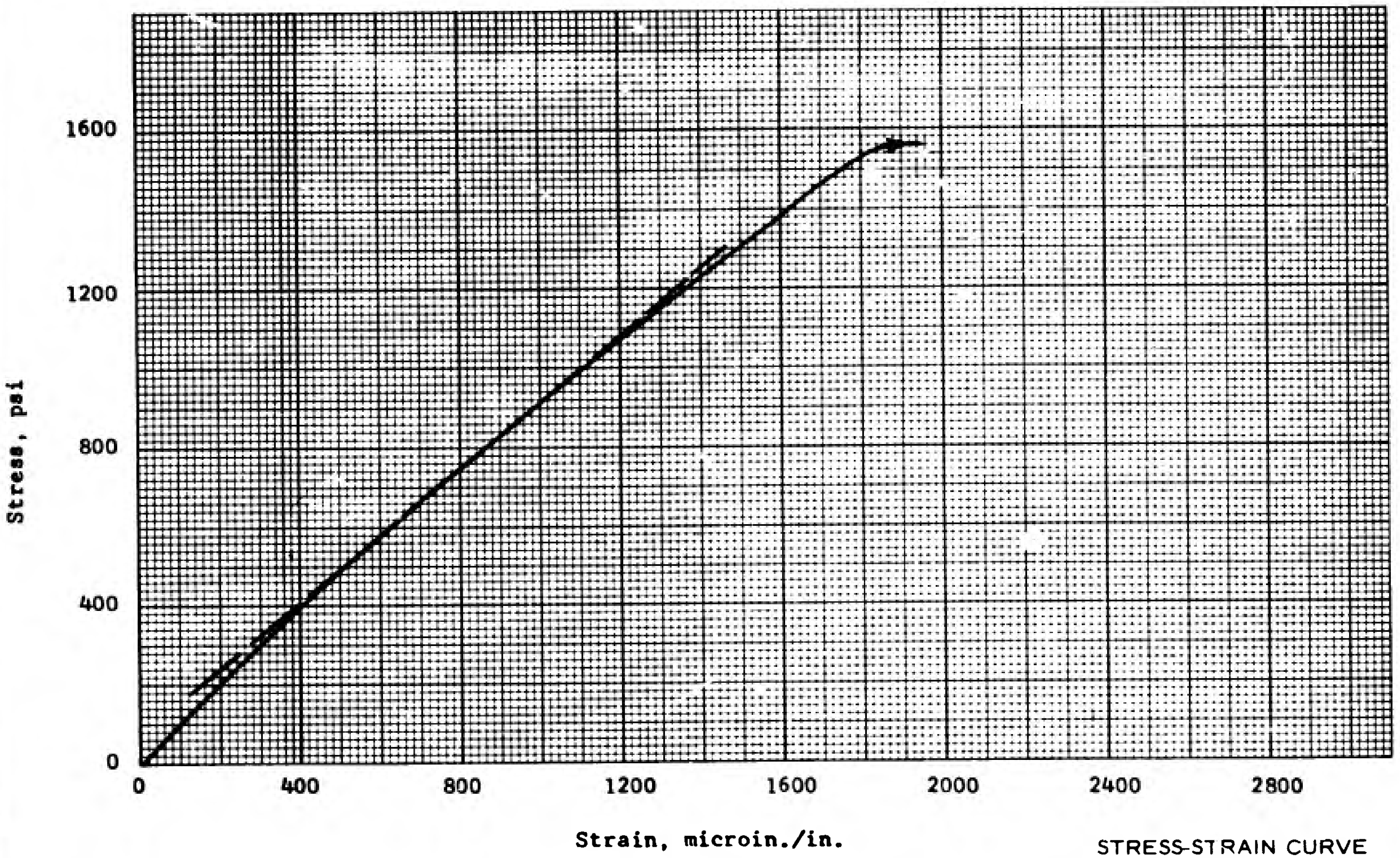


STRESS-STRAIN CURVE
MIXTURE 22

PLATE 5

PLATE 6



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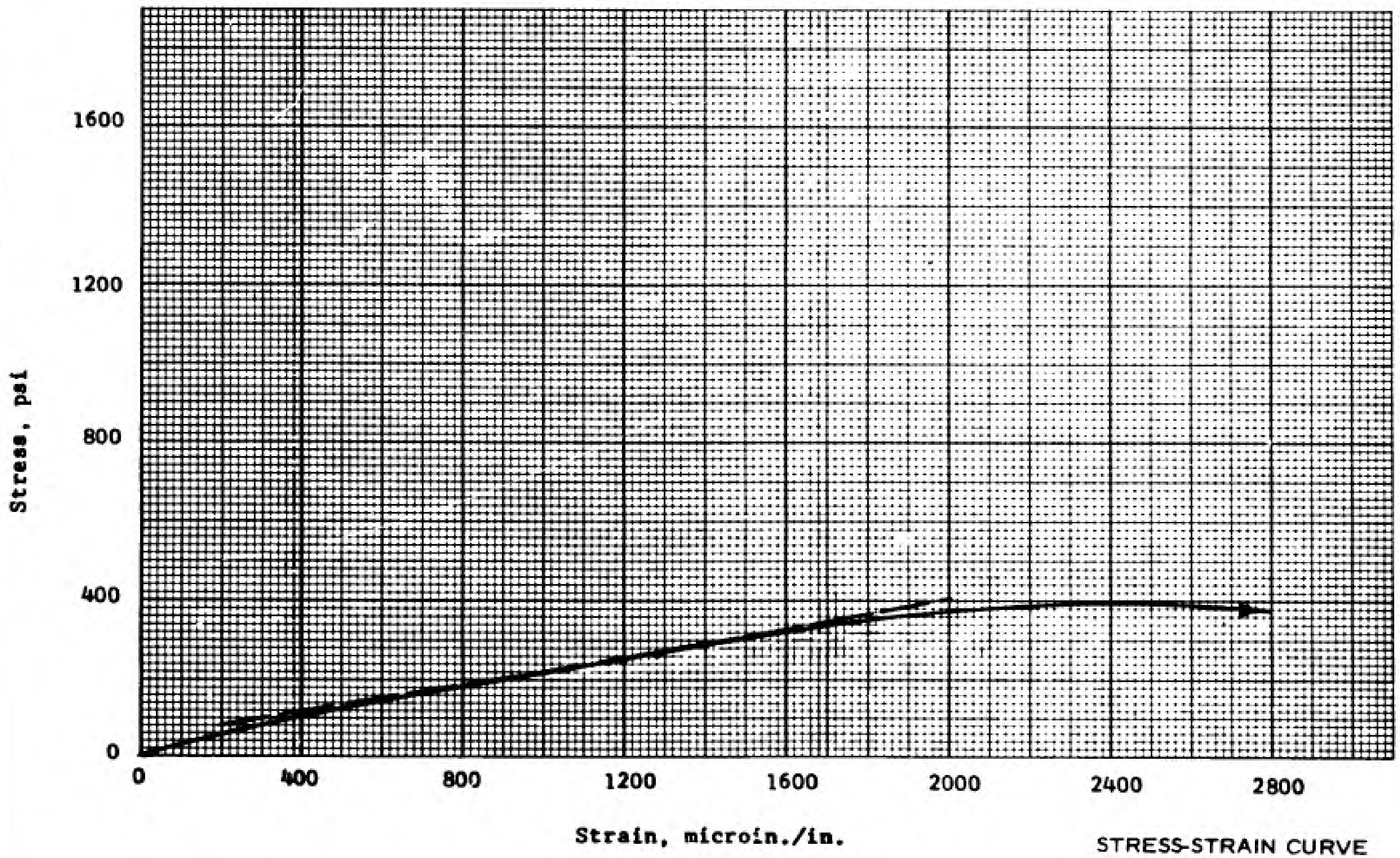

STRESS-STRAIN CURVE
MIXTURE 24

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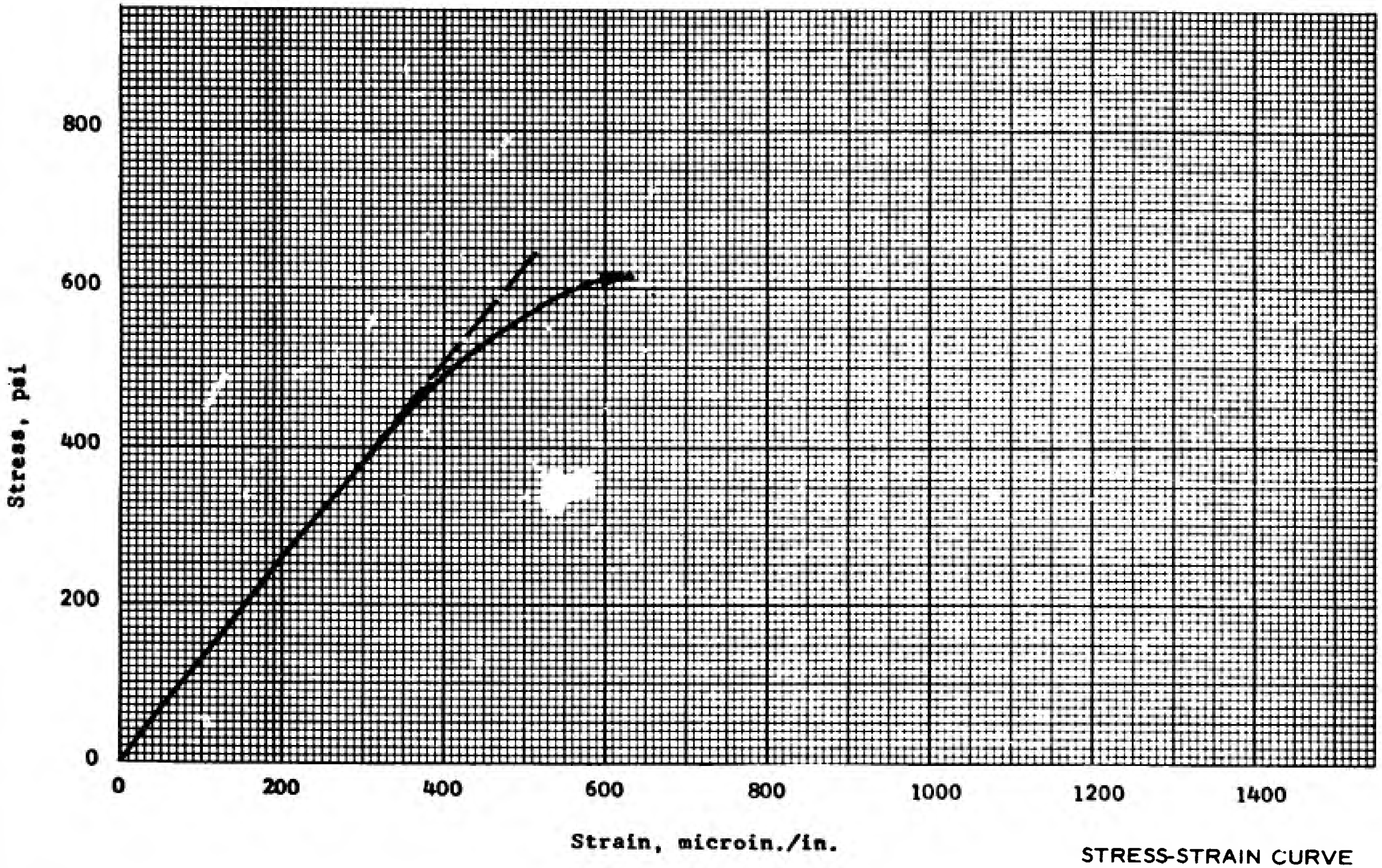

