A Report

on

THE PHYSICAL PROPERTIES OF CONCRETE AT EARLY AGES

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AT EARLY AGES

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I. INTRODUCTION

This is the final report of an investigation carried out as a part of a cooperative research project RP-19 entitled "The Effect of Curing, Air Content, and Types of Aggregate upon Certain Physical Properties of Concrete." The project was sponsored by the Texas Highway Department, and it was activated September 1, 1959, and terminated August 31, 1961. A report entitled "The Curing of Portland Cement Concrete" was prepared as a part of this project in August 1960.

This portion of the study reported herein was undertaken in order to obtain a better understanding of the physical properties of concrete at an early age. The data presented in this report includes the strength, shrinkage, coefficient of expansion and contraction, and tensile deformation properties of concrete from 12 hours of age to 28 days of age. This research was planned to provide information on hardening and strength increase in concrete pavements or structures during early ages. It was intended, also, to provide information from which stresses could be determined in pavements or structures due to length changes occasioned by shrinkage and temperature changes at different ages. In addition, the data should indicate the ability of the concrete to sustain such length changes which may occur at different ages. This information was desired because most of the problems associated with the design and proper functional performance of concrete structures and pavements can be traced directly to the physical properties of the concrete. It is hoped that the information in this report will help engineers to more accurately predict the behavior of concrete and also to exercise better control in designing mixes and in writing specifications to produce the desired properties at the desired time.

Two types of aggregate were used in the concrete mixes; a crushed limestone from the Texas Crushed Stone quarry, near Georgetown, Texas, and a siliceous-calcareous gravel and sand from the Brazos River deposit near Hearne, Texas. Other variables in the concrete batches were cement content, air content, and four different admixes. Specimens were taken from each batch design so that the compressive strength, modulus of rupture, tensile strength, bond strength, modulus of elasticity, ultimate tensile strain, extensibility, and coefficient of expansion and contraction could be determined at 12 hours, 1 day, 2 days, 7 days, and 28 days of age. Shrinkage specimens were also cast, and initial measurements were made when the concrete became hard enough to hold the gage points securely; i. e., usually 12 hours or 24 hours of age.

II. CONCLUSIONS

The concrete batches reported on in this paper were designed to indicate the effects of cement content, entrained air content, type of admix, and type of aggregate on the compressive strength, flexural strength, direct tensile strength, bond strength, modulus of elasticity, coefficient of expansion and contraction, shrinkage, and extensibility of concrete at early ages. Some of the more significant conclusions drawn from this study are as follows:

1. High cement content concrete has a greater effect of increasing the relative strength of concrete at early ages than at later ages when compared to low cement content concrete. For example, at 12 hours of age, a 6½ sack mix has over four times the compressive strength of a 3½ sack mix. This ratio of strength gradually decreases until at 7 days of age, the 6½ sack mix has only about 2 times the compressive strength of the 3½ sack mix.
   Similar effects were observed for flexural strength, direct tensile strength, and bond strength.
2. Entrained air content has a tendency to reduce concrete strength at all ages. When entrained air is used in moderate amounts, up to about 5%, this reduction in strength is usually slight and is tolerable, particularly in view of its other beneficial effects.

3. Calcium chloride, which is a hydration accelerator, increases the early strength gain of concrete. At 12 hours of age, the concrete with calcium chloride had over three times the compressive strength of concrete with no admix. This ratio of strength decreased with age until at 28 days of age, it was only about 1.1. Similar effects were observed for flexural strength, direct tensile strength, and bond strength.
4. The water reducing admix used in this investigation usually reduced the water requirement for a given slump from 10 to 20% when compared to a batch with no admix. It increased the relative strength properties of concrete at all ages. It, too, had a greater effect of increasing the relative strength at early ages than at later ages.
5. Water reducing admixes which were also set retarders were found to improve the concrete strength properties at ages from 12 hours through 28 days. At 12 hours of age, however, the strength improvement was not as great as that achieved by the water reducing admix without set retardation. It should be pointed out that a set retarder only retards the set and not the hydration and strength gain of the cement.
6. When strength properties of concrete batches poured with the siliceous-calcareous gravel and sand were compared with values from similar batches poured using crushed limestone as fine and coarse aggregate, no discernible difference

could be detected, which could be attributed to the aggregate type.

7. The type of aggregate was found to have a significant effect on the drying shrinkage, coefficient of expansion and contraction, modulus of elasticity, ultimate tensile strain capacity, and extensibility.

   The shrinkage of the crushed limestone concrete was 1 2/3 times that of the sand and gravel concrete.

   The coefficient of expansion and contraction of the crushed limestone concrete was only about 80% of that of the sand and gravel concrete.

   The modulus of elasticity of the crushed limestone concrete was 2/3 of that of the sand and gravel concrete.

   The ultimate tensile strain capacity of crushed limestone concrete was approximately 1.4 times that of the sand and gravel concrete.

8. The coefficient of expansion and contraction appeared to be effected little by different cement contents, air contents, and admixes. The age of the concrete also appeared to have little effect on the coefficient.

9. High cement content and entrained air tends to increase the tensile strain capacity of concrete. Calcium chloride and the water reducing admixes also tended to increase the tensile strain capacity of concrete.

III. TEST PROCEDURE

Twenty-one batches of concrete were poured in this study, and each batch consisted of approximately 71 specimens. The size and shape of the specimens varied, depending upon the type of test to be performed. In general, however, each batch of 71 specimens contained about 9 cubic feet of concrete. The batch proportions of all batches are given in Table 1. Batches AU-1 through AU-10 were made from a crushed limestone aggregate, and batches GR-1 through GR-11 were made with a siliceous-calcareous gravel and sand. The unit weight, specific gravity, absorption, and sieve analysis of these aggregates are presented in Table 2. It will be noted that the absorption of the limestone coarse aggregate changed from 2.5% to 2.0% in two different shipments of aggregate from the manufacturer. It should be pointed out, however, that the specific gravity and absorption of crushed limestone can vary considerably from time to time, even in the same quarry.

Batching and Molding Specimens

In general, the major variables in mix designs which were studied in these batches were the type of aggregate, air content, cement content, and type of admix. All batches were designed by the absolute volume method to yield concrete having the desired proportion of ingredients, i. e., air content, cement content, aggregate, and admix. These batches were mixed in a two-cubic foot vertical drum Lancaster

TABLE 1

CONCRETE MIX DATA

Batches AU-1 thru 10 and GR-1 thru 11

Batch Designation	Aggregate Type	Quantities per C. Y. Concrete: Cement Sacks	Aggregate (SSD): Coarse lb.	Aggregate (SSD): Fine lb.	Mixing Water lb.	W/C	Air Content %	Slump in.	Initial Unit Wt. Lb./c.f.	Admix	
AU-1	Limestone	4.95	1823	1237	294	0.6	1.3	3¼	141.3	none	
AU-2	Limestone	4.92	1812	1143	270		4.7	3¼	136.3	Vinsol Resin	
AU-3	Limestone	4.93	1802	1037	254		8.7	3¼	131.5	Vinsol Resin	
AU-4	Limestone	5.00	1838	1324	244		1.2	3	143.3	Pozzolith 3R	
AU-5	Limestone	3.69	1901	1381	234	0.63	0.8	3	143.1	none	
AU-6	Limestone	5.10	1870	1269	254	0.5	1.6	3	143.4	none	
AU-7	Limestone	6.62	1852	1164	236	0.35	2.0	3	143.5	none	140.0
AU-8	Limestone	5.11	1860	1295	240		2.3	3	143.9	Calcium Chloride	
AU-9	Limestone	5.03	1833	1341	212		2.7	3	142.9	Pozzolith 3	
AU-10	Limestone	5.00	1811	1262	232		2.1	3	144.1	Plastiment	
GR-1	Siliceous-Calcareous	5.02	2112	1131	310		0.3	3¼	149.1	none	
GR-2	Siliceous-Calcareous	4.88	2049	1082	275		4.6	3¼	143.5	Vinsol Resin	
GR-3	Siliceous-Calcareous	5.00	2098	917	243		8.2	3¼	138.0	Vinsol Resin	
GR-4	Siliceous-Calcareous	5.05	2130	1223	244		0.7	3¼	150.5	Pozzolith 3R	
GR-5	Siliceous-Calcareous	3.52	2114	1268	275		1.4	3	147.7	none	150.0
GR-6	Siliceous-Calcareous	5.09	2130	1142	280		1.3	3	149.3	none	
GR-7	Siliceous-Calcareous	6.63	2139	1001	296		1.4	3¼	150.3	none	
GR-8	Siliceous-Calcareous	5.05	2115	1130	250		2.1	3	147.4	Calcium Chloride	
GR-9	Siliceous Calcareous	5.00	2097	1205	249		2.6	3	148.9	Pozzolith 3	
GR-10	Siliceous-Calcareous	5.05	2116	1241	239		1.8	3	150.8	Plastiment	
GR-11	Siliceous-Calcareous	4.02*	2254	1127	226		4.0	¼	147.6	Sika-Aer	

* Type III Cement (Longhorn)
All other cement was a blend of three brands of Type I (Longhorn, Lonestar, and Atlas).

TABLE 2. AGGREGATE PROPERTIES

	Limestone Used in Batches AU-1 thru 10		Siliceous-Calcareous Used in Batches GR-1 thru 11	
	Coarse 3/4" to #4	Fine < #4	Coarse 3/4" to #4	Fine < #4
Unit Weight in lb./c.f.(dry loose)	84	87	96	104
Specific Gravity (SSD)	2.54	2.50	2.63	2.61
Absorption (% of dry wt.)	2.5 (AU-1-4) 2.0 (AU-5-10)	9.3	1.3	1.1
Sieve Analysis (AU-1 thru 4 and GR-1 thru 4)				
% Passing				
3/4"	100		100	
1/2"	53		65	
3/8"	28		40	
#4	5.0	100	5.0	100
#8	2.2	97	1.9	84
#16		53		67
#30		28		48
#50		16		18
#100		7.1		1.1
#200	1.0	2.5	0.2	0.3
Sieve Analysis (AU-5 thru 10 and GR-5 thru 10)				
% Passing				
3/4"	100		100	
1/2"	53		53	
3/8"	28		28	
#4	5.0	100	3.0	100
#8		95		84
#16		51		67
#30		27		48
#50		15		18
#100		7.2		1.1
#200		3.3		0.3
Sieve Analysis (GR-11)				
% Passing				
1"			100	
3/4"			77	
1/2"			53	
3/8"			28	
#4			3.0	100
#8				84
#16				67
#30				48
#50				18
#100				1.1
#200				0.3

Mixer for a minimum of five minutes. The air content values reported in this paper are total air which included entrapped air plus entrained air. The method of test conforms with ASTM Method C231-56T.

After the concrete was mixed and checked for slump, unit weight, and air content, it was placed in the molds of the desired shapes and sizes. The molds were clamped to a vibrating table and were filled in two equal layers. After each layer of concrete was placed in the molds, the specimens were vibrated through a frequency range varying from zero to a maximum of 7200 cycles per minute, held for a given period of time, and then reduced to zero again.

Curing of Specimens

In batches AU-1 through AU-4 and GR-1 through GR-4, three methods of curing were used on different specimens from each batch. After the specimens were molded, they were troweled level and smooth and then covered with a damp cotton cloth for approximately 12 hours. The molds were then stripped, and the specimens began their different curing processes. The three methods were (1) continuous moist room curing, (2) moist curing for 6½ days, then air dried indoors, and (3) sprayed with liquid membrane curing compound (A. C. Horn process 50D), then air dried indoors. The specimens in batches AU-5 through AU-10 and GR-5 through GR-10 were exposed to only two curing processes, methods (1) and (3) above.

Concrete batch GR-11 was a special batch designed to simulate the concrete quality poured on a continuously reinforced pavement job in

Walker County during August 1960. These specimens were batched and molded in the morning when the temperature was 90° F. in the shade. After molding, the specimens were placed outdoors in the sun and covered with a sheet of polyethylene clear plastic. During the first afternoon the temperature of the specimens under the plastic reached as high as 107° F. After two days of this curing, a portion of the specimens was placed in the moist room for curing.

Flexural Strength

The flexural strength values were obtained by breaking a 3" x 4" x 16" prism specimen with a center point load applied parallel to the 4" axis over a 14" span. Except for the span, this test was conducted according to ASTM Method C293-54T.

Compressive Strength

The Modified Cube compressive strength test used here was conducted according to ASTM Method C116-49. The two ends of the specimen left after the flexural strength test were placed separately in a steel box loading device for the compressive test.

Bond Strength

The bond strength test used here was the standard bar pull out test, conducted according to ASTM Method C234-57T, except that wooden molds were used instead of steel. The wooden molds were well oiled, however, and checked for tightness to see that no mortar or water seeped out while molding. A 3/4" diameter deformed steel reinforcing bar was embedded 6" in the 6" x 6" x 6" cube. The steel bar was a standard

A 305 reinforcing bar manufactured by Sheffield Steel Company. The ultimate bond strength was taken as the value when the bar slipped .01" with respect to the concrete or the value at which the specimen split due to tension, whichever was the least.

Tensile Test

The tensile strength test was performed by pulling 3" x 3" x 22" prism specimens in direct tension parallel to the 22" axis until failure. The specimen was gripped by means of 3/8" diameter deformed bars which were cast in the concrete while pouring. During the tensile test, the strain in the specimen was measured by means of an extensometer.

The extensometer utilized four Ames dial gages capable of reading .0001 inch which were located at 90° intervals around the extensometer ring. Thumb screws at the top and bottom of the extensometer held it to the test specimen with a 10" gage length. By using the average strain taken from these four gages, practically all error due to eccentric and non-uniform stress distribution within the specimen was eliminated. In this way a stress-strain curve was obtained from each specimen up to failure. From this information the ultimate tensile strength, ultimate tensile strain (approximate), and static modulus of elasticity in tension was determined. Since it was impractical, if not impossible, to measure the strain at the ultimate load, the approximate ultimate strain was obtained by extending the stress-strain curve from the last strain reading up to the ultimate stress.

Modulus of Elasticity (Dynamic)

The dynamic modulus of elasticity was run on 3" x 4" x 16" specimens according to ASTM Method C215-55T, where the modulus is computed from the fundamental flexural frequency of vibration. A "sonometer" was used to measure the fundamental flexural frequency of vibration. It consisted of (1) a "driving transducer" capable of vibrating the specimen at variable frequencies, (2) a "pickup transducer" for detecting the amplitude and mode of vibration of the specimen, and (3) a cathode-ray indicator for comparing driver and pickup frequency and phase relationship.

This same method of test and apparatus was used to determine the dynamic modulus of rigidity and dynamic Poisson's ratio. The modulus of rigidity (elastic modulus in shear) was computed from the fundamental torsional frequency of vibration. Poisson's ratio was computed from the fundamental relationships between modulus of elasticity and modulus of rigidity.

Shrinkage

Shrinkage as used here is defined as the "contraction of concrete due to drying and chemical changes, dependent on time, but not on stresses induced by external loading." Gage points were cast in each of the 3" sides of a 3" x 4" x 16" prism specimen with a 10" gage length. Measurements were taken with an instrument reading to 0.0001 inch, and all readings were referenced to a standard steel bar. The initial measurements were made at either 12 hours or 24 hours of age, depending on when the concrete became hard enough to hold the gage points securely.