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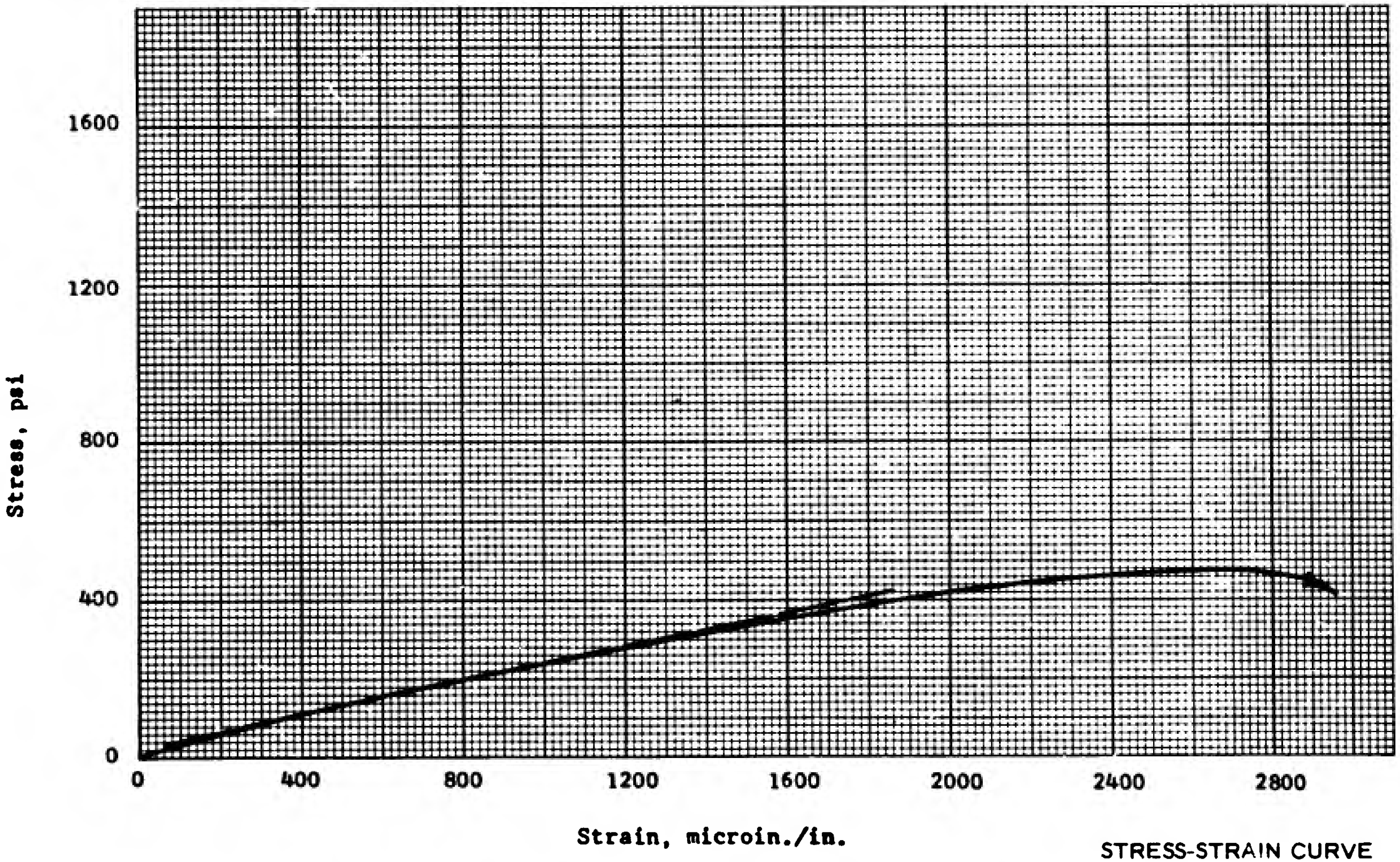

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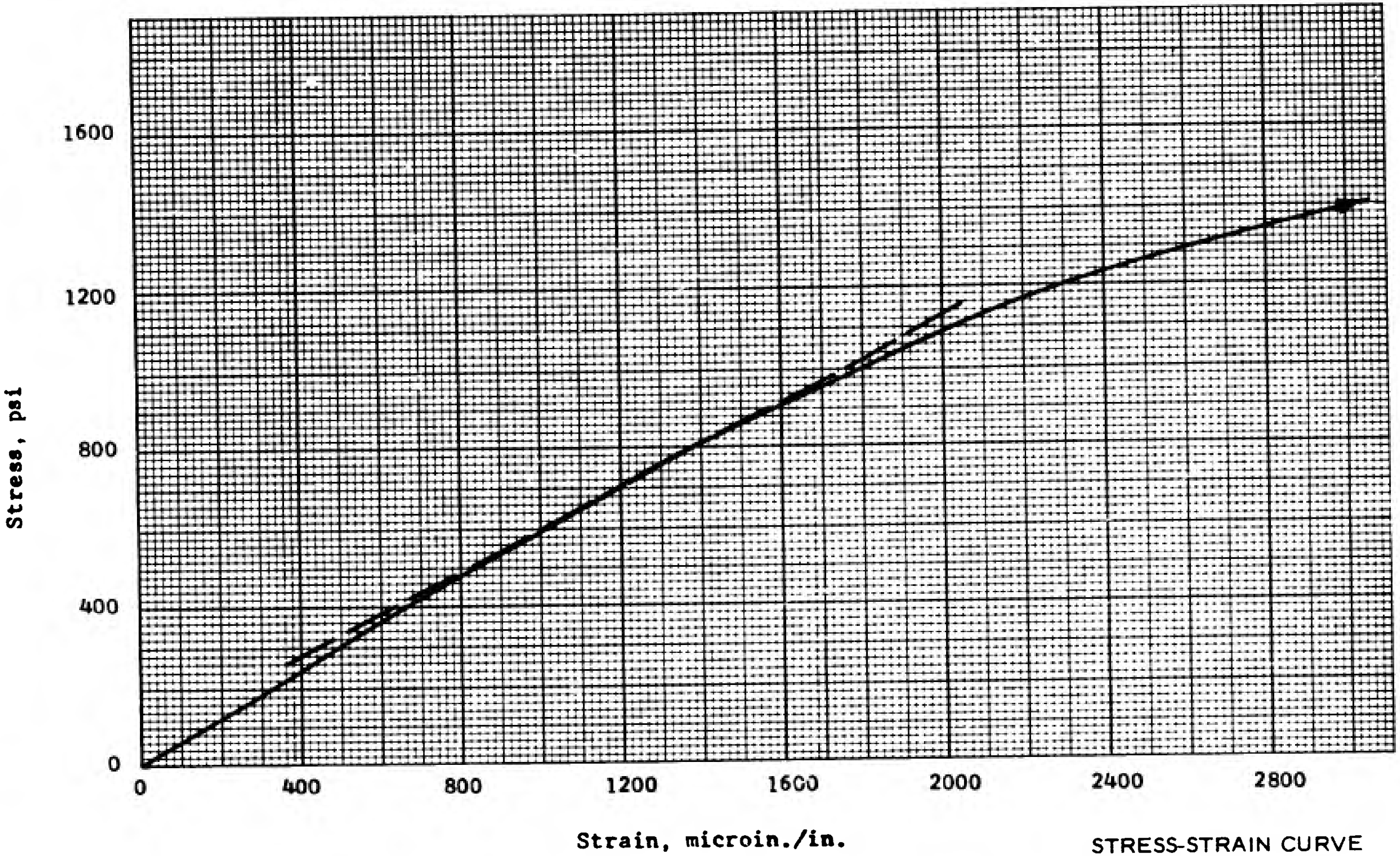

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MIXTURE 29

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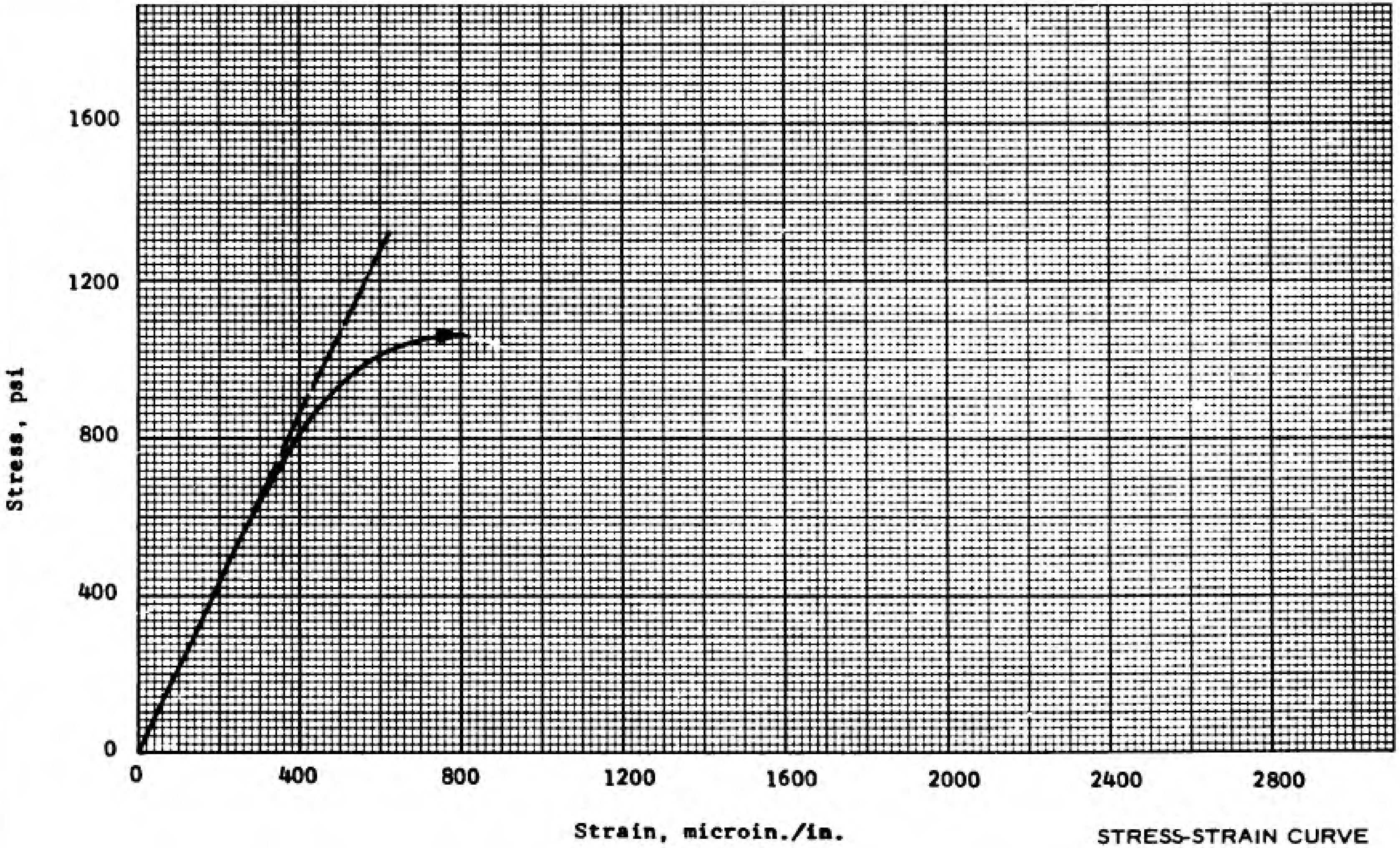

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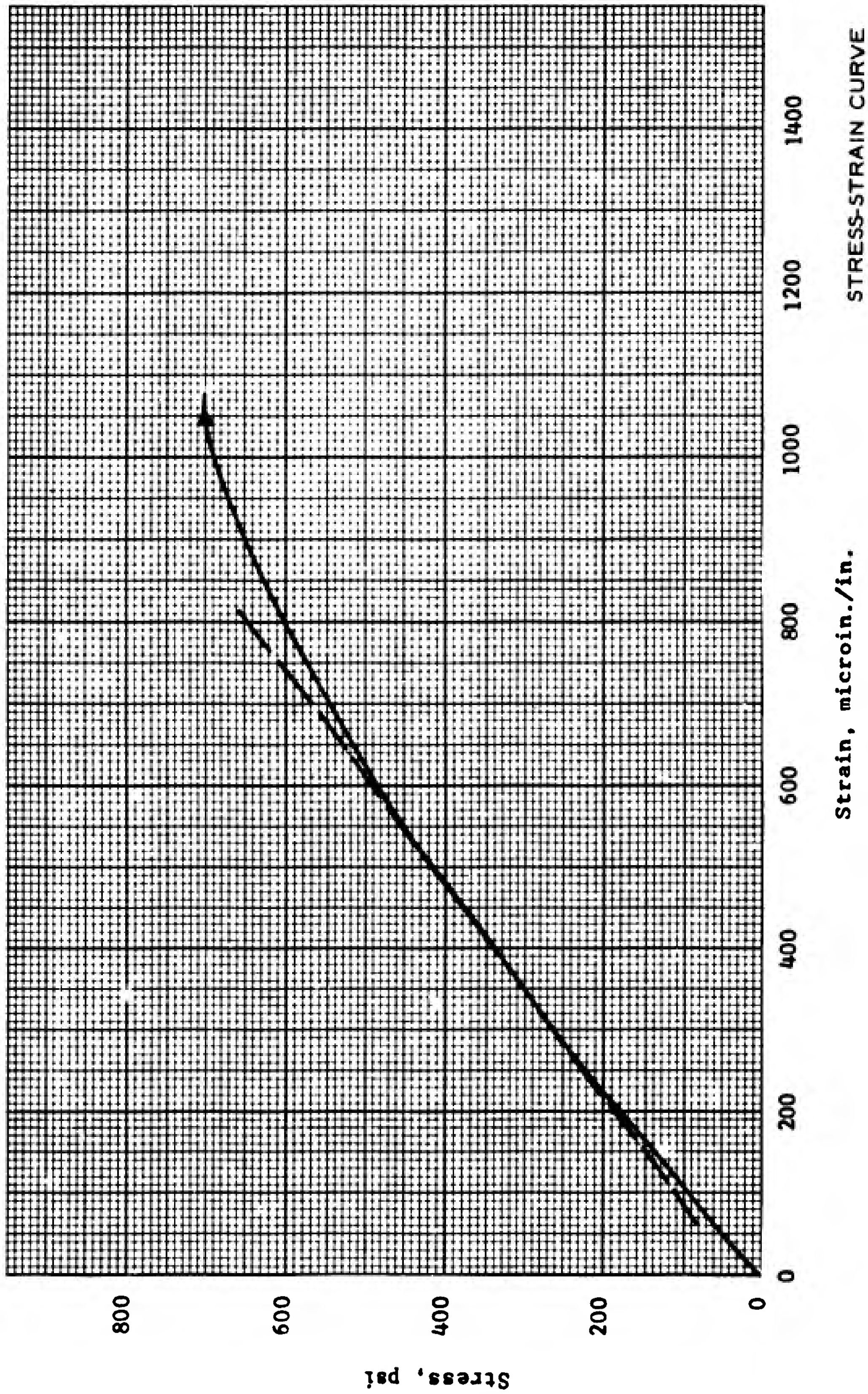