Coefficient of Expansion and Contraction

The coefficient of expansion and contraction reported here is the average length change per degree Fahrenheit of a 3" x 4" x 16" prism specimen which was cooled from room temperature (approximately 85°F.) down to the freezing point of water (approximately 32°F.) and then warmed back up to room temperature. Gage points for measuring length changes were cast in the specimens in the same manner as for shrinkage. In some cases small steel buttons were glued to the concrete with epoxy resin and used as gage points. Copper-constantan thermocouples were also cast in the specimens so that temperature could be measured with a potentiometer. Before commencing with the test, each specimen received a coat of paraffin wax so that it could not give up or take on moisture during the test. Using the same instrument as in the shrinkage tests, length measurements were made at room temperature. The specimen was then packed in ice until its temperature was lowered to approximately 32°F.; then length change measurements were again made. The specimen was removed from the ice and allowed to return to room temperature and measured again. The time lapse for the complete test was approximately 8 hours. The values reported are the average of contraction and expansion. It is assumed that changes in the concrete properties due to hydration during this time lapse are negligible in view of the freezing temperature.

Extensibility

The extensibility of concrete as used here may be defined as the ultimate tensile strain of concrete subjected to a sustained and gradually increasing tensile stress. These tests were performed on 3" x 3" x 16" prism specimens, as used in the tensile test. Gage points like those used in the shrinkage specimens were cast in these specimens for measuring the tensile strain. The tensile load was applied to the extensibility specimen by means of loading devices fabricated of steel plates, channels, a rod, and a stress relieved railroad coil spring.

Gage readings were made on the gage points cast in the specimen prior to placing it in the loading device. All specimens were subjected to an initial tensile load of 20 psi, and gage readings were again made. The load was then increased in increments and sustained for a given period. Gage readings were made before and after each load increase. Regardless of the curing or exposure conditions, each extensibility specimen was accompanied by a shrinkage specimen of the same size and shape, which was used for control purposes in calculating tensile strain due to actual stress. The gage measurements made on the loaded specimen indicated tensile strain plus shrinkage. The algebraic difference between the value from the loaded specimen and the value from the accompanying shrinkage specimen is defined as tensile strain (elastic plus inelastic strain).

In general, the gradually increasing load was applied in two different ways. In one method, the specimen was initially loaded at 1 day of age and then placed in a moist room for continuous curing. The load was gradually increased in increments applied daily until the specimen failed. In the other method, the specimen was initially loaded at a determined age and then allowed to air dry and shrink. As shrinkage occurred the load was increased daily as required to maintain the specimen at its original length, as determined at the age of initial loading.

IV. RESULTS OF CONCRETE TESTS

The concrete batches reported on in this paper were designed to indicate the effects of cement content, entrained air content, type of admix, and type of aggregate on the compressive strength, flexural strength, direct tensile strength, bond strength, modulus of elasticity, coefficient of expansion and contraction, shrinkage, and extensibility of concrete at early ages. The voluminous tabulated data obtained from this investigation are presented in the appendix. Only a few of the more obvious and useful presentations of this data will be made in this report. In addition to the above mentioned data, values of the static modulus of elasticity in tension, modulus of rigidity, and Poisson's ratio are also included in the appendix.

Compressive Strength

Figure 1 illustrates the effect of cement content on the compressive strength of concrete at early ages. When more cement is added to a concrete batch and the slump is held constant, the volume of cement paste is increased and the water/cement ratio is decreased. This double effect of increasing the quantity and quality of paste produces higher compressive strengths at all ages. At 12 hours of age the 6½ sack mix has over 4 times the strength of the 3½ sack mix. This ratio of strength gradually decreases with age until at 7 days of age the 6½ sack mix has only about 2 times the compressive strength of the 3½ sack mix.

In general, entrained air will have a tendency to reduce the compressive strength of concrete at all ages. Figure 2 illustrates this effect. Entrained air has two basic effects on a concrete batch. It reduces the water requirement to produce a given slump and this in turn improves the quality of the cement paste. On the other hand, however, it decreases the effective area of concrete and the net result is usually a decrease in strength. When entrained air is used in moderate amounts up to about 5%, this reduction in strength is usually slight and is tolerable (see Figure 2). Greater amounts, however, are definitely detrimental to the strength of concrete at all ages.

Figure 3 illustrates the qualitative effect of four different admixes on the compressive strength of concrete. The calcium chloride is a hydration accelerator and increases the early strength gain of the concrete. It can be seen that it increased the strength with respect to the batch with no admix through 28 days of age.

The Pozzolith 3 is a water reducing agent and usually reduces the water requirement for a given slump from 10 to 20% when compared to a batch with no admix. In the comparison presented here, it increased the strength at ages from 12 hours through 28 days.

The other two admixes, Pozzolith 3R and Plastiment, were water reducing agents and also set retarders. As can be seen in Figure 3, they also improved the concrete strength at ages from 12 hours through 28 days. At 12 hours of age, however, the strength improvement was not as great as that achieved by the water reducer without set retarder (Pozzolith 3). It should be pointed out that these two admixes only retard the set and not the hydration of the cement. Consequently, the water reducing effect usually gives greater concrete strengths even at 12 hours of age. The physicochemical phenomenon which causes the "set" of concrete is not the same as "hydration" which accounts for the majority of the strength characteristics.

In this investigation ten batches of concrete were poured with a siliceous-calcareous gravel and sand aggregate, and ten similar batches were poured using a crushed limestone as fine and coarse aggregate. When compressive strength values of all the similar batches were compared, no discernible difference could be detected which could be attributed to the aggregate type.

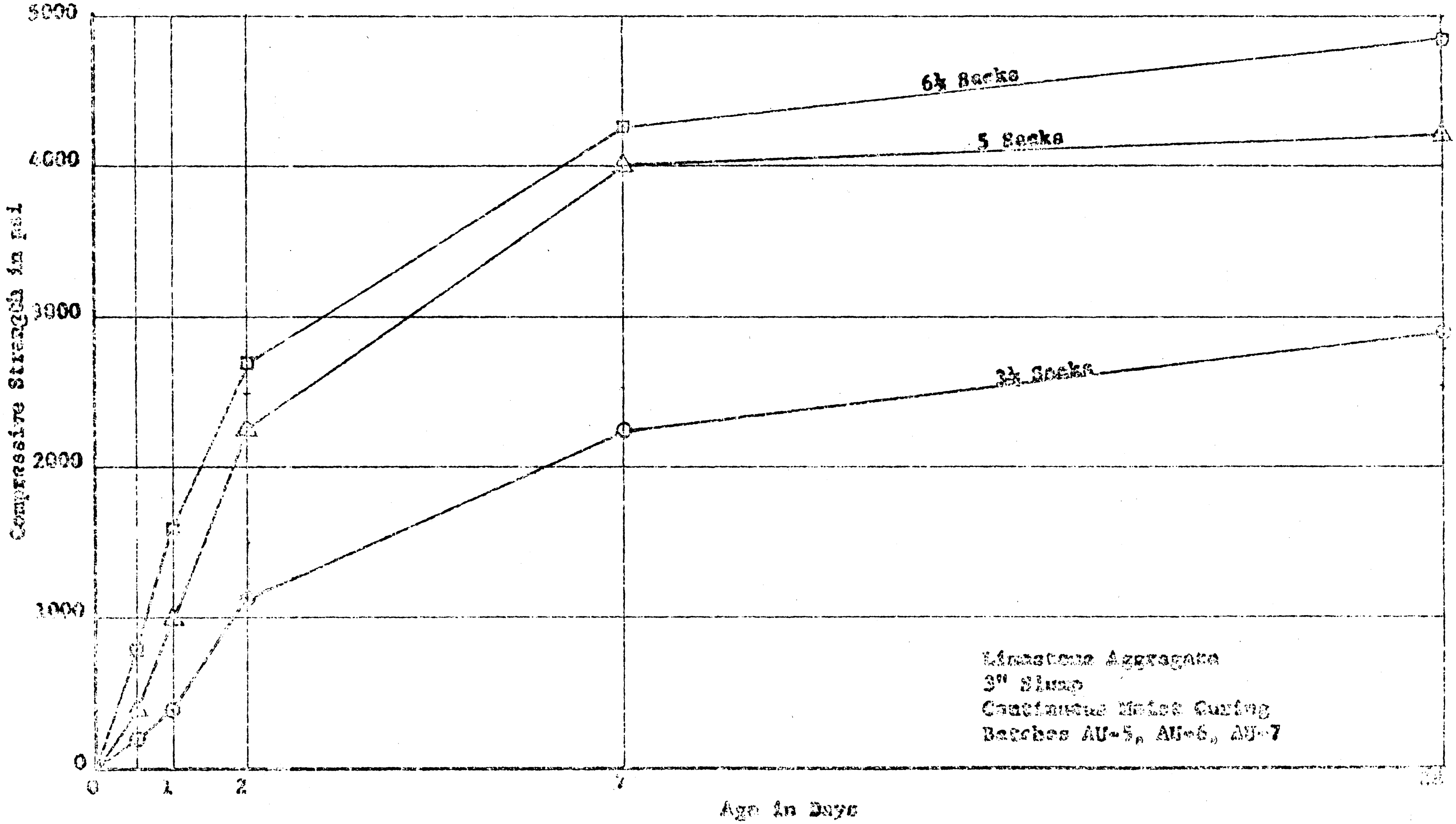

FIGURE 1 EFFECT OF CEMENT CONTENT ON COMPRESSIVE STRENGTH

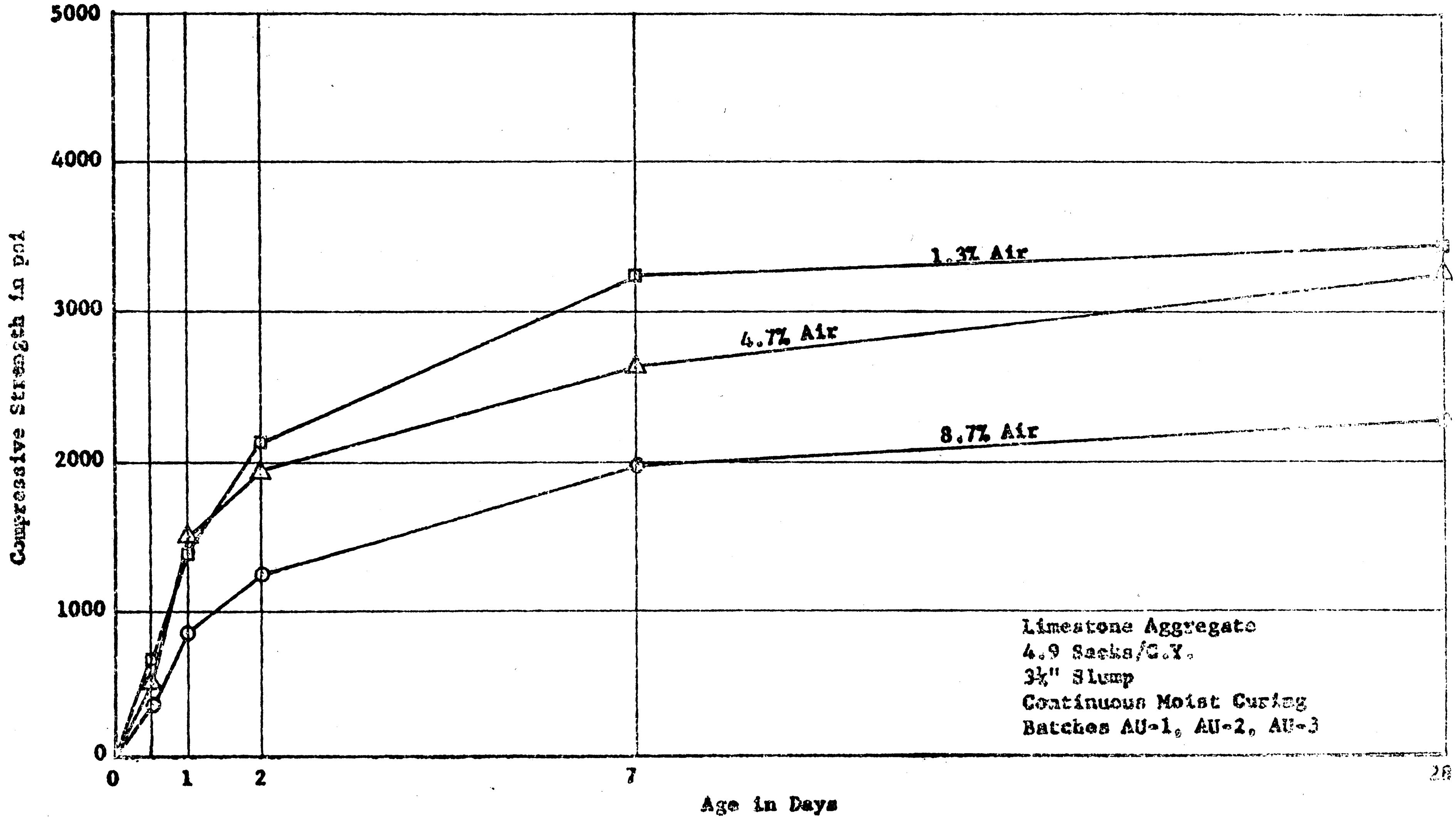

FIGURE 2 EFFECT OF AIR CONTENT ON COMPRESSIVE STRENGTH

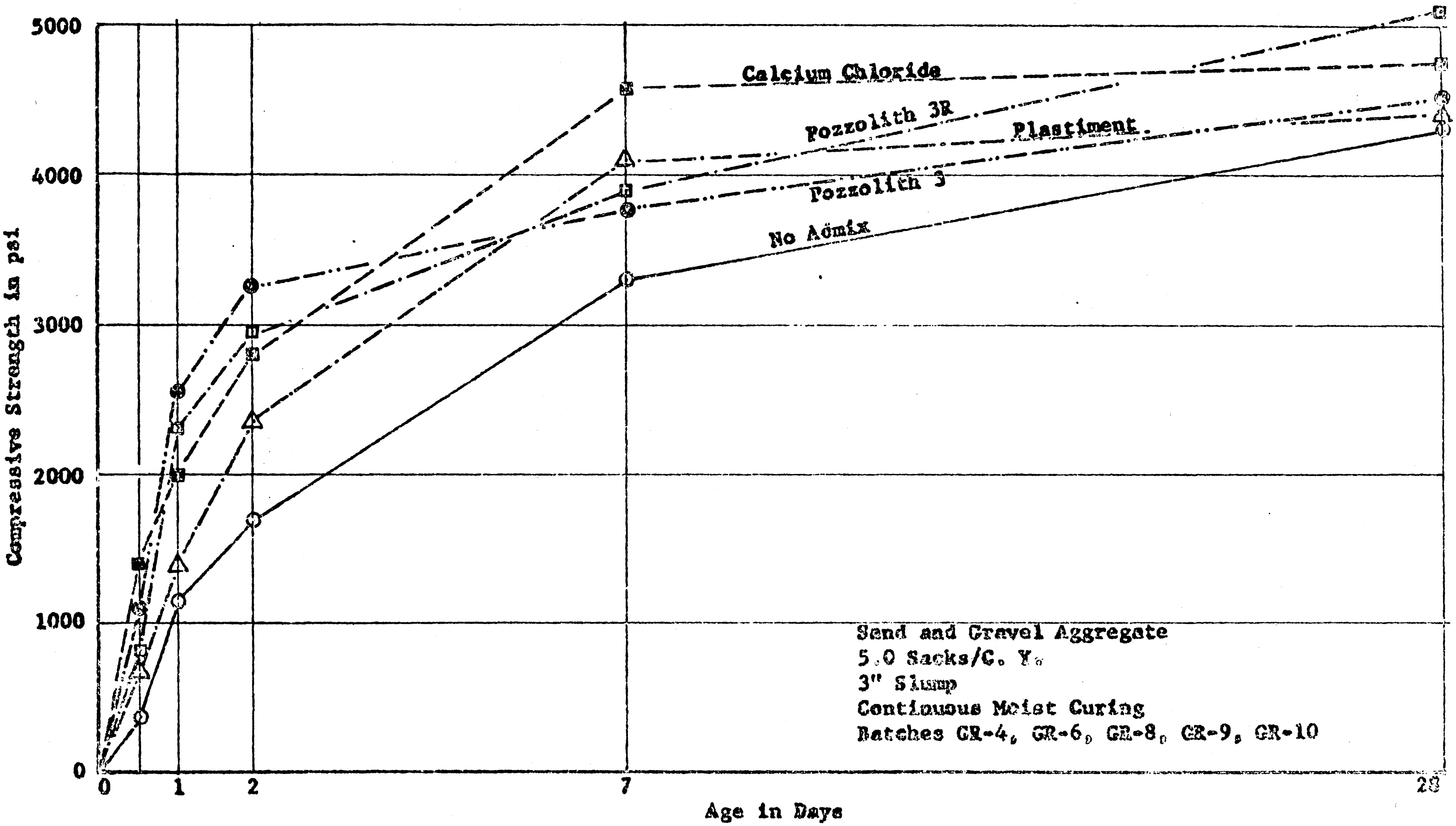

FIGURE 3 EFFECT OF ADMIX ON THE COMPRESSIVE STRENGTH

Flexural Strength

The flexural strength, or modulus of rupture as it is often called, is an indication of the tensile strength of concrete. The flexural strength values are dependent upon (1) the tensile strength of the cement paste, (2) the tensile strength of the aggregate, (3) the bond between the cement paste and aggregate, and (4) the strain properties of the concrete.