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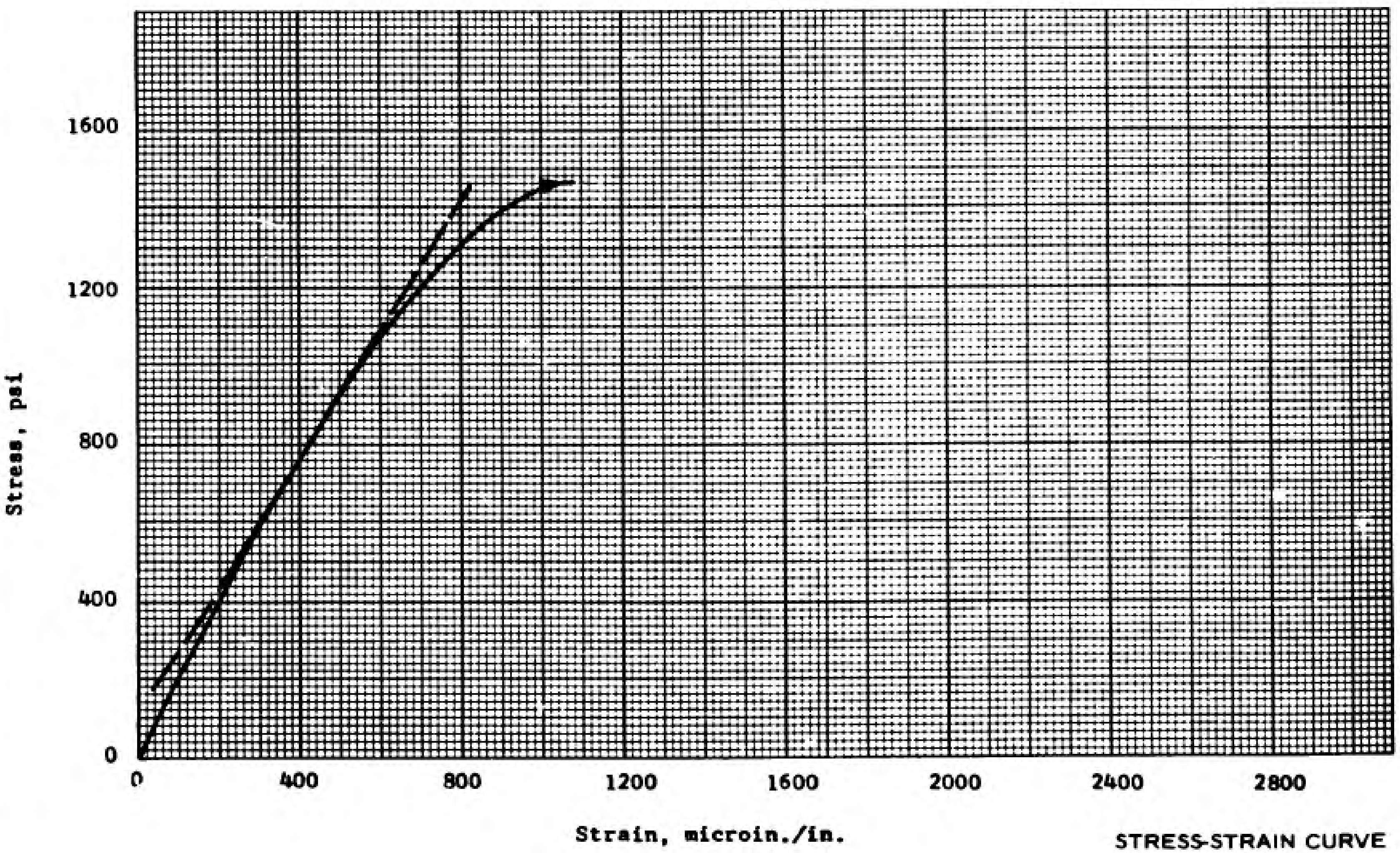

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MIXTURE 32

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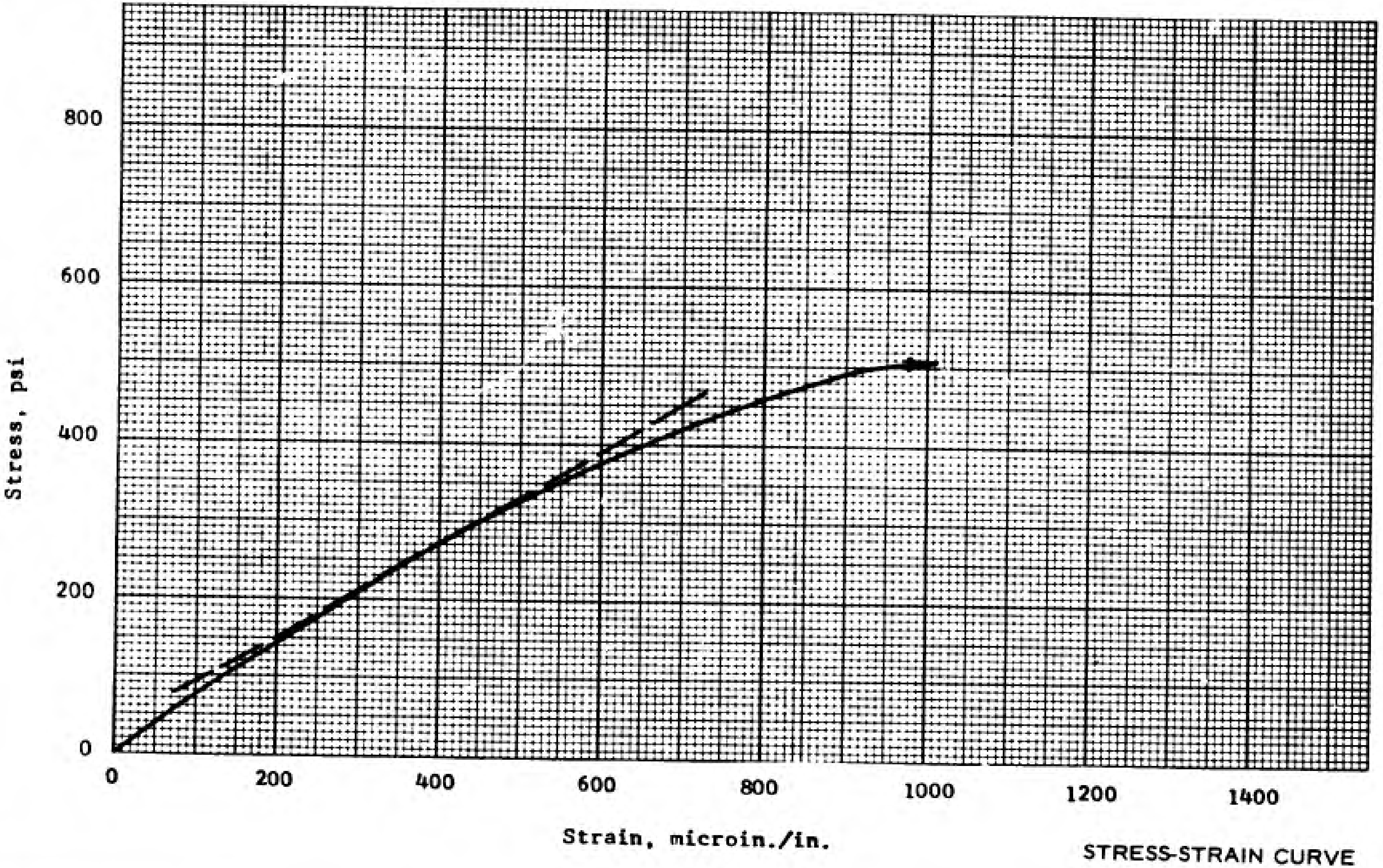