Figure 4 illustrates the effect of the cement content on the flexural strength at early ages. When more cement is added to a concrete batch, the quantity and quality of the cement paste is increased and consequently the strength is increased. This increase in flexural strength appears to be more pronounced at early ages. As can be seen in Figure 4, the flexural strength of the 6½ sack mix is over 3 times that of the 3½ sack mix at 12 hours and 1 day of age. At 28 days of age, however, this strength ratio is only about 1 1/3. A possible explanation for this is that at early ages the flexural strength is controlled largely by the low strength of the paste, while at later ages, after the paste has cured, the flexural strength is possibly limited by the strength of the aggregate.

Figure 5 illustrates the effect of air content on the flexural strength. The curve labeled 0.3% air has no air entraining agent added, and this is the amount of entrapped air in the cement paste and pores of the aggregate. The amount shown on the other curves is the entrapped plus entrained air. In general, entrained air reduces the water requirement to produce a given slump, and this in turn improves the quality of the cement paste. On the other hand, however, it decreases the effective area of concrete, and the net result is usually a decrease in the flexural strength. In Figure 5, however, it will be noticed that the batch with 4.6% air has for all practical purposes the same strength as the batch with no entrained air. This is due to the fact that the desirable and undesirable strength effects of entrained air tend to offset each other when air is entrained in moderate amounts up to 5%.

Figure 6 illustrates the qualitative effect of four different admixes on the flexural strength of concrete at early ages. The calcium chloride, which is a hydration accelerator, increased the early strength gain considerably when compared to the batch with no admix. This flexural strength gain is not too apparent at the 7 and 28 day tests, however. Other investigators have found that calcium chloride is even detrimental to the flexural strength at 6 months and 1 year of age. The exact reasons for this phenomenon are not understood at the present.

The Pozzolith 3, which is a water reducing agent, increased the flexural strength considerably at all ages from 12 hours through 28 days. At 12 hours of age the flexural strength of this batch is 3 times that of the mix with no admix. At 28 days of age this strength ratio has fallen off to only about 1.25.

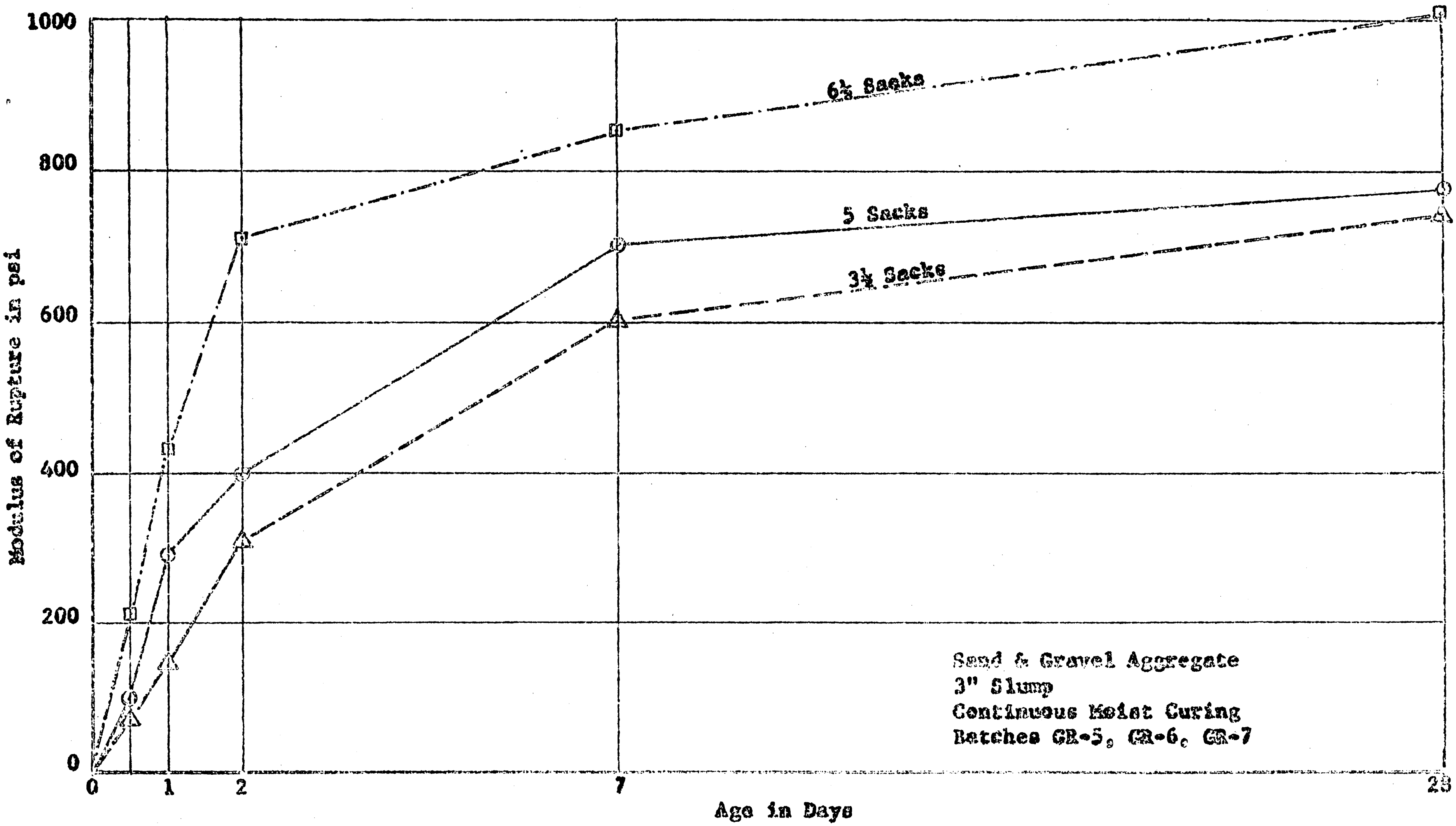

FIGURE 4 EFFECT OF CEMENT CONTENT ON FLEXURAL STRENGTH

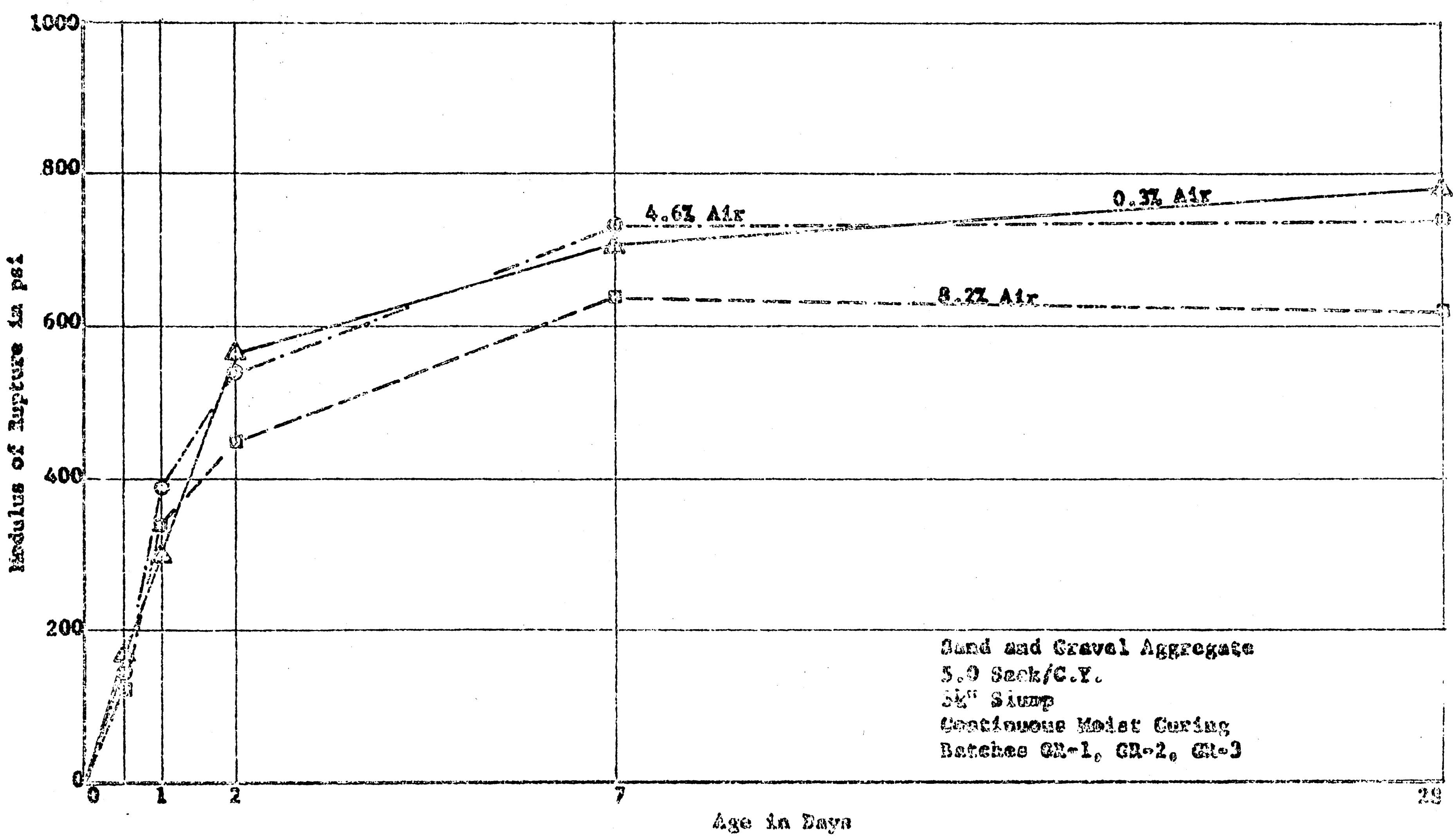

FIGURE 5 EFFECT OF AIR CONTENT ON FLEXURAL STRENGTH

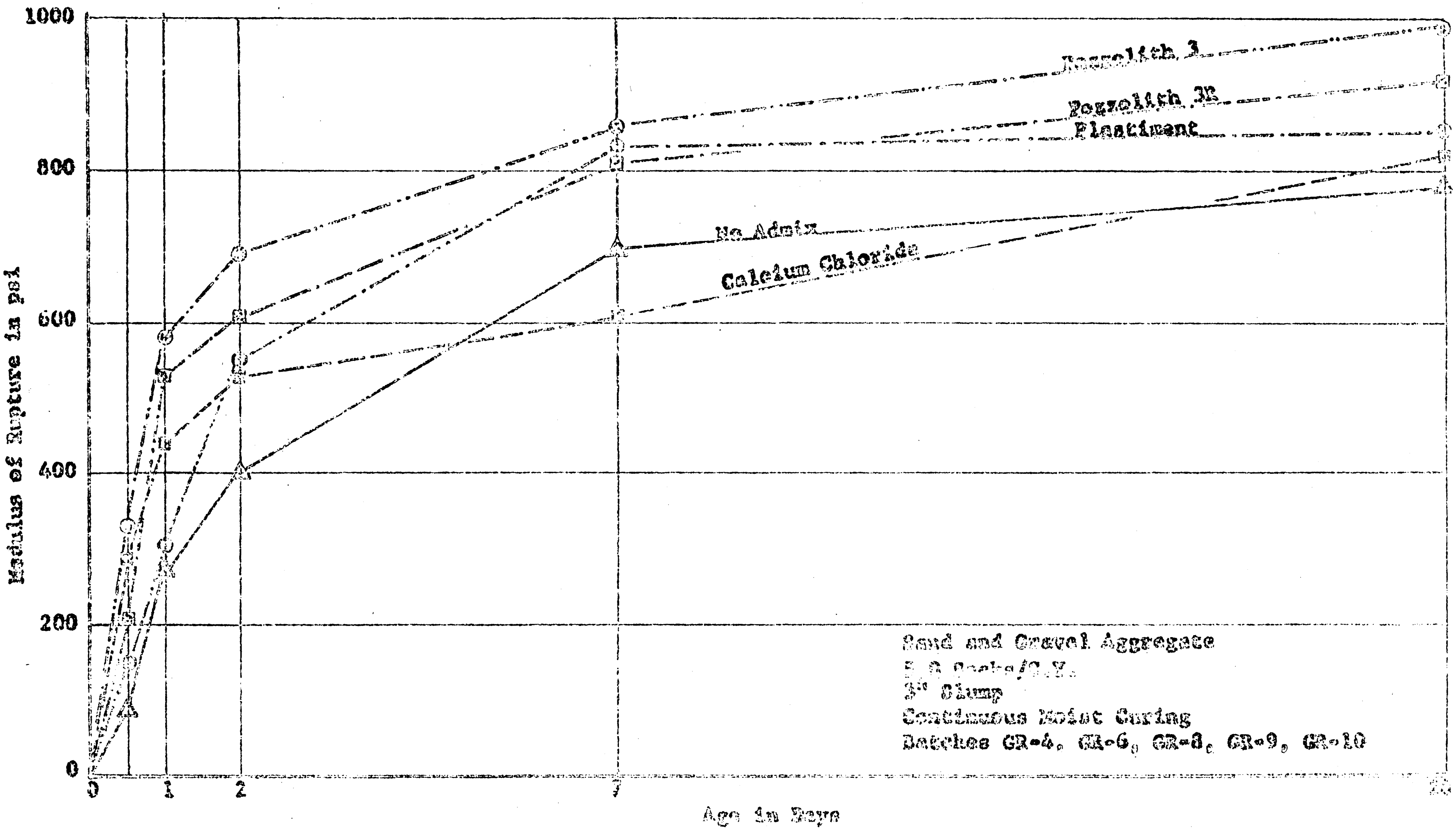

FIGURE 6 EFFECT OF ADMIX ON THE FLEXURAL STRENGTH

The other two admixes, Pozzolith 3R and Plastiment, were water reducing agents and also set retarders. As can be seen in Figure 6, they also improved the concrete strength at ages from 12 hours through 28 days. At 12 hours of age, however, the strength improvement was not as great as that achieved by the water reducing agent without set retarder.

When flexural strength values from concrete batches poured with the siliceous-calcareous gravel and sand were compared with values from similar batches poured using crushed limestone as fine and coarse aggregate, no discernible difference could be detected which could be attributed to the aggregate type.

Tensile Strength

In this investigation direct tension tests were also conducted on specimens from the concrete batches. Curves illustrating the effect of cement content, air content, and type of admix on the direct tensile strength are shown on Figures 7, 8 and 9 respectively. In general the qualitative effects of these variables on the tensile strength at early ages are the same as observed for the flexural strength. Quantitatively, however, the tensile strength values are only about ½ of the flexural strength values.

Bond Strength

The bond strength reported here is the standard bar pull out test as described previously. The ultimate bond strength was computed from

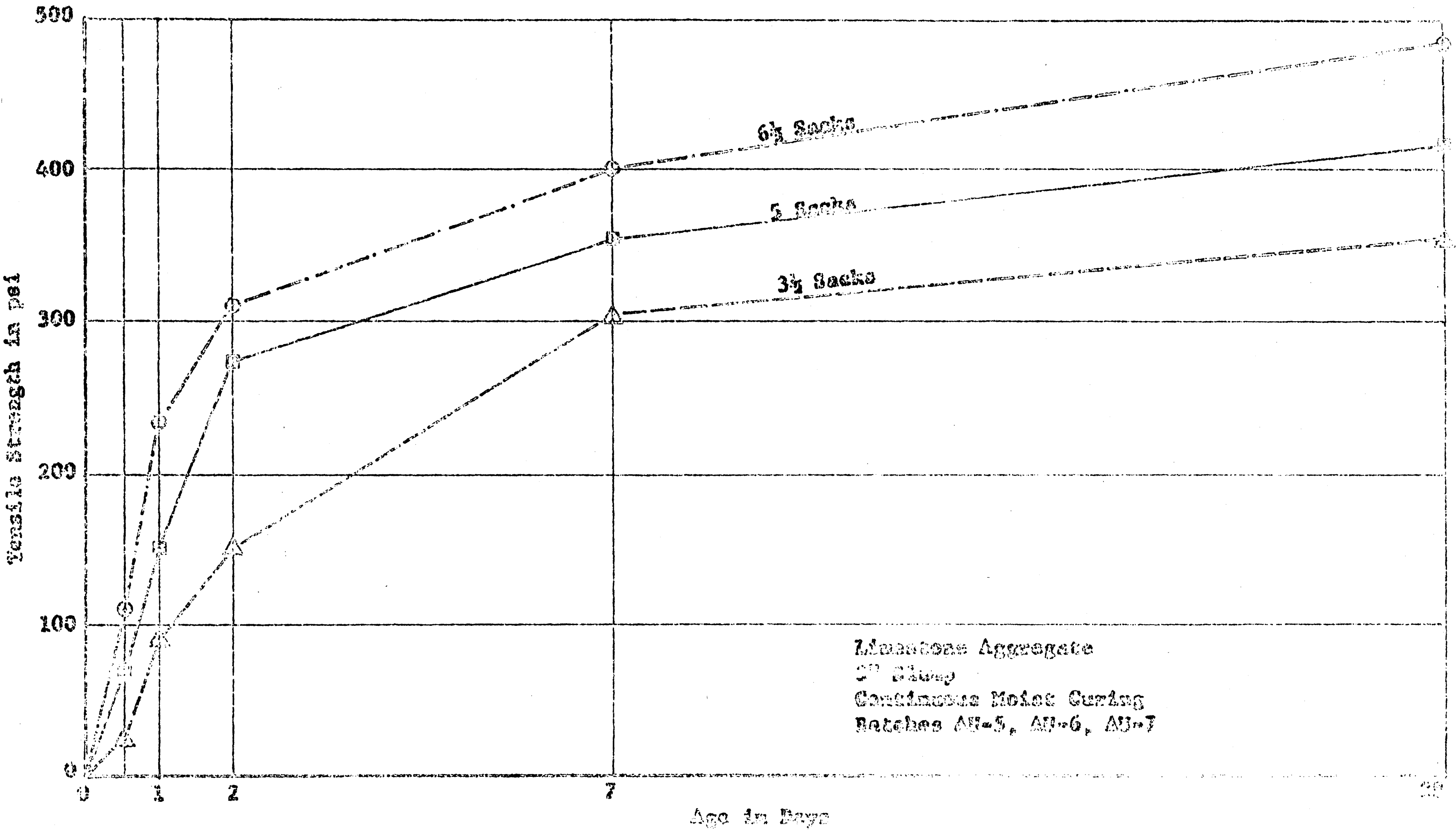

FIGURE 7 EFFECT OF CEMENT CONTENT ON TENSILE STRENGTH

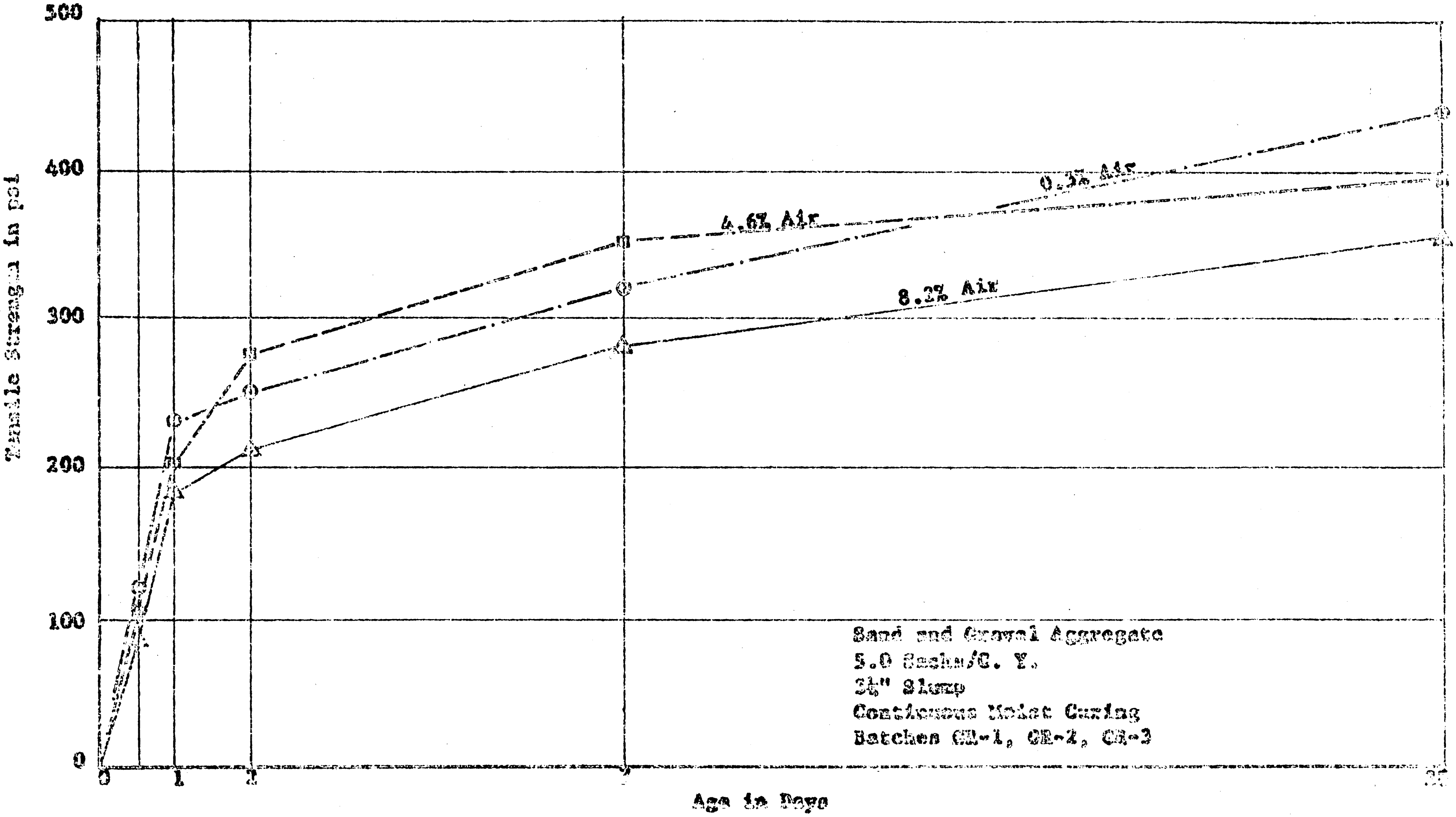

FIGURE 9. EFFECT OF AIR CONTENT ON TENSILE STRENGTH

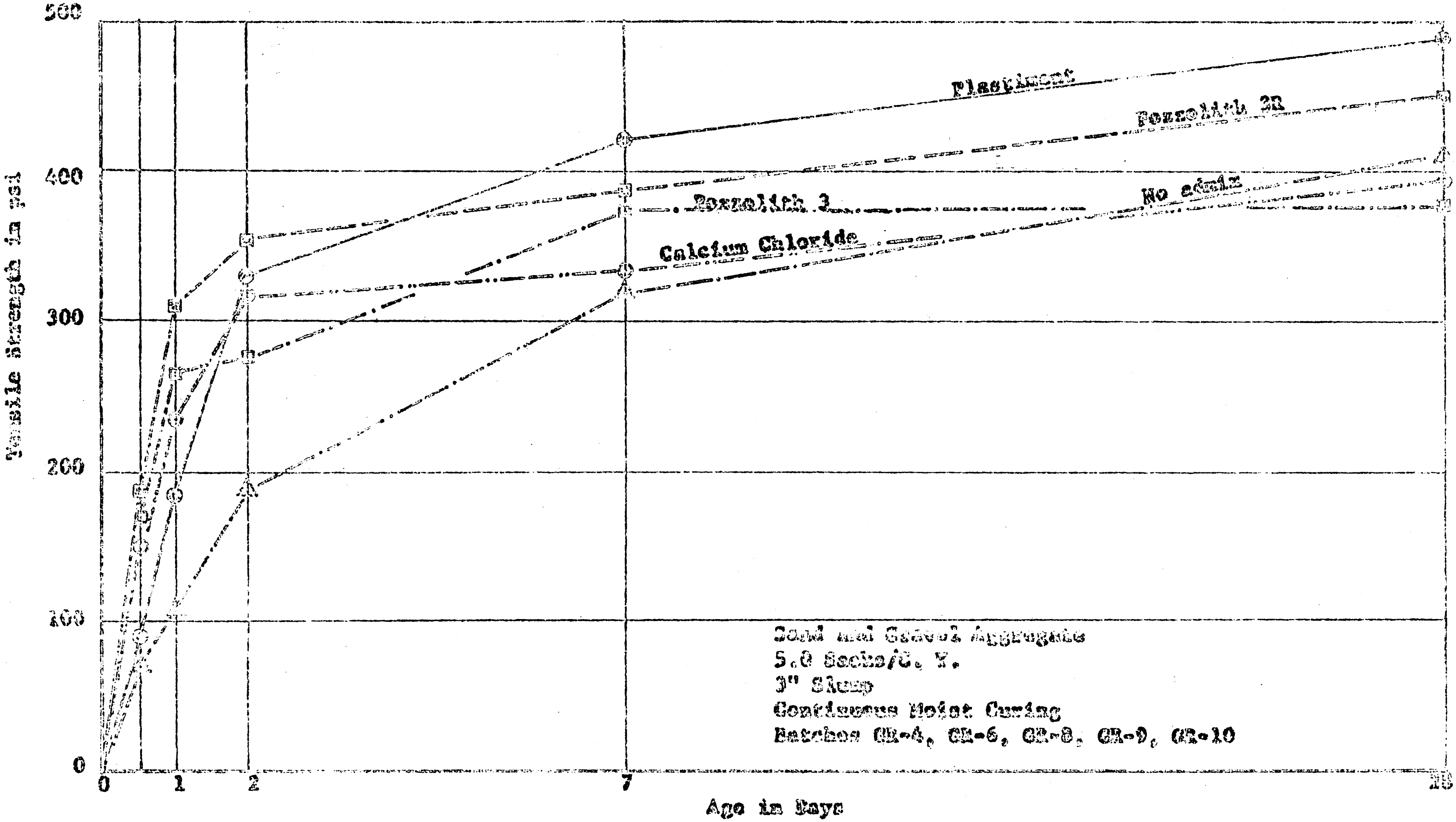

FIGURE 9 EFFECT OF ADMIX ON THE TENSILE STRENGTH

the pull force when the bar slipped 0.01" with respect to the concrete, or from the pull force at which the 6" x 6" x 6" cube specimen split due to tension, whichever was the least.

Figure 10 illustrates the effect of cement content on the bond strength at early ages. It can be noted that at 12 hours and 1 day of age the 6½ sack mix had several times the strength of the 3½ sack mix. At 7 and 28 days of age, however, this ratio of the two strengths dropped off to about 1.2.

Figure 11 illustrates the effect of air content on bond strength. When entrained air is used in moderate amounts up to about 5%, it has little effect on the bond strength values at 2, 7, and 28 days of age when compared to concrete with no entrained air. At 12 hours and 1 day of age, however, entrained air definitely makes the concrete a little tender. Higher air content such as the 8.2% air curve illustrates, definitely lowers the bond strength at all ages, however.

Figure 12 illustrates the effect of the four different admixes on the bond strength. Qualitatively, this effect is similar to that discussed on the flexural strength and tensile strength. Since many of the bond specimens failed due to tensile splitting of the 6" x 6" x 6" cube at about the same time the .01" slip occurred, there is a fairly good correlation between the results of the flexural, tensile, and bond tests.