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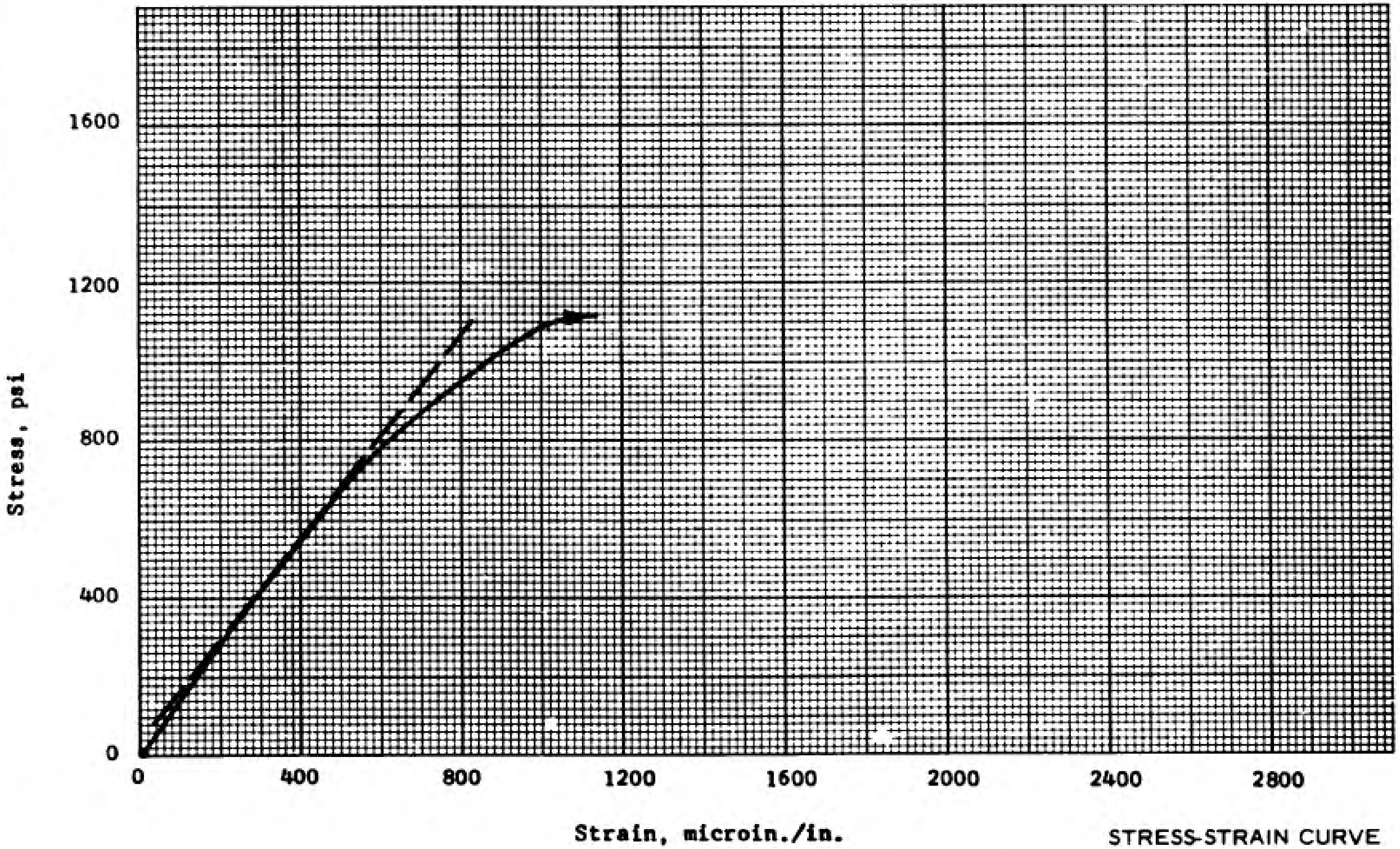
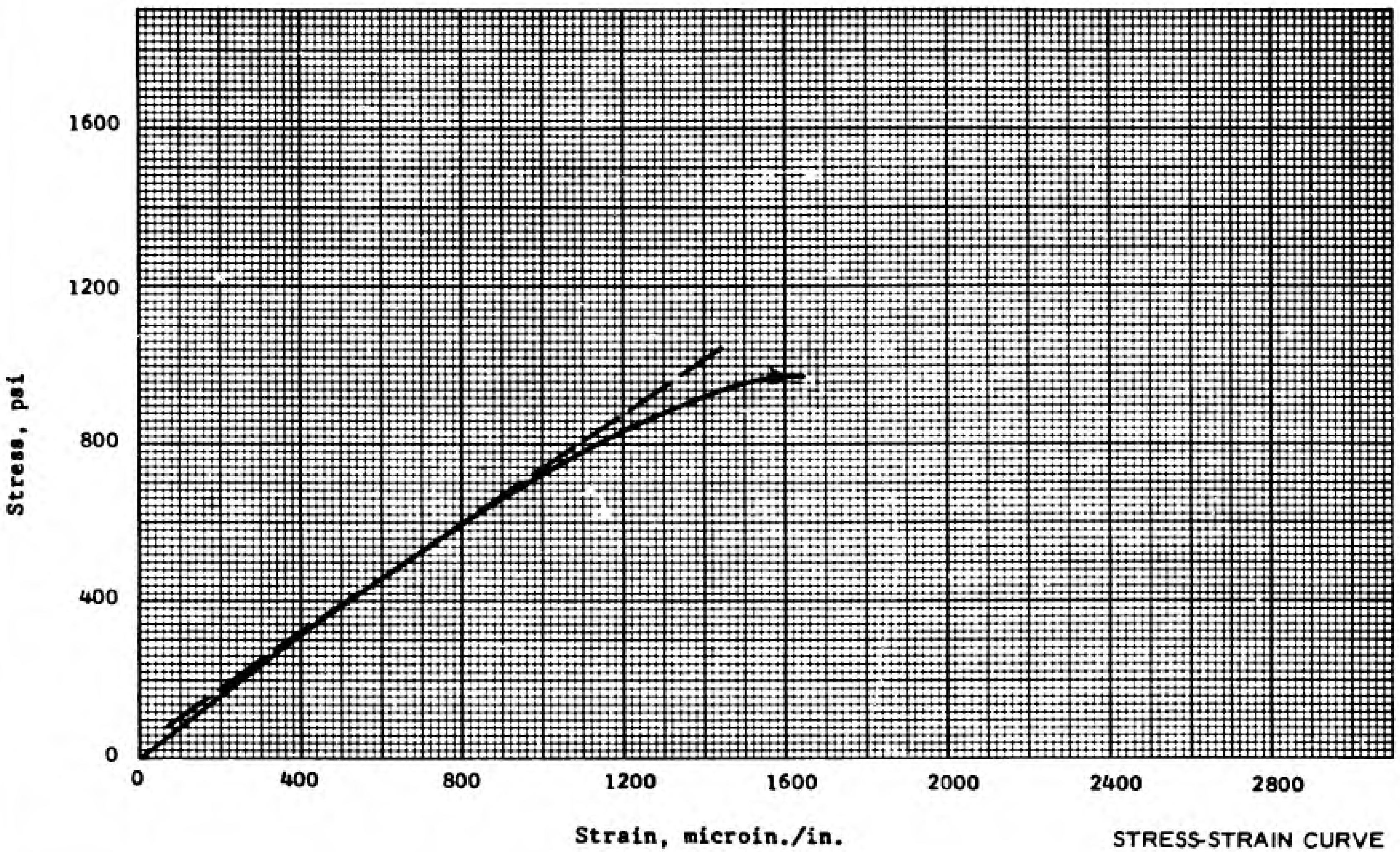


STRESS-STRAIN CURVE
MIXTURE 34

PLATE 15



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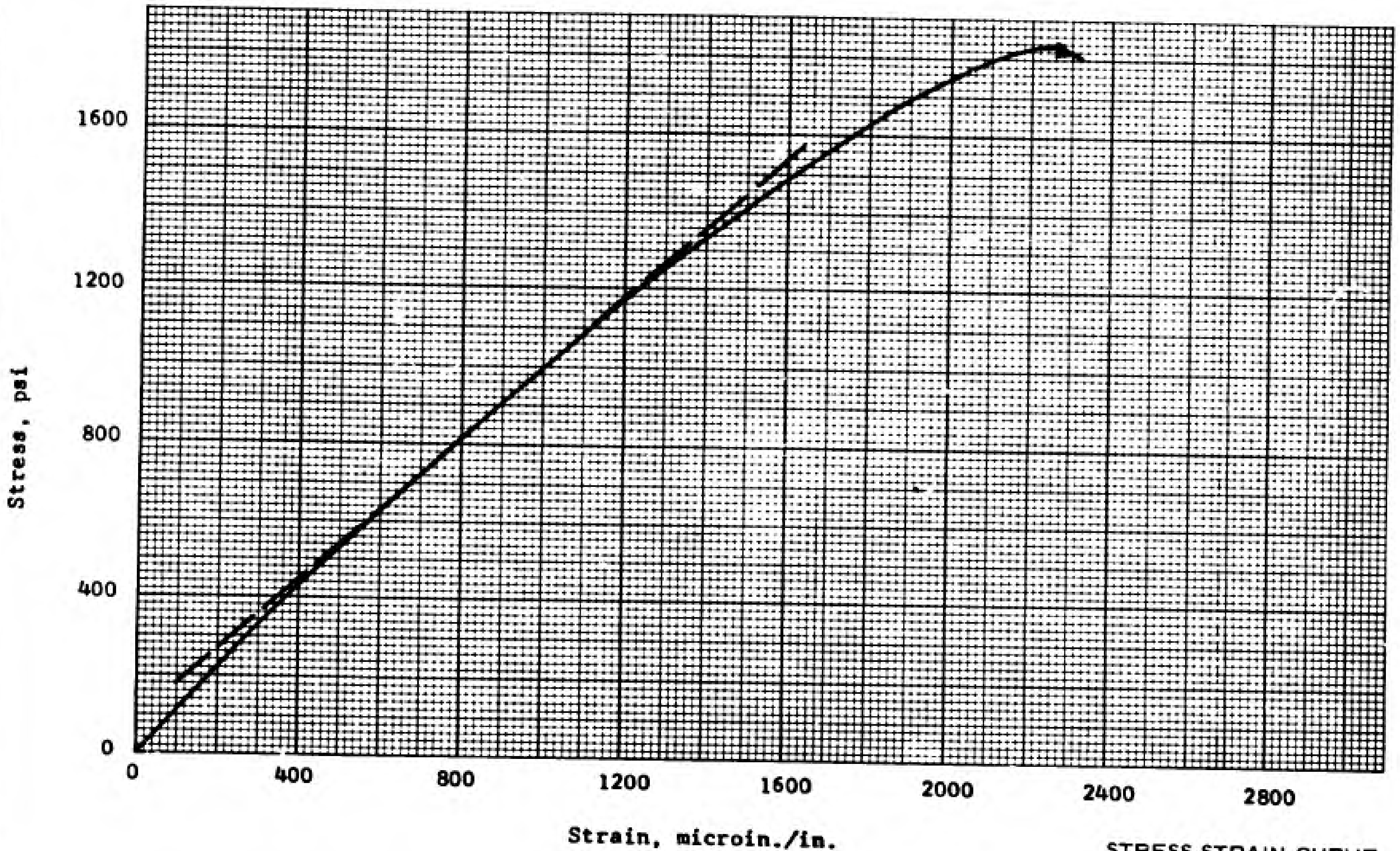
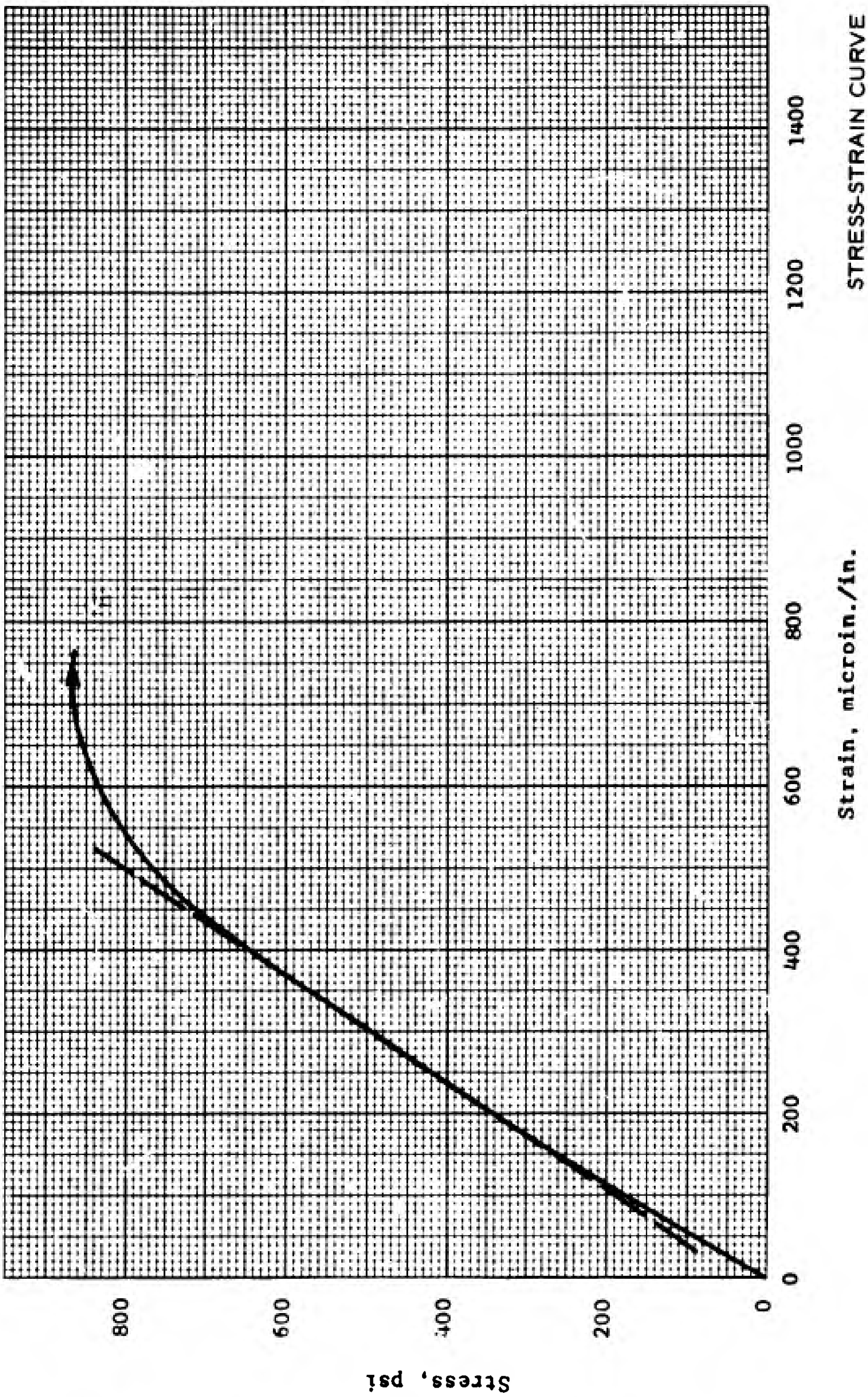


STRESS-STRAIN CURVE
MIXTURE 37

PLATE 17



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MIXTURE 38

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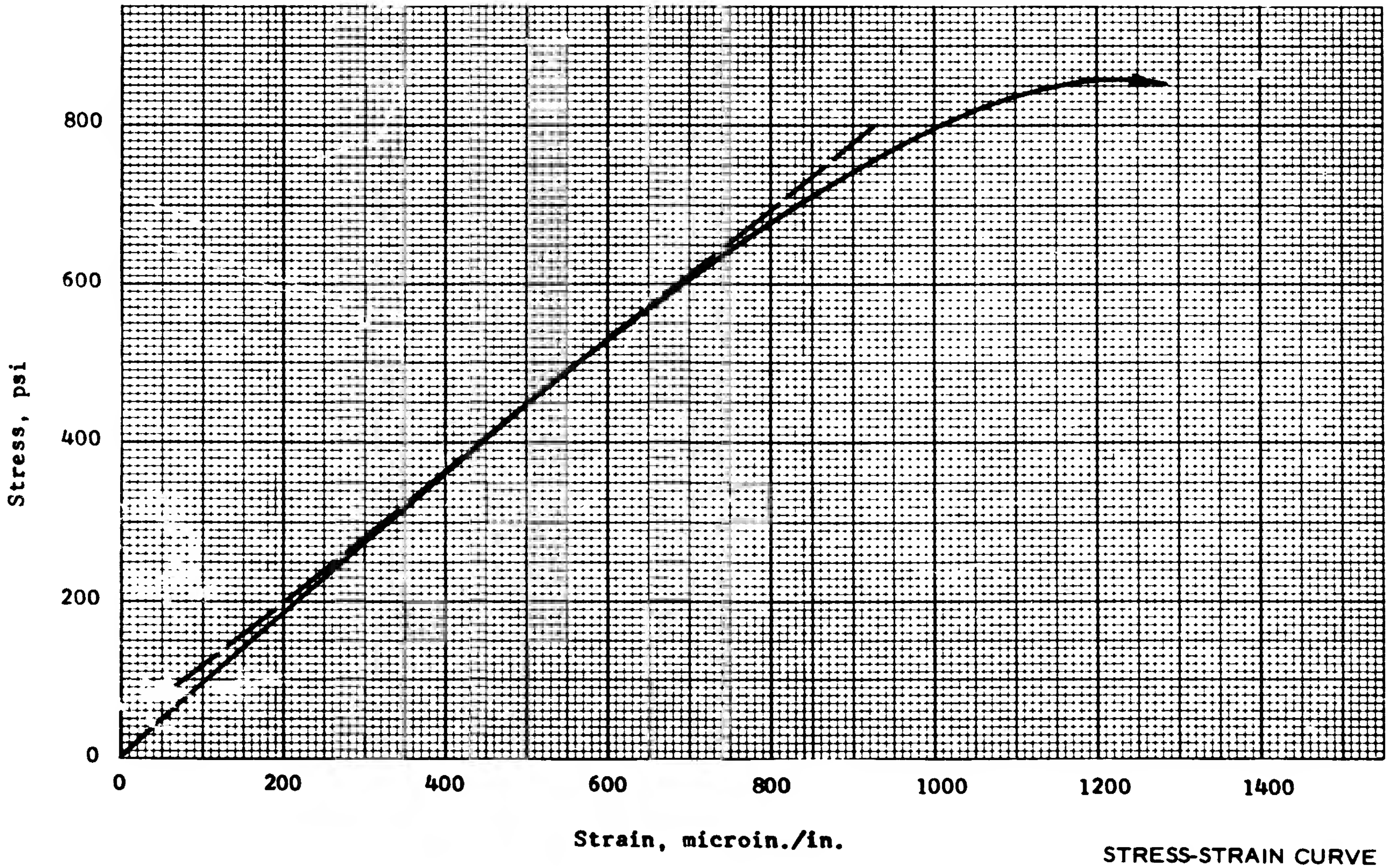

STRESS-STRAIN CURVE
MIXTURE 39

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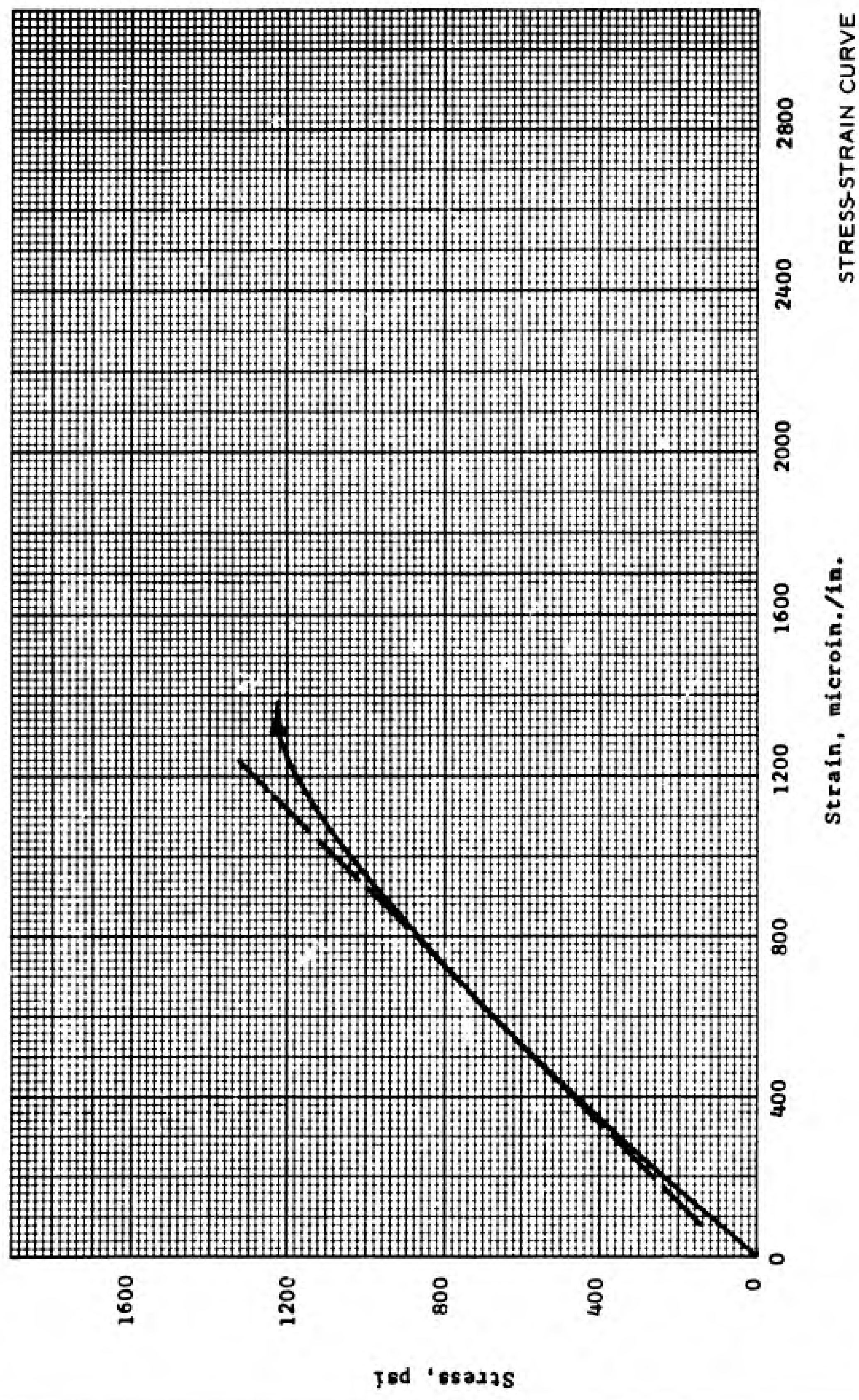

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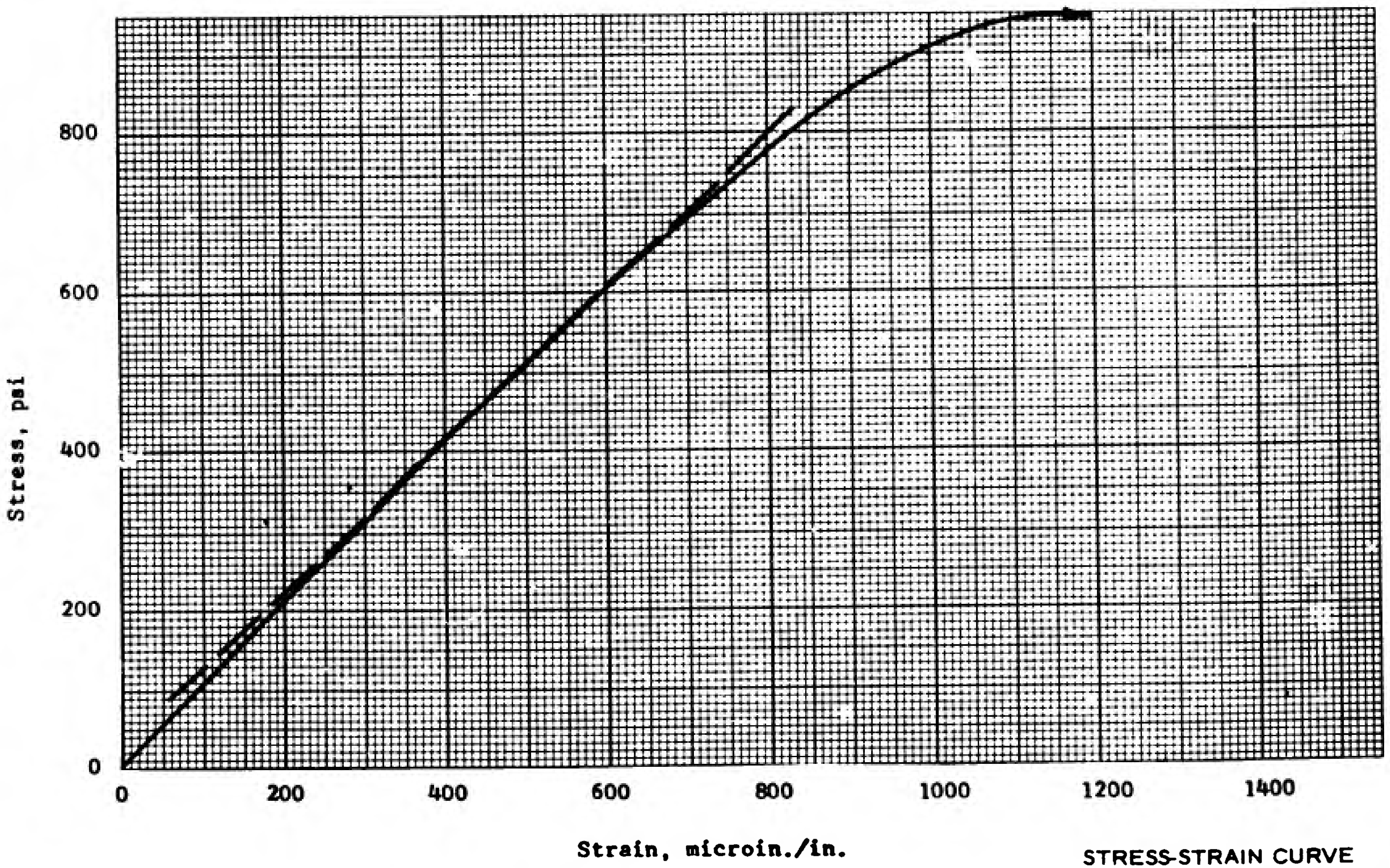