When bond strength values from concrete batches poured with the siliceous-calcareous gravel and sand were compared with values from

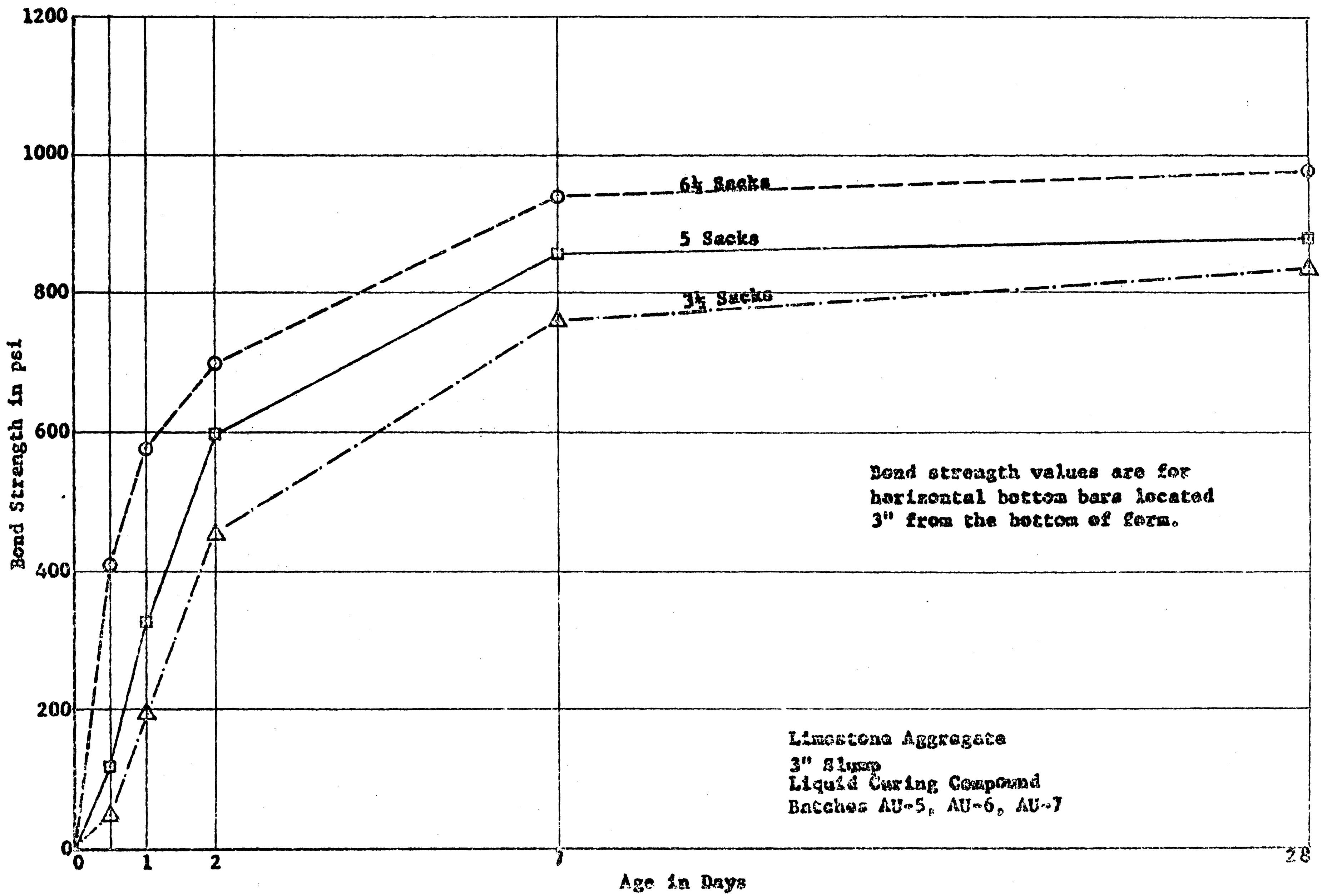

FIGURE 10 EFFECT OF CEMENT CONTENT ON BOND STRENGTH

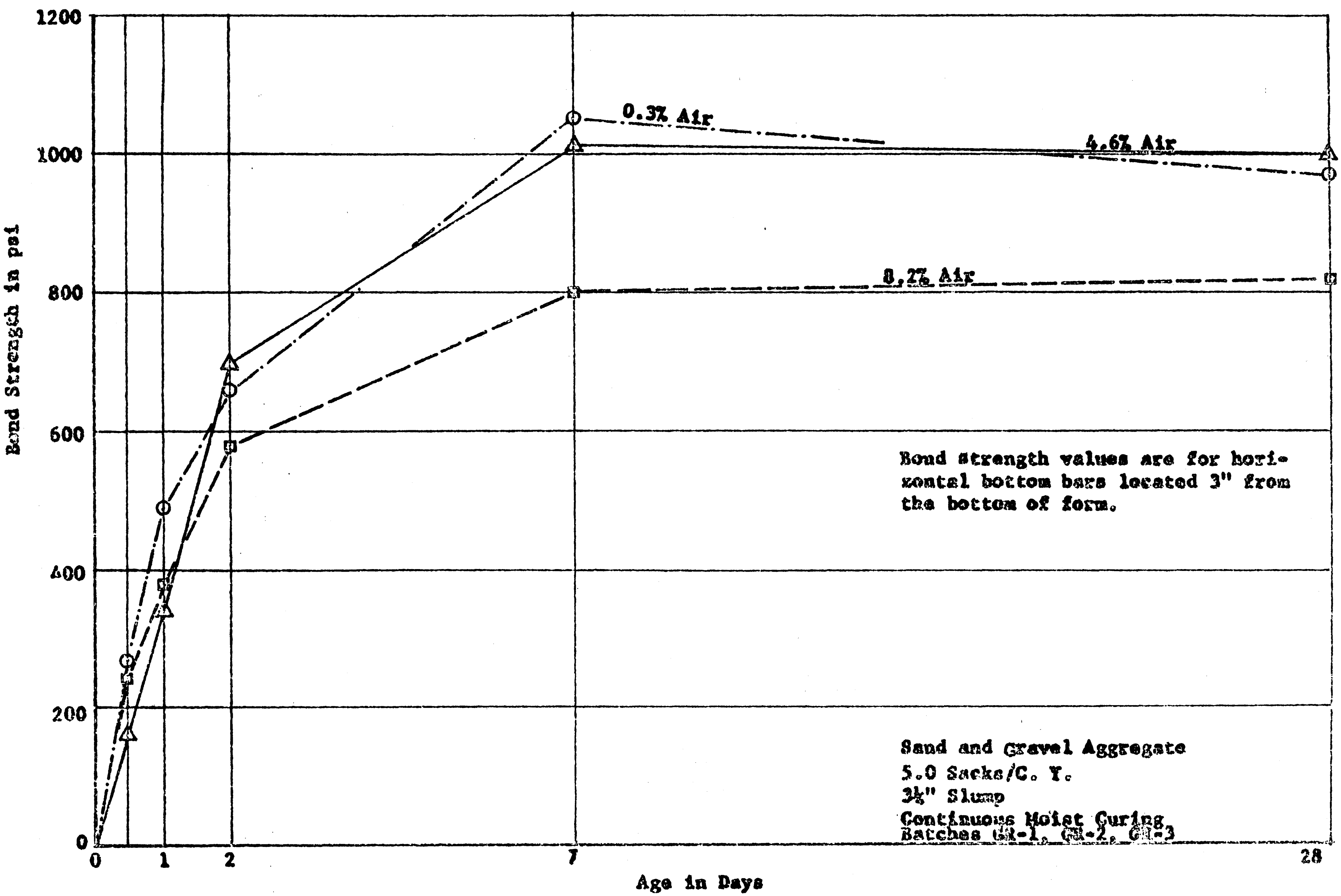

FIGURE 11 EFFECT OF AIR CONTENT ON BOND STRENGTH

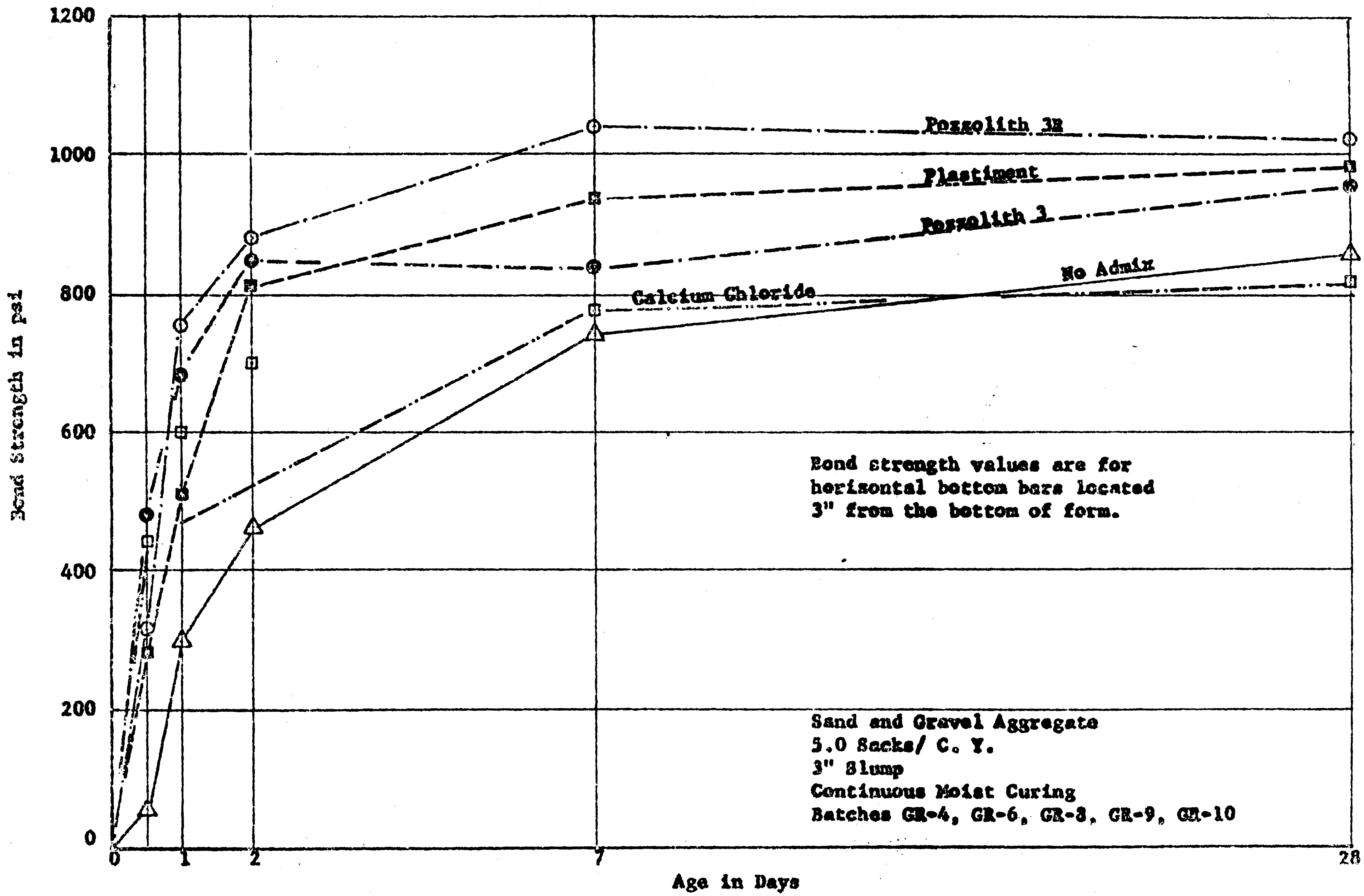

FIGURE 12 EFFECT OF ADMIX ON BOND STRENGTH

similar batches using crushed limestone fine and coarse aggregate, no discernible difference could be detected which could be attributed to the aggregate type.

Modulus of Elasticity (Dynamic)

The modulus of elasticity depends on the modulus of elasticity of the aggregate and modulus of the cement paste.

Figure 13 illustrates the effect of cement content on the dynamic modulus of elasticity. When more cement is used and the slump is kept constant, the volume and elastic modulus of the cement paste increases, and consequently the modulus of the concrete increases at all ages as shown.

Figure 14 illustrates that entrained air will always reduce the modulus of elasticity of concrete at all ages. When air bubbles replace aggregate which has great elastic stiffness, the net effect is obvious.

Figure 15 illustrates the effect of the four different admixes on the dynamic modulus of elasticity of concrete. The calcium chloride increased the modulus values considerably at the early ages of 12 hours and 1 day when compared to the mix with no admix. The advantage, however, was not maintained at later ages. The same qualitative statement can be made about the other three water reducing admixes also. Even though the elastic properties of the paste were improved by cutting the water, the net effect on the elastic modulus of the concrete at later ages was slight.