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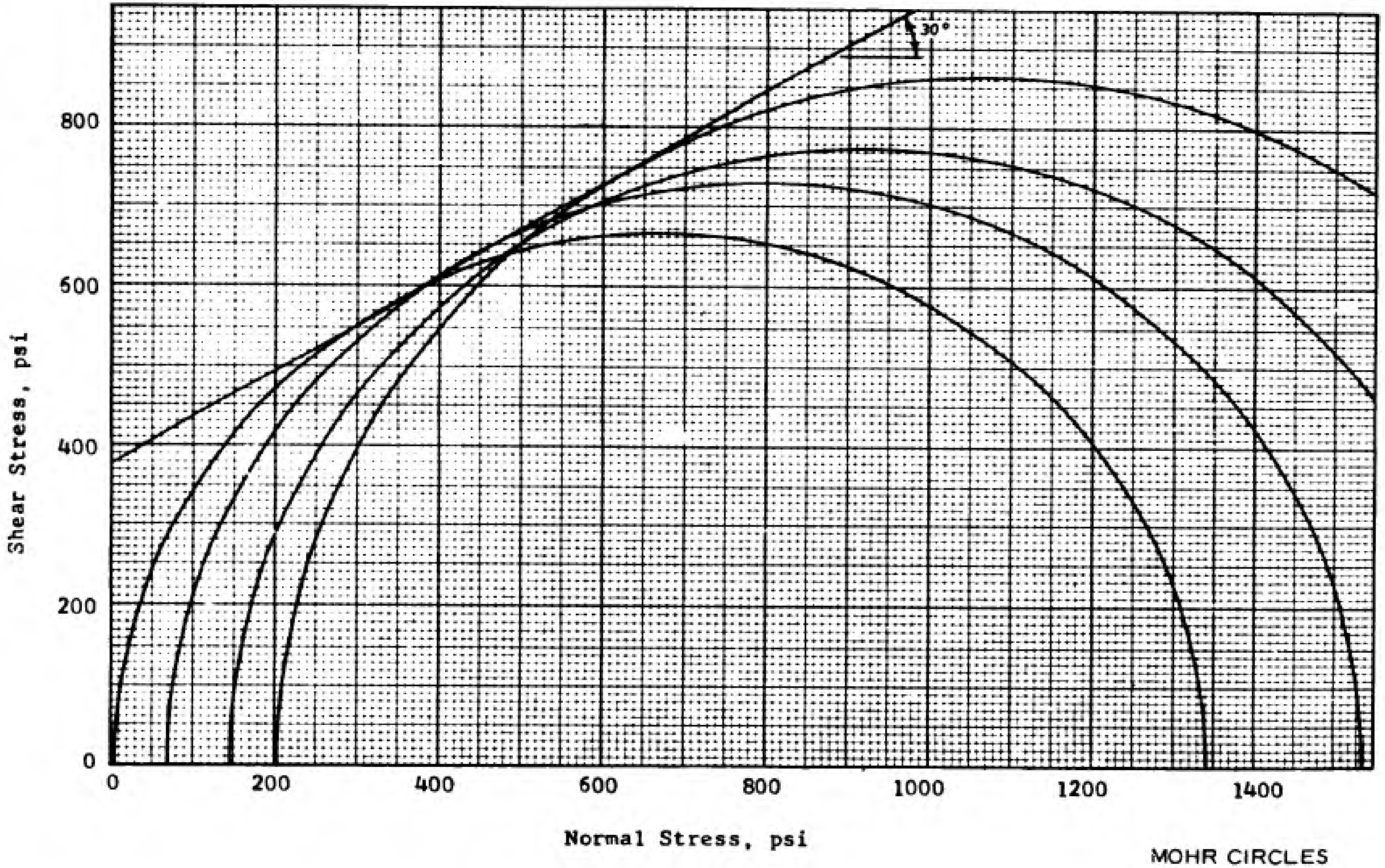

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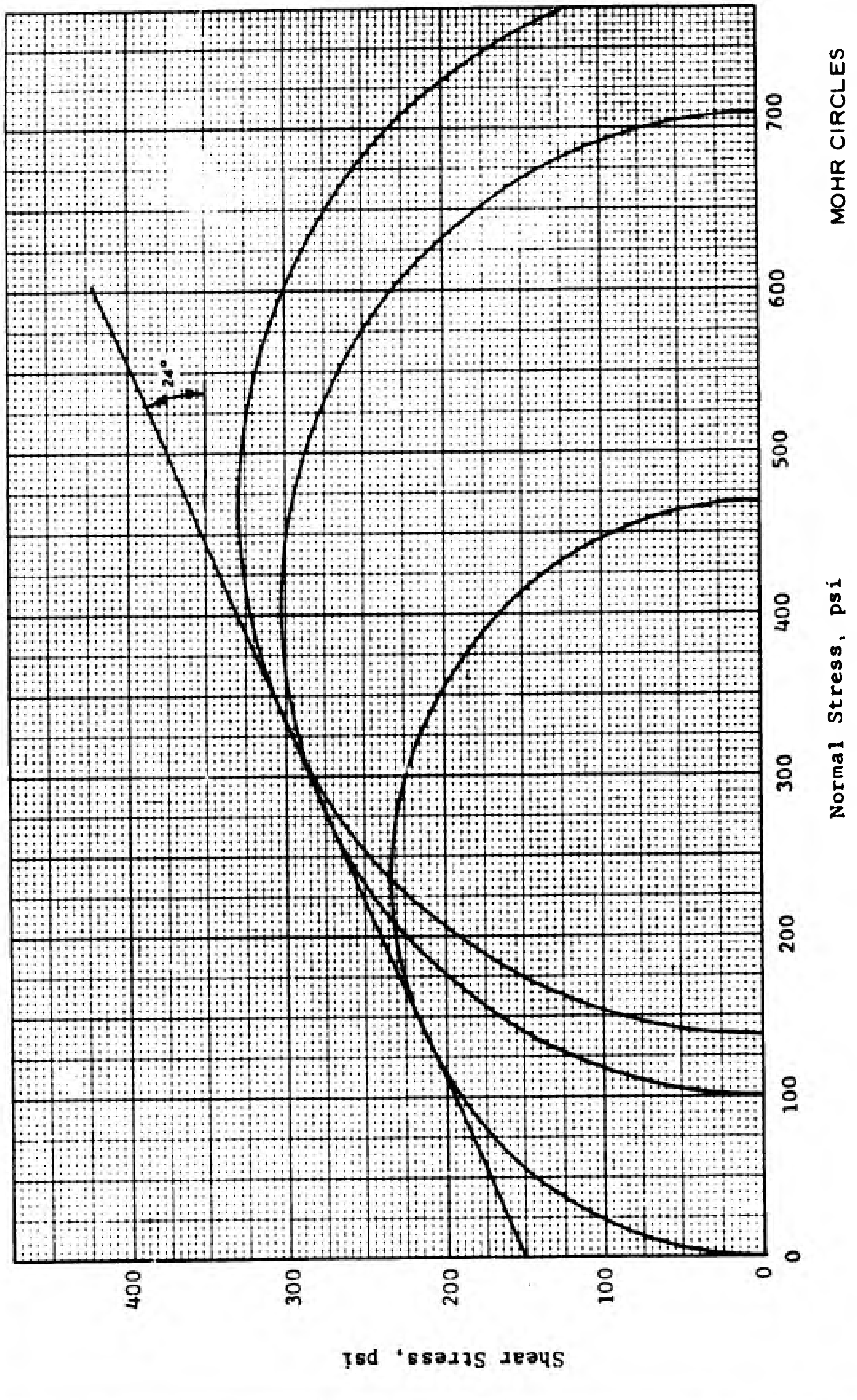
PLATE 22



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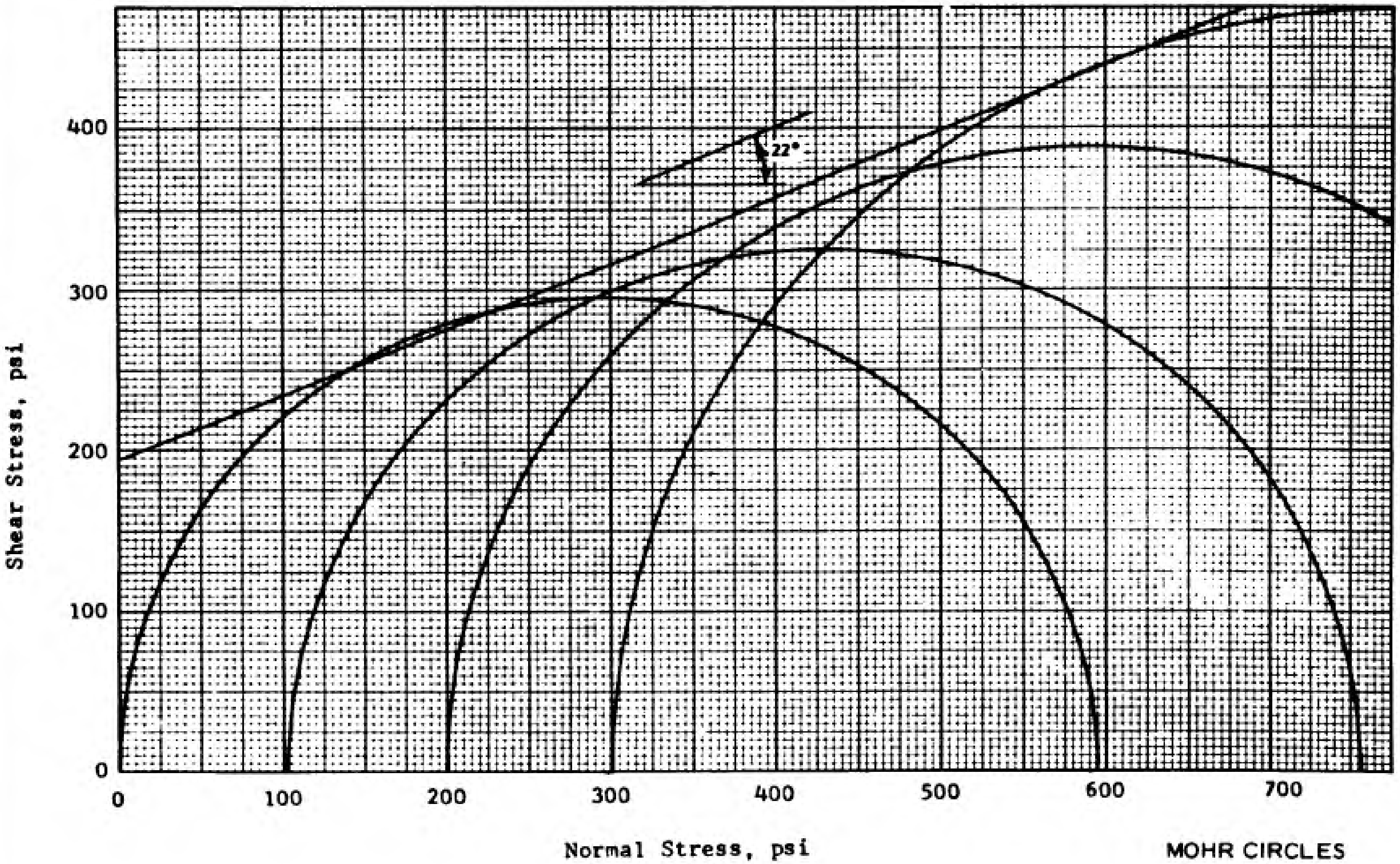

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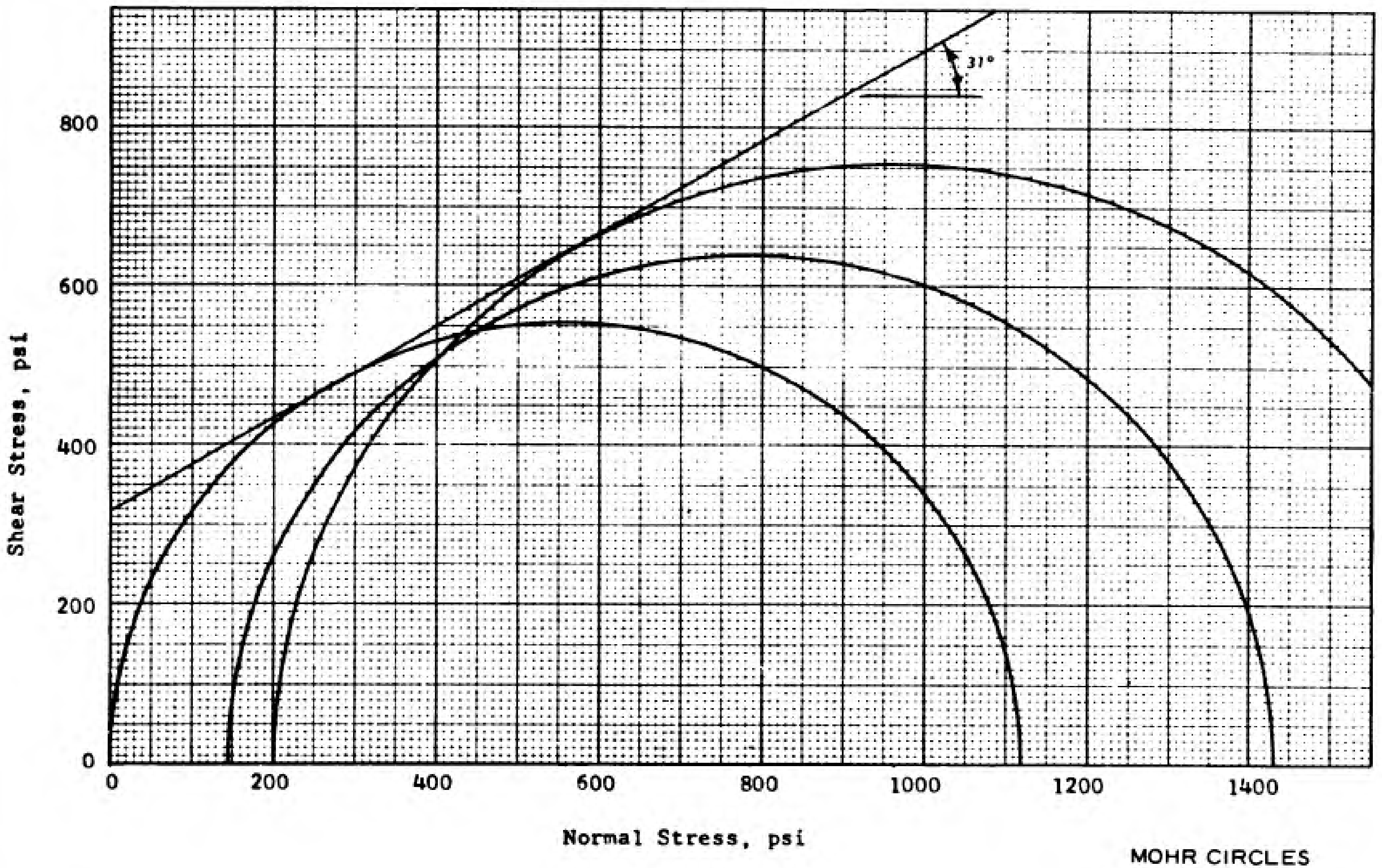

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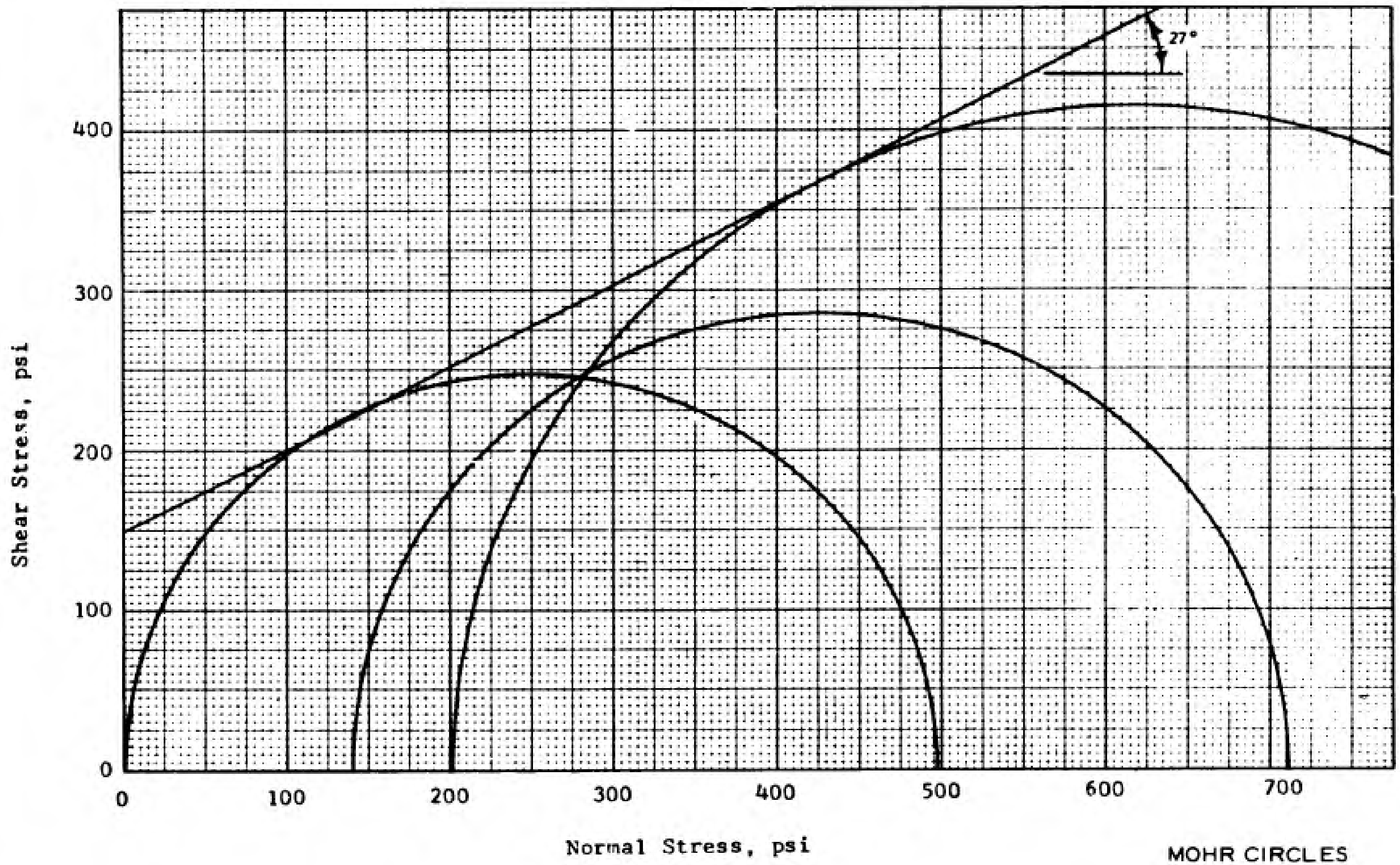

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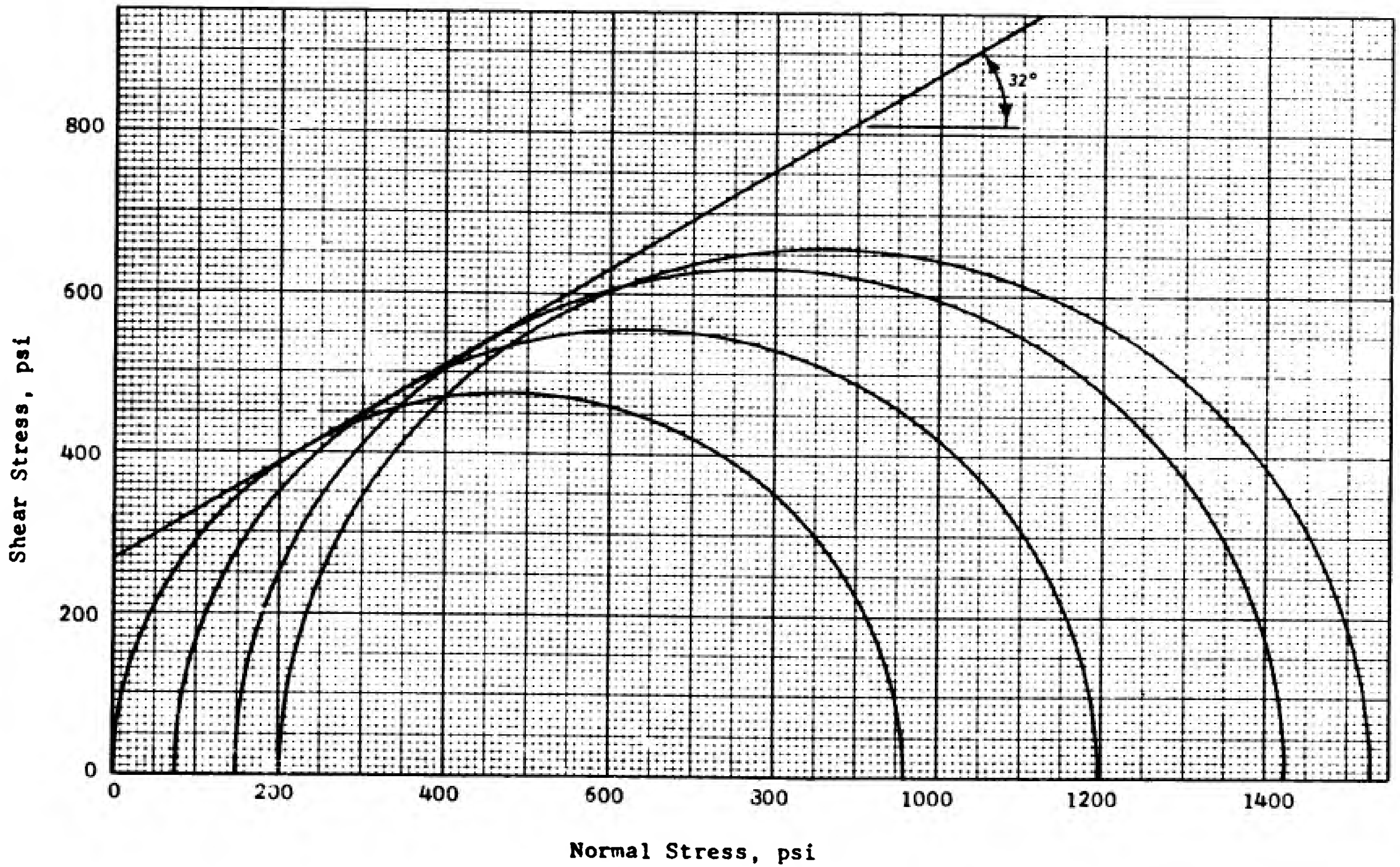

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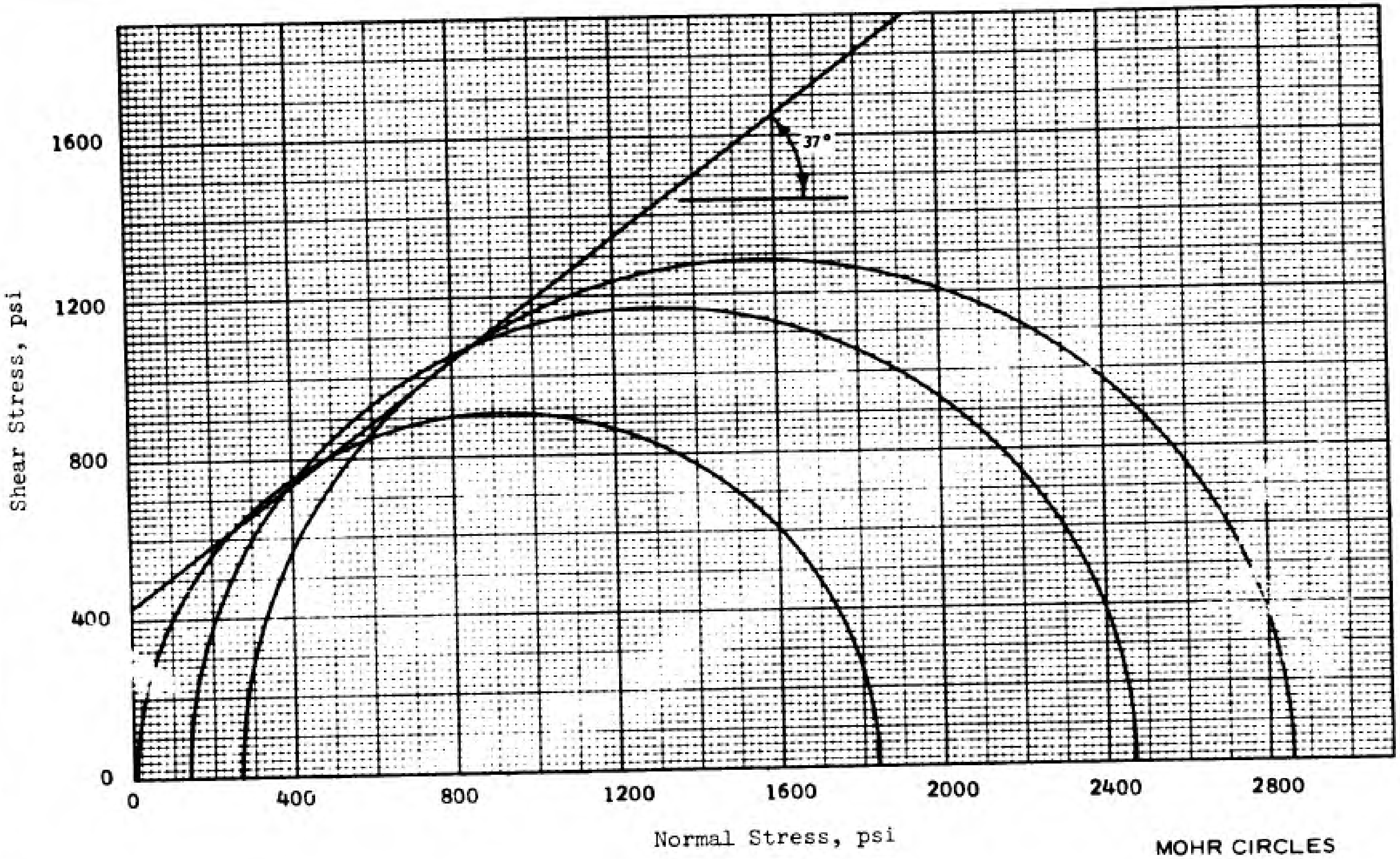