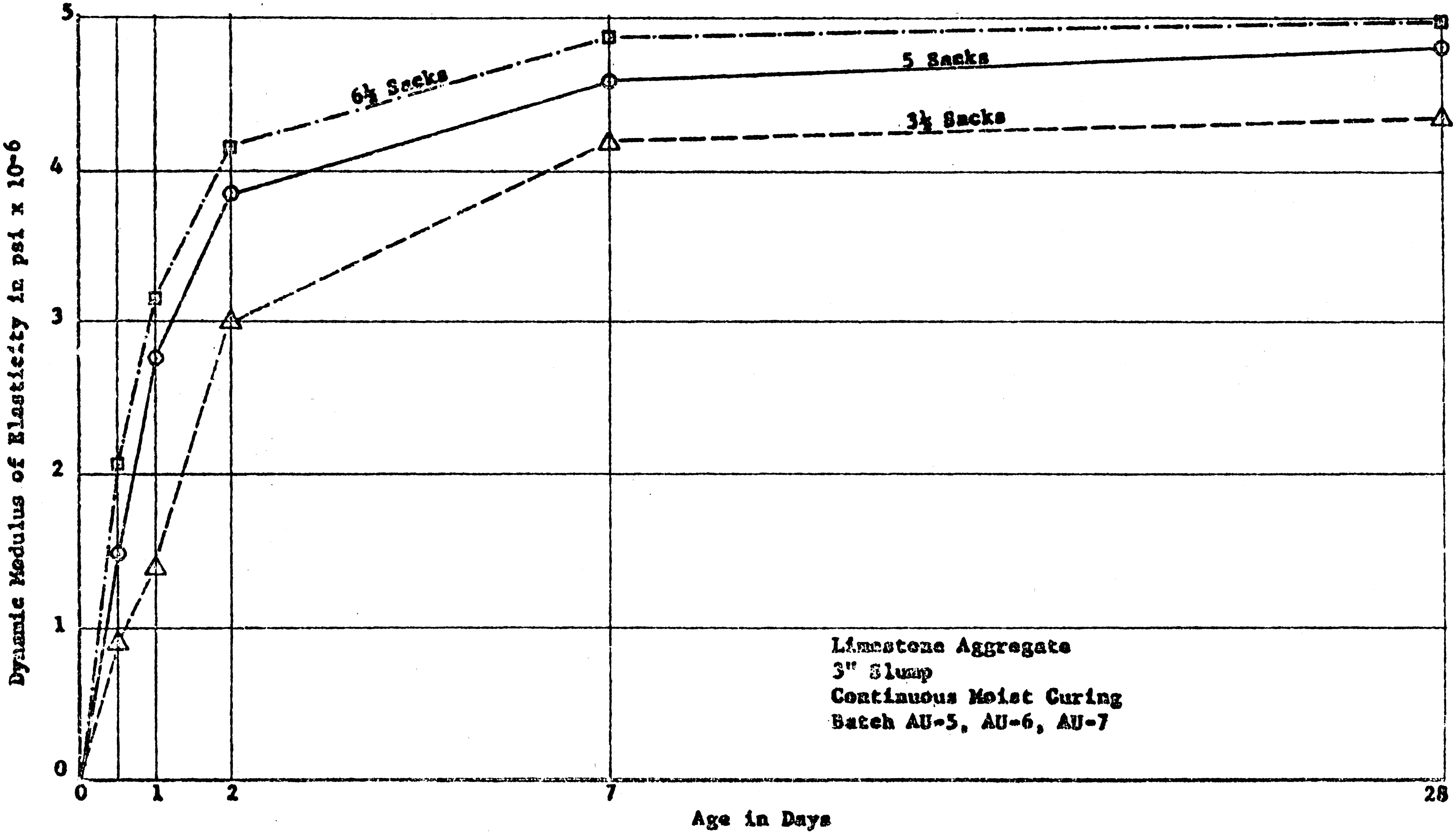

FIGURE 13 EFFECT OF CEMENT CONTENT ON THE DYNAMIC MODULUS OF ELASTICITY

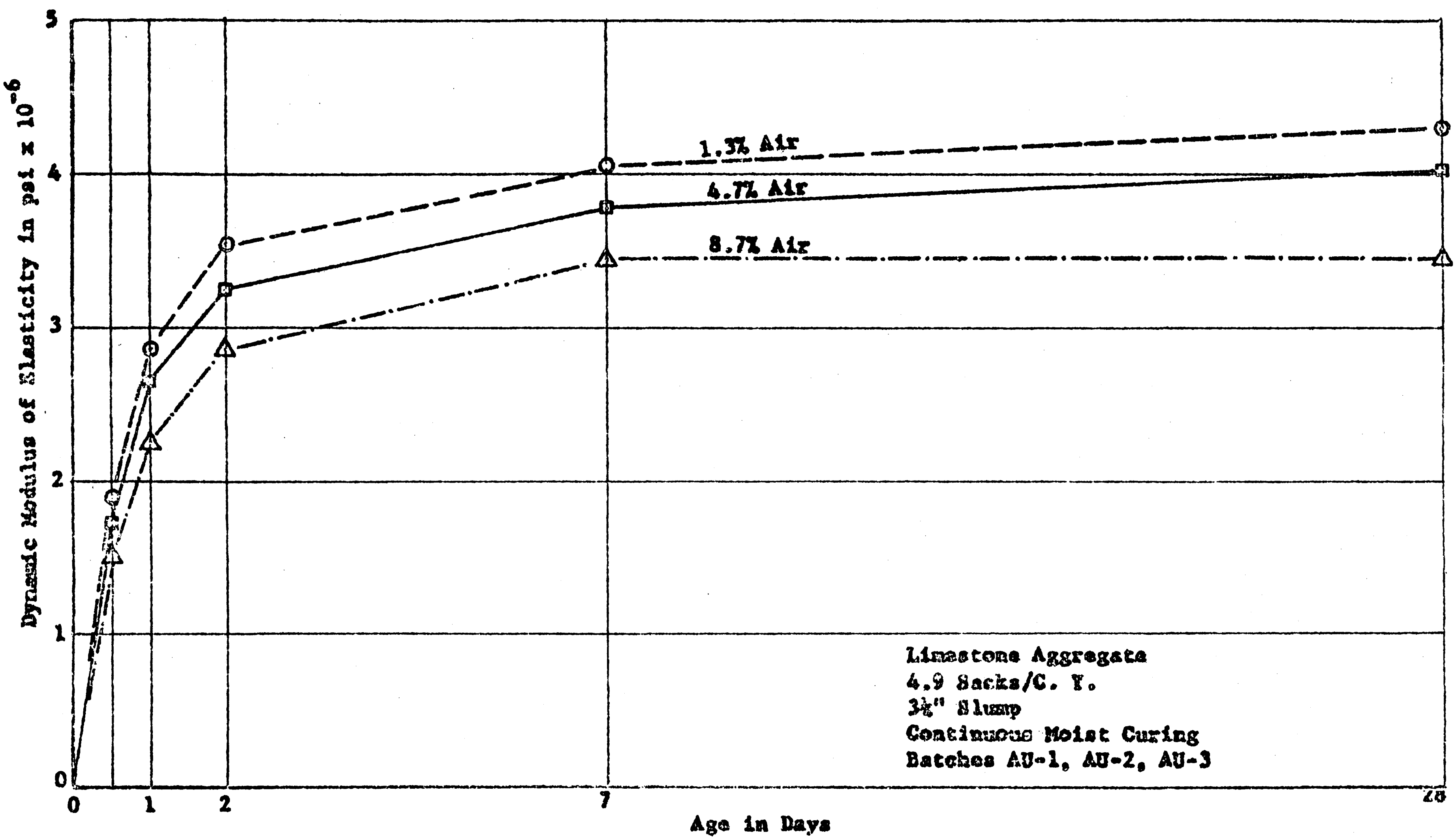

FIGURE 14 EFFECT OF AIR CONTENT ON DYNAMIC MODULUS OF ELASTICITY

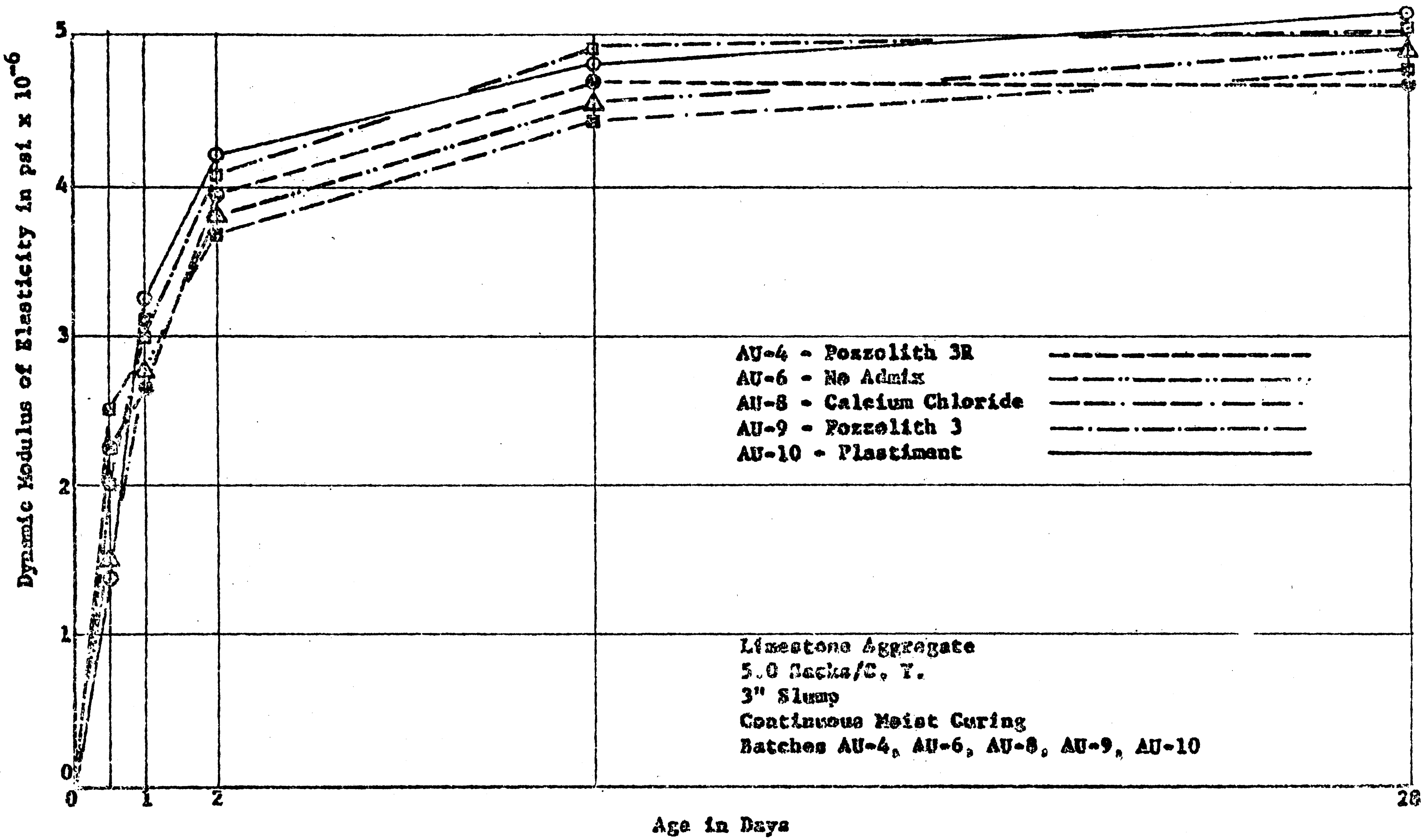

FIGURE 15 EFFECT OF ADMIX ON THE DYNAMIC MODULUS OF ELASTICITY

The aggregate type was found to have a significant effect on the modulus of elasticity of the concrete, since it depends directly on the elastic moduli of the aggregate as well as that of the cement paste. The concrete made with the crushed limestone fine and coarse aggregate has a modulus of elasticity of only 2/3 of that of the siliceous-calcareous gravel and sand. Numerically, the average limestone concrete dynamic modulus of elasticity is about 4,400,000 psi while that of the sand and gravel concrete is about 6,500,000 psi.

Coefficient of Expansion and Contraction

The coefficient of expansion and contraction reported here is the average length change per degree Fahrenheit determined by cooling a concrete specimen from room temperature down to 32°F. and then warming it back up to room temperature. The values for specific batches at specific ages are presented in Appendix F. A study of this data indicated no discernible difference which could be attributed to cement content, air content, type of admix, or age. The aggregate type, however, had a definite effect on the thermal coefficient. The average coefficient of expansion and contraction of the siliceous-calcareous gravel and sand concrete was 4.4×10^{-6} in./in. °F. while the average value for the crushed limestone aggregate concrete was 3.5×10^{-6} in./in. °F. Consequently, the coefficient of the crushed limestone aggregate concrete is only about 80% of the coefficient of sand and gravel concrete.

Extensibility

The extensibility of concrete as used here may be defined as the ultimate tensile strain of concrete subjected to a sustained and gradually increasing load. Such tests were performed as described previously, and the total tensile strain obtained included elastic plus inelastic strain occurring over the time period of the test. In addition to these tests, an ultimate tensile strain was also obtained from the ordinary tensile strength test where the load was applied relatively instantaneously, i. e., total time for test approximately 5 minutes, when compared to days for the extensibility test.

The detailed extensibility test results are presented in Appendix H. Since only one test specimen of each type was tested from each batch, the test results are rather eratic, and a detailed comparison to determine the effect of cement content, air content, etc. is not possible. However, the effect of the aggregate and the effect of the curing process on the extensibility values can be illustrated by using average values as shown in Table 3. It will be noted that moist cured specimens exhibit greater strain than air dried specimens, and that the limestone aggregate concrete has greater strain capacity than the sand and gravel concrete.

In order to illustrate the qualitative effect of cement content, air content, and type of admix on the tensile strain properties of concrete, some of the ultimate tensile strain values obtained from the tensile strength test will be presented here.

Table 3. Average Ultimate Tensile Strain in Microinches Per Inch from Extensibility Tests of Concrete

Aggregate Type	Continuous Moist Curing (Spec. No. A)	Treated Liquid Curing Compound Air Dried Indoors (Spec. No. B & C)
Limestone Batches AU-1 through 10	127 Avg.	103 Avg.
Siliceous-Calcareous Batches GR-1 through 10	107 Avg.	96 Avg.

Figure 16 illustrates the effect of cement content on the ultimate tensile strain. It can be seen that the 6½ sack mix increases the strain capacity of the concrete more than 60% when compared to the strain of the 3½ sack mix.

Figure 17 illustrates the effect of air content on the ultimate strain of concrete. At ages from 12 hours through 7 days, the presence of entrained air appears to increase the strain capacity of the concrete. This phenomenon may be due to the lower modulus of elasticity of the concrete containing entrained air. However, the ultimate tensile strength would also be lowered.

Figure 18 illustrates the effect of the four different types of admixes on the ultimate tensile strain. The effect of the calcium chloride to increase the strain capacity was very pronounced at the

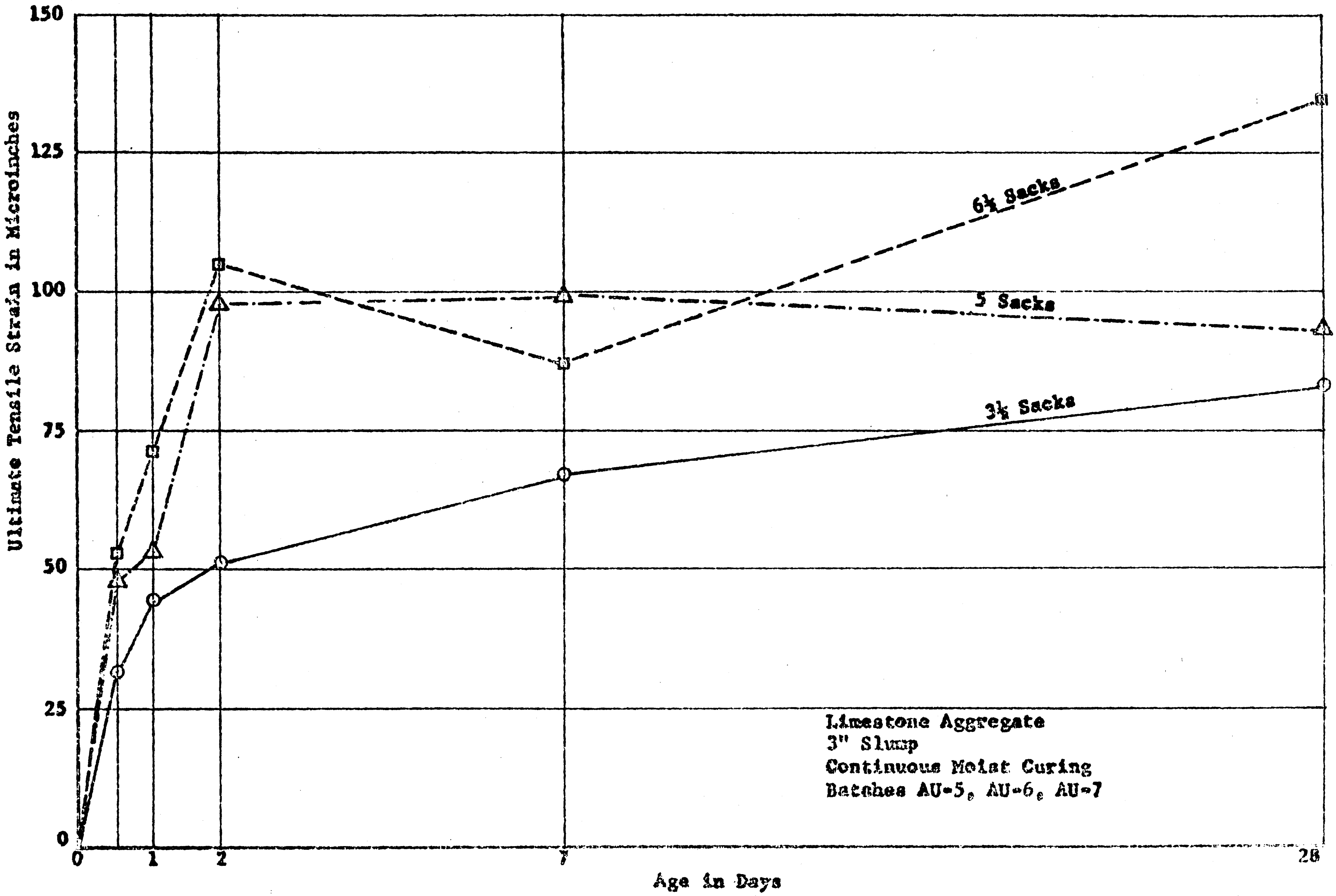

FIGURE 16 EFFECT OF CEMENT CONTENT ON ULTIMATE TENSILE STRAIN

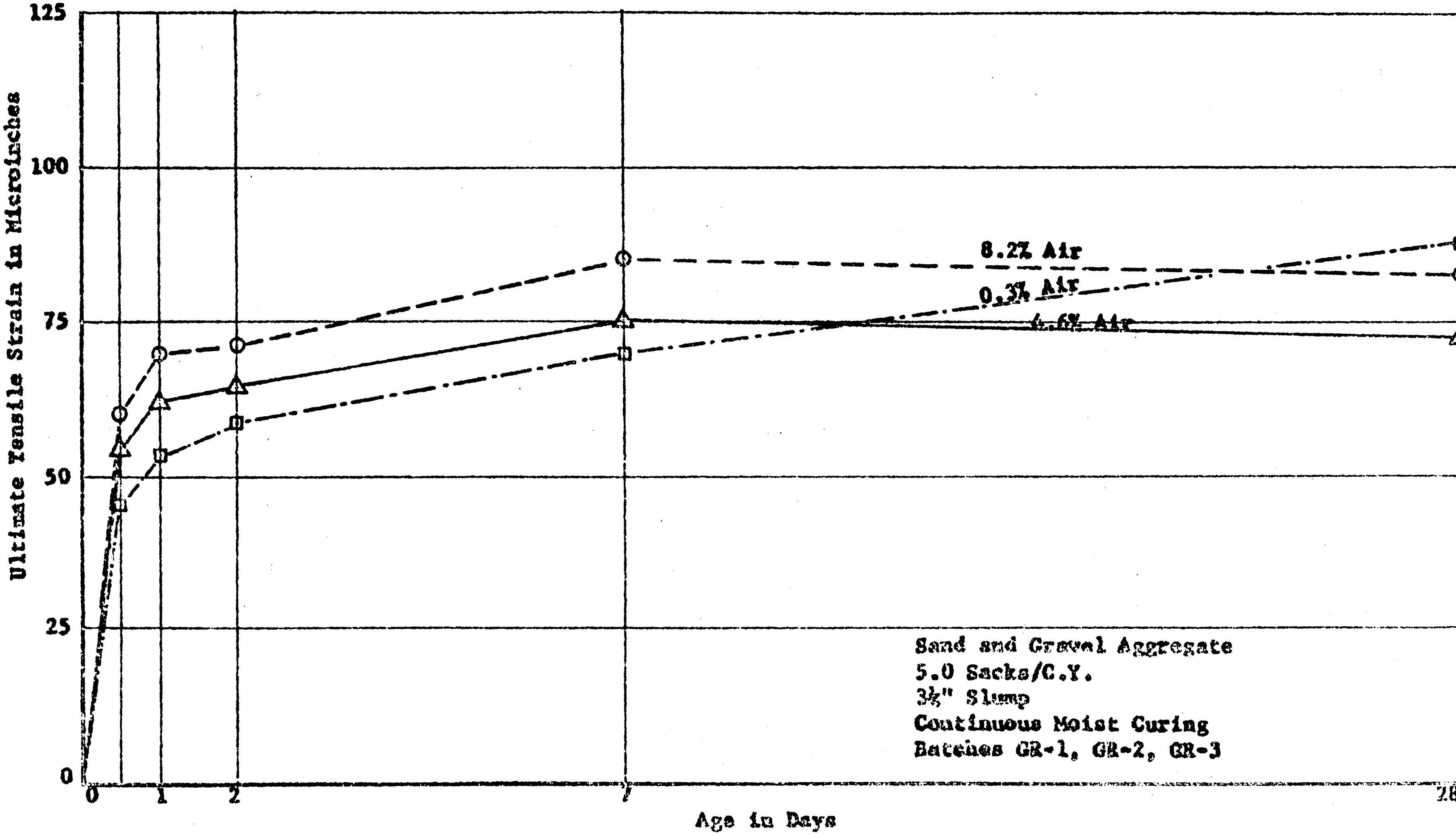

FIGURE 17 EFFECT OF AIR CONTENT ON ULTIMATE TENSILE STRAIN

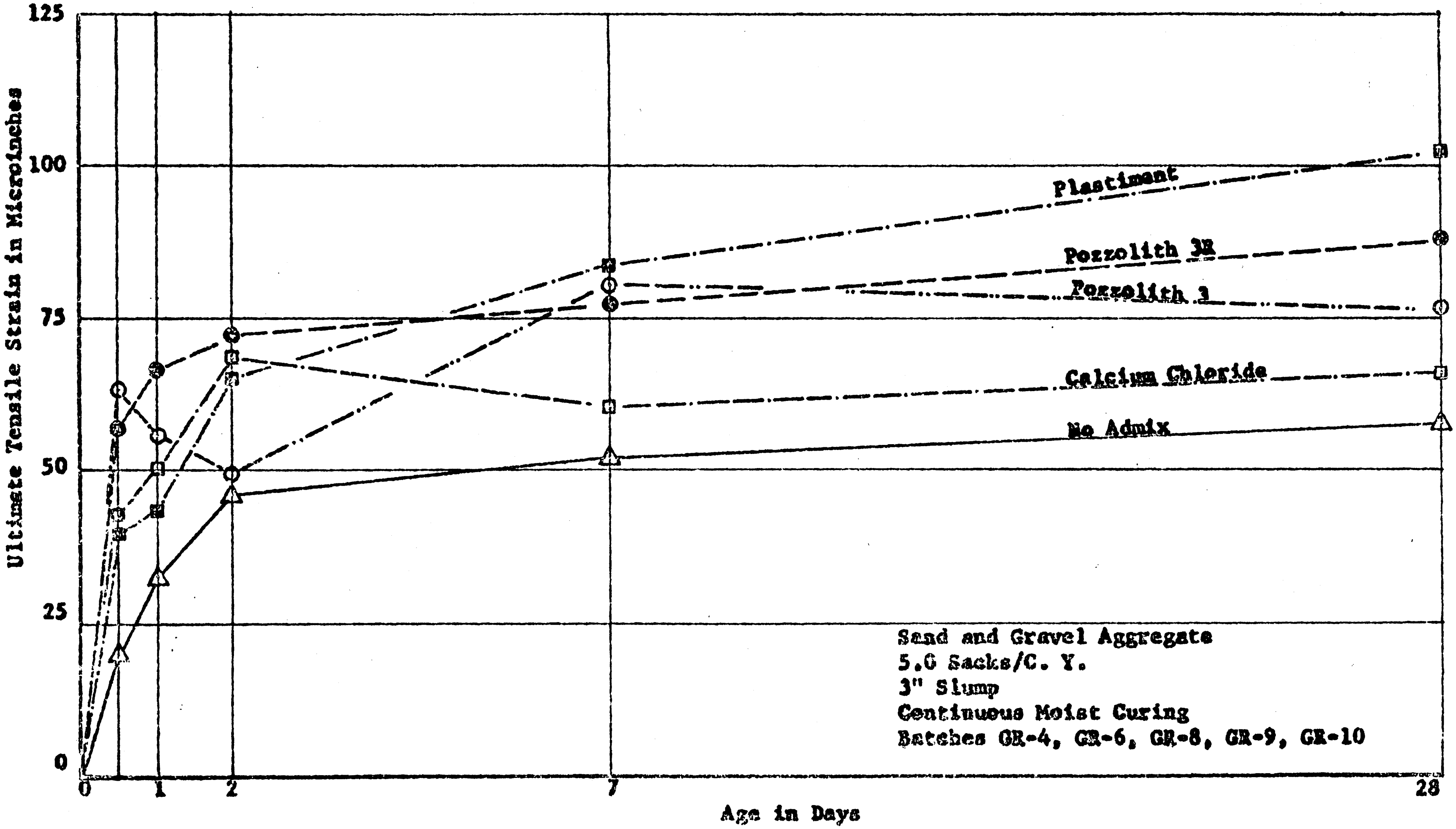

FIGURE 18 EFFECT OF ADMIX ON THE ULTIMATE TENSILE STRAIN

early ages when compared to the concrete with no admix. All three of the water reducing agents produce greater strain capacity at all ages shown here. In general, this improvement in ultimate strain capacity is about 50%.

In order to illustrate the effect of the type of aggregate and the effect of age on the ultimate strain capacity of concrete, Table 4 is presented below. These values are the average strain values taken from the tensile strength tests.

Table 4. Average Ultimate Tensile Strain of Continuously Moist Cured Concrete Specimens. Tensile Strain in Microinches per Inch.

Aggregate Type	Age of Tests				
	12 hr.	1 day	2 day	7 day	28 day
Limestone Batches AU-1 thru 10	54	72	90	93	109
Siliceous-Calcareous Batches GR-1 thru 10	47	50	60	70	77

It will be noted that tensile strain capacity definitely increases with age, and that the limestone aggregate concrete has about 40% more strain capacity than sand and gravel concrete.

Shrinkage

The phenomenon of shrinkage of concrete is for the most part caused by contraction of the cement paste due to drying. As the cement paste drys and shrinks, it is restrained or resisted by the aggregate embedded in it. The degree of this restraint to shrinkage depends on the amount of stiffness (modulus of elasticity) of the embedded aggregate. In addition to these factors which affect shrinkage, it has been found that not all mineral particles in an aggregate act as restraining bodies. If an aggregate contains clay or other very fine material, this material can form a shrinkable paste also. This mineral paste, in some cases, may shrink much more than an equivalent quantity of cement paste. Consequently, the resulting shrinkage observed in a concrete specimen depends on the properties and relative amounts of both the cement paste and aggregate.

Figure 19 illustrates the shrinkage curves of nine of the ten batches of concrete poured using the crushed limestone fine and coarse aggregate. The average 90 day shrinkage value of these batches is about 475 microinches per inch.

Figure 20 illustrates the shrinkage curves of the ten batches of concrete poured using the siliceous-calcareous gravel and sand aggregate. It will be noted that the average 90 day shrinkage of these batches is about 285 microinches per inch. A comparison of these values shows that the limestone concrete shrinks 1 2/3 times as much as the sand and gravel concrete. This higher shrinkage can be attributed largely to two factors: (1)the much lower stiffness or modulus of elasticity of the limestone aggregate particles which resist shrinkage, and (2) the relatively large amount of crushed limestone fines passing the #100 and #200 sieves (see Table 2.)

In general, high cement content tends to increase shrinkage. High entrained air content also tends to increase shrinkage. Since the shrinkage curves presented here did not consistently illustrate this point, no such comparison was attempted.

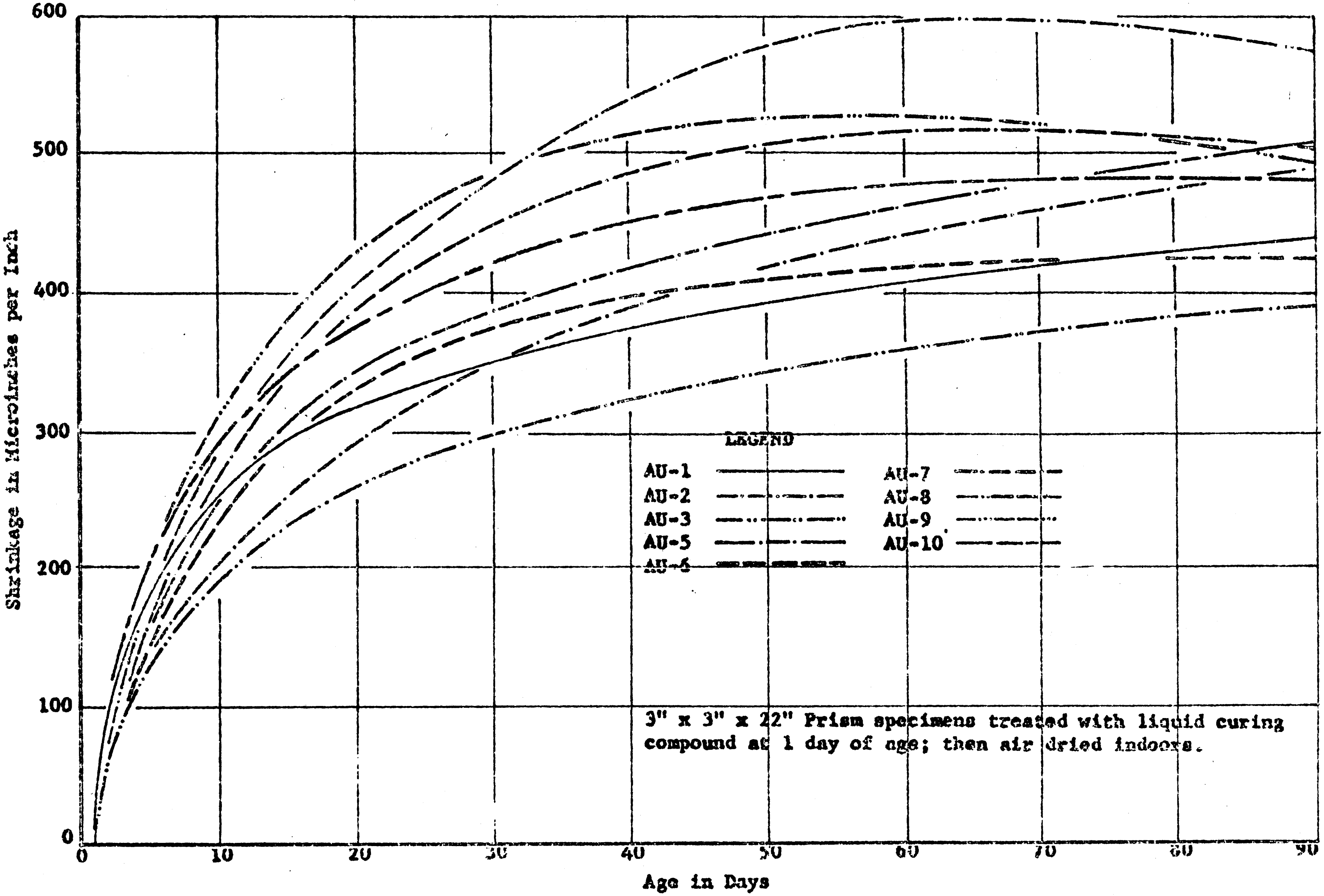

FIGURE 19. SHRINKAGE OF CRUSHED LIMESTONE AGGREGATE CONCRETE.