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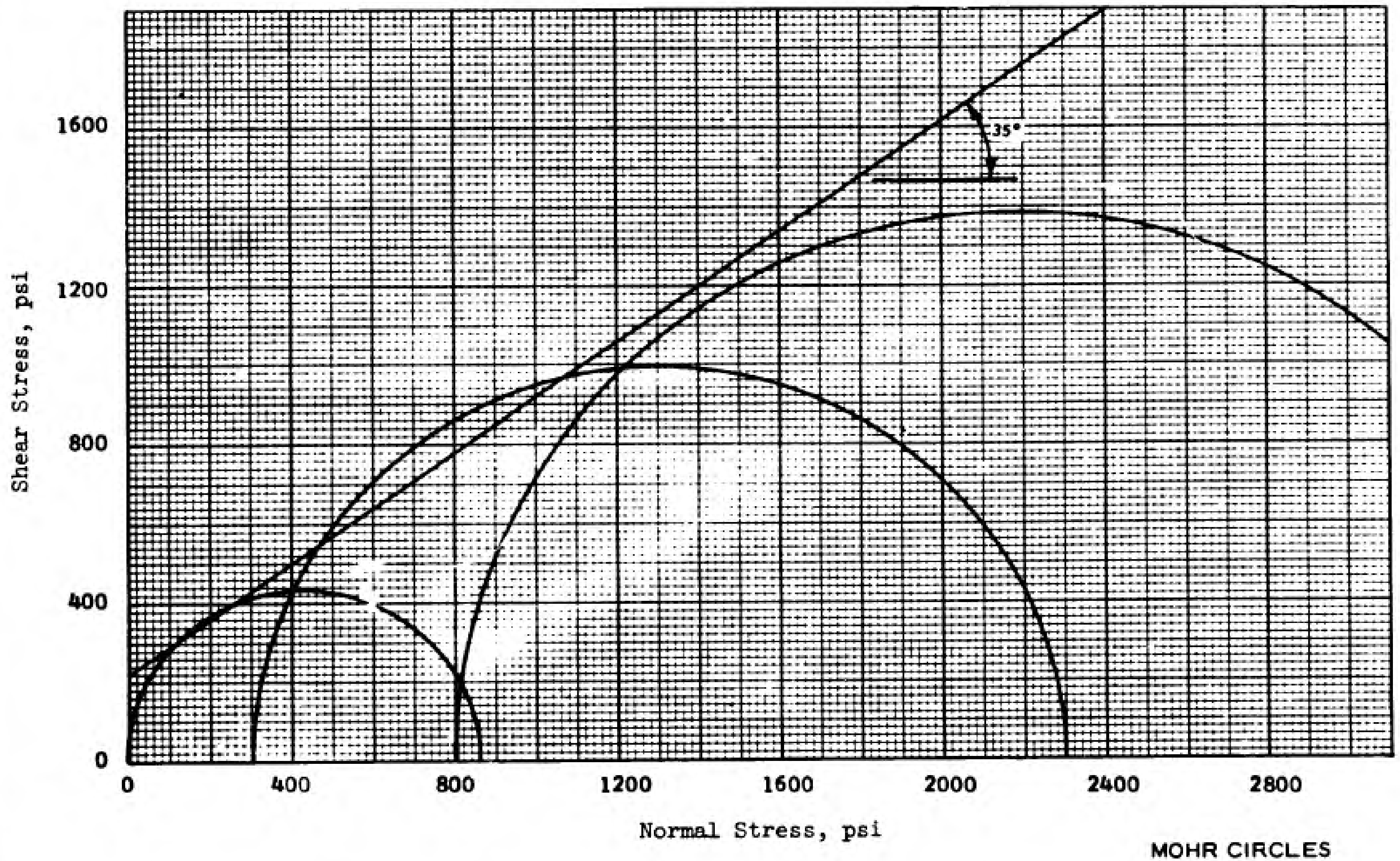

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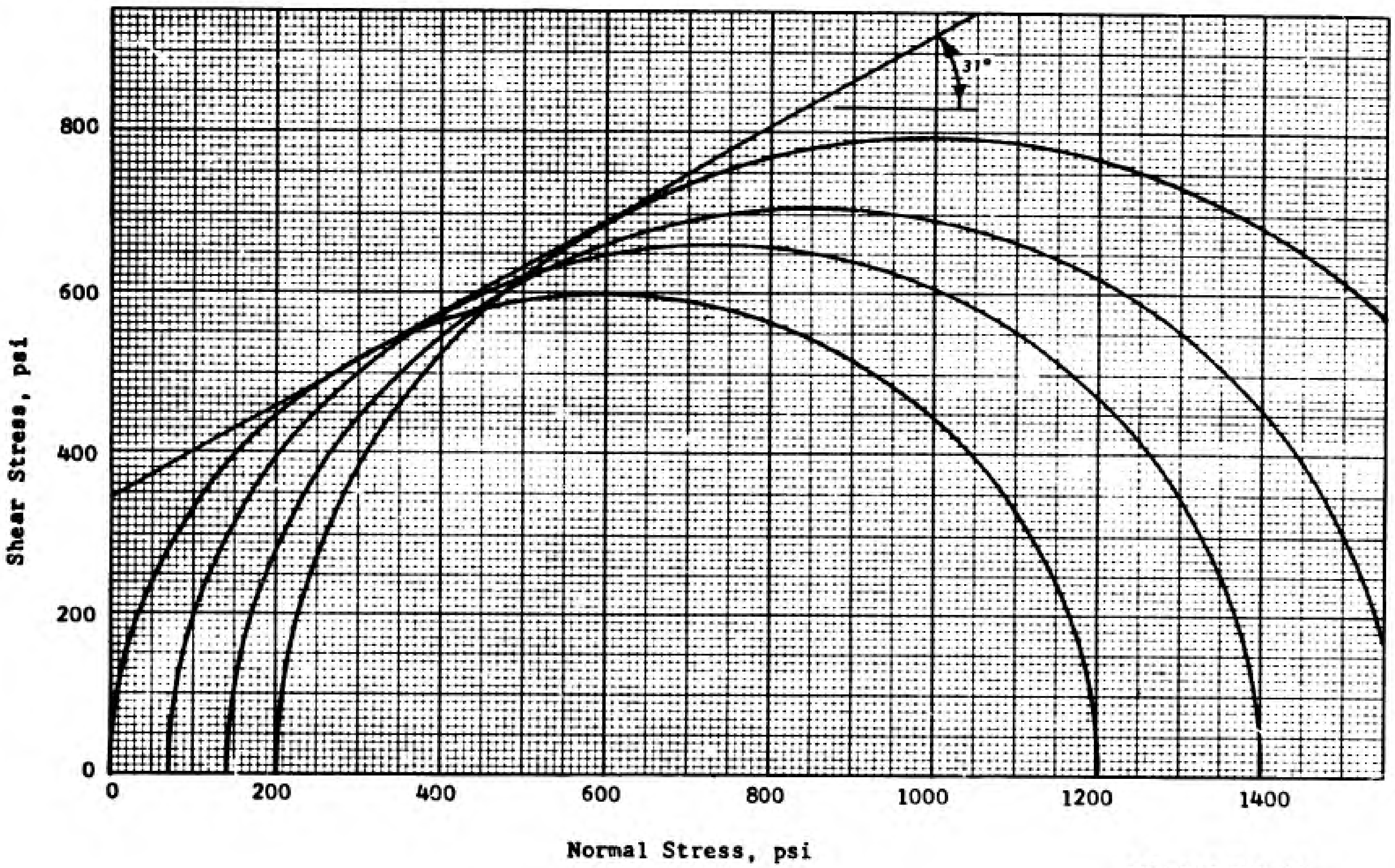

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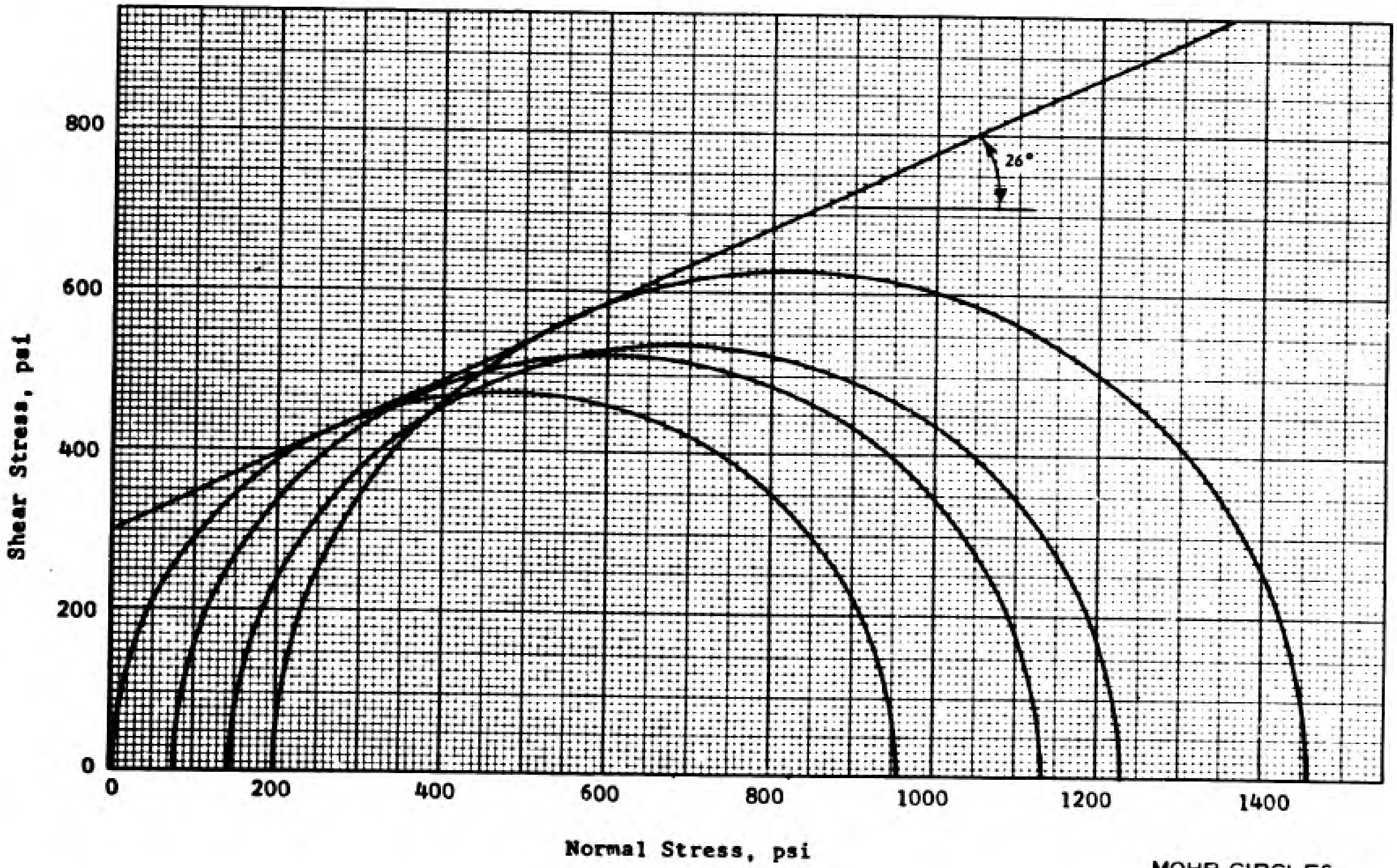

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13. ABSTRACT

Successful modeling of structures and explosive effects indicates that modeling of rock by the use of equivalent material could likewise prove fruitful. The purpose of this investigation was to develop mixtures of practical materials to model geological formations. The similitude principles utilized are: (a) similar and similarly oriented Mohr's envelopes (from triaxial tests) of model and structural materials, and (b) coefficients of elasticity in the same relation. A literature review revealed that the most promising model material was probably a mixture of gypsum cement (plaster), fillers, and water. Tensile, compressive, and triaxial strength tests and stress-strain tests were conducted on combinations of plasters, sands, and other filler materials. Results indicated that brittle rocklike material could be easily formulated to secure a wide range of physical properties. With regard to the above-mentioned principles, the stress-strain curves are linear over a wide range, but the triaxial stress condition is restricted by low ϕ angles, approximately 30 degrees compared to 40 degrees and above for most rocks.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Geologic formations						
Gypsum cement						
Models (Simulations)						
Rock (Geology)						

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