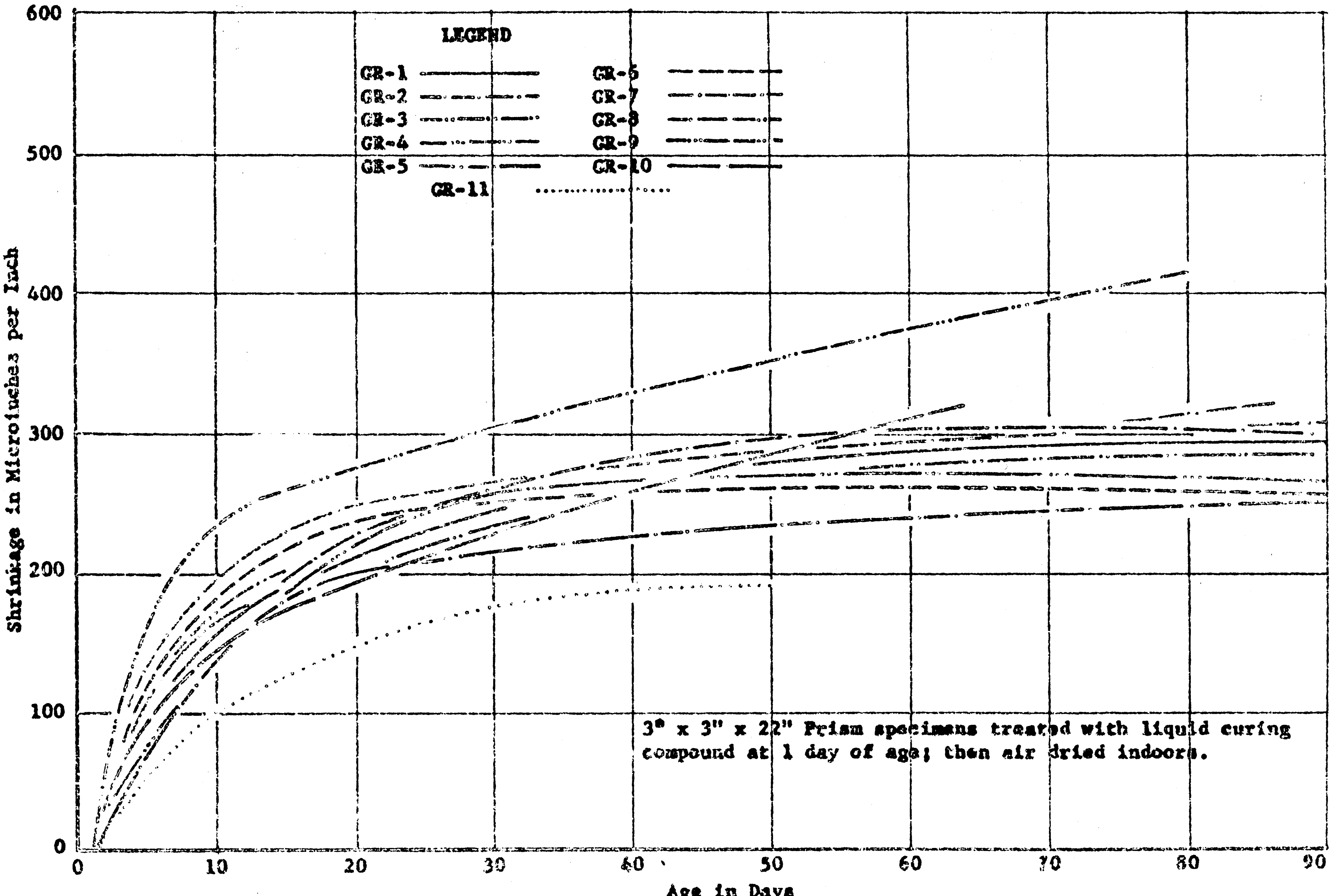

FIGURE 20. SHRINKAGE SILICEOUS-CALCAREOUS SAND AND GRAVEL CONCRETE

V. APPENDIX

Compressive Strength in lb. in.^{2}
ASTM Method C116-49

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	635	1385	2140	3220	3435
	Compound**			1815	2625	3160
	Dry***					4230
AU-2	Moist	430	1465	1920	2620	3220
	Compound			1815	2420	2550
	Dry					3435
AU-3	Moist	395	870	1260	1970	2240
	Compound			1205	2150	2320
	Dry					2470
AU-4	Moist	630	1795	2535	3550	3850
	Compound			2160	3510	3760
	Dry					4500
AU-5	Moist	184	451	1161	2290	2885
	Compound			1059	2215	2580
AU-6	Moist	379	986	2257	4020	4190
	Compound			2065	3505	4290
AU-7	Moist	790	1659	2734	4280	4885
	Compound			2159	3365	3770
AU-8	Moist	1134	1659	2378	3030	4565
	Compound			2203	2915	3680
AU-9	Moist	689	1219	2102	3810	4250
	Compound			2361	3170	4470
AU-10	Moist	344	1011	2586	3765	4210
	Compound			2102	2635	4135
GR-1	Moist	590	1460	2365	3335	3710
	Compound			2125	3340	3650
	Dry					4490
GR-2	Moist	480	1545	2000	2595	3420
	Compound			2050	2870	3380
	Dry					4075
GR-3	Moist	390	1100	1510	2185	2710
	Compound			1400	2330	2610
	Dry					2500
GR-4	Moist	610	2280	2830	3800	5220
	Compound			3000	3865	6280
	Dry					6700
GR-5	Moist	251	459	1176	2340	2625
	Compound			808	2245	2550
GR-6	Moist	363	1161	1696	3300	4335
	Compound			1323	2275	2880
GR-7	Moist	604	2240	3117	5060	4980
	Compound			2221	3030	4120
GR-8	Moist	1409	2023	2892	4580	4740
	Compound			2801	3520	4160
GR-9	Moist	1101	2552	3223	3885	4395
	Compound			2559	3240	4180
GR-10	Moist	646	1430	2342	4095	4385
	Compound			1891	3515	3740
GR-11	Moist				3460	4155
	Polyethylene	2180	3185	3535	4160	4340

* Continuous Moist Room Curing

** Moist Cured 1 Day, treated with liquid membrane curing compound and air dried indoors

*** Moist Cured 7 days, air dried indoors

Modulus of Rupture in $lb./in.^2$
Center Point Loading

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	150	290	400	590	730
	Compound**			450	500	595
	Dry***					725
AU-2	Moist	125	315	475	540	665
	Compound			410	465	600
	Dry					740
AU-3	Moist	115	265	375	530	575
	Compound			355	410	550
	Dry					550
AU-4	Moist	115	430	615	745	730
	Compound			545	670	685
	Dry					610
AU-5	Moist	49	105	289	635	670
	Compound			275	520	470
AU-6	Moist	77	269	394	760	825
	Compound			583	650	565
AU-7	Moist	155	355	561	745	880
	Compound			523	570	665
AU-8	Moist	272	380	481	565	775
	Compound			486	510	720
AU-9	Moist	180	366	481	695	815
	Compound			581	620	685
AU-10	Moist	72	204	532	640	845
	Compound			455	565	545
GR-1	Moist	165	300	550	710	780
	Compound			560	550	605
	Dry					650
GR-2	Moist	145	390	545	720	735
	Compound			540	580	695
	Dry					730
GR-3	Moist	135	340	455	640	615
	Compound			470	485	575
	Dry					600
GR-4	Moist	205	530	610	810	920
	Compound			610	720	860
	Dry					830
GR-5	Moist	70	146	313	615	745
	Compound			328	505	645
GR-6	Moist	98	285	405	695	780
	Compound			427	510	630
GR-7	Moist	213	533	739	755	1085
	Compound			554	660	775
GR-8	Moist	297	442	528	615	815
	Compound			543	520	645
GR-9	Moist	335	580	696	840	990
	Compound			571	725	905
GR-10	Moist	151	293	545	830	825
	Compound			561	655	630
GR-11	Moist				700	960
	Polyethylene	515	555	660	665	805

* Continuous Moist Room Curing

** Moist Cured 1 Day, treated with liquid membrane curing compound and dried indoors

*** Moist Cured 7 Days, air dried indoors

Tensile Strength in lb./in.^{2}
3" x 3" x 22" Prism

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	95	170	250	330	360
	Compound**			245	270	340
AU-2	Moist	100	140	190	290	332
	Compound			210	215	280
AU-3	Moist	85	150	240	355	360
	Compound			---	250	345
AU-4	Moist	120	295	330	370	435
	Compound			295	335	335
AU-5	Moist	28	93	151	305	355
	Compound			136	205	230
AU-6	Moist	70	154	276	400	415
	Compound			254	285	385
AU-7	Moist	110	232	306	355	485
	Compound			307	360	420
AU-8	Moist	136	187	207	310	365
	Compound			221	260	245
AU-9	Moist	107	165	281	375	410
	Compound			304	395	340
AU-10	Moist	43	145	255	370	425
	Compound			248	275	290
GR-1	Moist	115	225	250	315	440
	Compound			270	345	460
GR-2	Moist	100	200	275	350	395
	Compound			320	350	330
GR-3	Moist	100	190	205	280	355
	Compound			255	310	310
GR-4	Moist	190	310	355	380	450
	Compound			330	370	415
GR-5	Moist	33	62	81	300	330
	Compound			148	200	290
GR-6	Moist	---	107	195	320	405
	Compound			197	205	265
GR-7	Moist	77	229	291	490	460
	Compound			310	280	375
GR-8	Moist	156	234	316	325	395
	Compound			279	315	280
GR-9	Moist	175	263	272	380	380
	Compound			285	290	300
GR-10	Moist	72	194	330	420	485
	Compound			344	---	285
GR-11	Moist				290	345
	Polyethylene	181	194	250	285	305

* Continuous Moist Room Curing

** Moist Cured 1 Day, treated with liquid membrane curing compound and air dried indoors

Bond Strength in lb./in.^{2} at 0.01 inches slip
ASTM Method C 234-57T
Horizontal <u>Bottom</u> Bars 3/4" diam. (deformed)

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day	28 Day*	28 Day**
AU-1	Moist	245	435	670	745	835	810	740
	Compound			620	670	770		
AU-2	Moist	170	330	455	525	745	607	645
	Compound			465	485	645		
AU-3	Moist	130	345	455	675	820	630	
	Compound			425	665	710		
AU-4	Moist	280	575	680	845	1000	795	795
	Compound			875	980	710		
AU-5	Moist	50	195	440	865	910	625	615
	Compound			450	760	830		
AU-6	Moist	115	325	620	1015	1040	635	846
	Compound			600	855	880		
AU-7	Moist	410	585	765	920	1015	1095	780
	Compound			705	945	980		
AU-8	Moist	350	445	685	820	1010	715	605
	Compound			620	775	960		
AU-9	Moist	165	340	630	805	895	945	---
	Compound			585	770	755		
AU-10	Moist	105	375	685	970	1040	940	---
	Compound			635	815	905		

* Values tabulated are for horizontal <u>"Top"</u> bars

** Values tabulated are for <u>Vertical</u> bars

Bond Strength in lb./in.^{2} at 0.01 inches slip
ASTM Method C 234-57T
Horizontal Bottom Bars 3/4" diam. (deformed)

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day	28 Day*	28 Day**
GR-1	Moist	220	490	660	1030	965	1020	935
	Compound			730	915	925		
GR-2	Moist	160	345	680	1010	1000	855	875
	Compound			505	630	990		
GR-3	Moist	200	380	590	620	825	555	920
	Compound			590	795	805		
GR-4	Moist	280	770	840	1050	1020	810	890
	Compound			870	910	865		
GR-5	Moist	90	235	460	645	865	800	745
	Compound			485	545	725		
GR-6	Moist	58	310	465	735	845	793	705
	Compound			450	635	605		
GR-7	Moist	245	560	975	1015	1105	1035	825
	Compound			745	790	940		
GR-8	Moist	440	600	700	755	830	725	---
	Compound			680	685	845		
GR-9	Moist	455	675	840	845	970	915	690
	Compound			1000	780	1195		
GR-10	Moist	245	510	815	935	970	790	785
	Compound			840	730	795		
GR-11	Moist				800	785	750	590
	Polyethylene	480	515	805	880	920		

* Values tabulated for horizontal "Top" bars.

** Values tabulated for vertical bars.

Dynamic Modulus of Elasticity in Flexure
$E \times 10^6$ in lb./in.^{2}
ASTM Method C 215-55T

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	1.90	2.86	3.54	4.02	4.23
	Compound**			3.62	3.85	3.90
	Dry***					4.05
AU-2	Moist	1.60	2.66	3.24	3.76	4.04
	Compound			3.14	3.55	3.54
	Dry					3.82
AU-3	Moist	1.54	2.23	2.85	3.45	3.48
	Compound			2.78	3.06	3.39
	Dry					3.43
AU-4	Moist	2.23	3.41	3.92	4.53	4.63
	Compound			3.85	4.40	4.51
	Dry					4.59
AU-5	Moist	.89	1.39	3.00	4.14	4.35
	Compound			2.92	3.88	3.85
AU-6	Moist	1.52	2.73	3.86	4.56	4.97
	Compound			4.07	4.41	4.57
AU-7	Moist	2.05	3.16	4.12	4.87	4.95
	Compound			4.00	4.41	4.45
AU-8	Moist	2.51	3.25	3.82	4.44	4.82
	Compound			3.56	4.23	4.10
AU-9	Moist	2.00	3.10	3.96	4.66	4.97
	Compound			3.96	4.40	4.30
AU-10	Moist	1.43	2.70	4.06	4.61	5.08
	Compound			3.77	4.34	4.24
GR-1	Moist	2.86	4.24	5.04	6.18	6.50
	Compound			4.84	5.44	5.43
	Dry					5.89
GR-2	Moist	2.47	4.00	4.76	5.61	5.84
	Compound			4.75	5.18	5.35
	Dry					5.57
GR-3	Moist	2.24	3.36	4.25	5.10	4.89
	Compound			4.04	4.37	4.34
	Dry					4.73
GR-4	Moist	3.13	4.74	5.82	6.53	6.74
	Compound			5.73	6.30	6.12
	Dry					6.54
GR-5	Moist	1.60	2.95	4.27	5.85	6.10
	Compound			4.19	5.34	4.81
GR-6	Moist	1.45	3.62	4.96	6.65	6.88
	Compound			4.57	4.53	5.01
GR-7	Moist	2.75	4.69	5.81	6.44	7.18
	Compound			5.21	5.48	5.38
GR-8	Moist	3.97	4.80	5.79	6.41	7.07
	Compound			5.77	5.63	5.61
GR-9	Moist	4.16	4.95	5.90	6.57	6.76
	Compound			5.64	6.00	5.91
GR-10	Moist	2.56	4.08	5.56	6.57	6.77
	Compound			5.29	6.01	5.69
GR-11	Moist				6.55	6.21
	Polyethylene	5.55	5.77	6.34	6.76	6.78

*Continuous Moist Room Curing

**Moist Cured 1 Day, treated with liquid membrane curing compound, air dried indoors

***Moist Cured 7 Days, air dried indoors

Coefficient of Expansion and Contraction
in./in °F. x 10^6

Batch Designation	Curing	12 Hours	1 Day	7 Day	28 Day
AU-1	Moist*	---	---	4.0	2.6
	Compound**			3.9	4.0
AU-2	Moist	2.3	3.1	3.2	3.1
	Compound			3.7	5.4
AU-3	Moist	2.0	4.2	4.4	---
	Compound			---	2.7
AU-4	Moist	1.7	2.6	3.4	3.3
	Compound			---	4.9
AU-5	Compound	2.2***	2.8	2.4	3.5
AU-6	Compound	3.3	---	3.9	3.3
AU-7	Compound	3.3	2.6	3.0	3.4
AU-8	Compound	3.2	---	2.9	3.5
AU-9	Compound	1.7	2.6	3.7****	4.1
AU-10	Compound	---	3.2*****	3.3	4.3
GR-1	Moist	3.1	3.4	4.3	4.0
	Compound			4.9	5.1
GR-2	Moist	3.6	4.7	---	3.7
	Compound			3.4	4.2
GR-3	Moist	2.3	3.8	---	4.3
	Compound			3.4	5.0
GR-4	Moist	4.5	4.8	4.8	3.0
	Compound			4.9	3.4
GR-5	Compound	5.0	4.1*****	4.4	5.0
GR-6	Compound	4.4	4.2	4.6	4.0
GR-7	Compound	4.9	4.1	5.4	4.6
GR-8	Compound	4.4	5.5*****	4.4	4.8
GR-9	Compound	3.8	3.9	4.4	4.0
GR-10	Compound	4.4	4.2*****	4.5****	4.5
GR-11	Compound	3.5***	4.3	4.9	4.1

* Continuous Moist Room Curing

** Moist Cured 1 Day, treated with liquid membrane curing compound and air dried indoors

*** Test performed at 1 day

**** Test performed at 10 days

***** Test performed at 3 days

Ultimate Tensile Strain
in in./in. x 10^6

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	63	67	93	91	108
	Compound**			88	77	121
AU-2	Moist	--	68	77	--	110
	Compound			78	--	105
AU-3	Moist	52	99	119	133	132
	Compound				95	121
AU-4	Moist	67	108	122	114	120
	Compound			99	98	87
AU-5	Moist	32	45	51	67	83
	Compound			52	63	75
AU-6	Moist	48	53	95	99	93
	Compound			89	76	93
AU-7	Moist	52	72	105	87	135
	Compound			108	91	101
AU-8	Moist	72	74	78	71	114
	Compound			79	80	82
AU-9	Moist	63	54	83	92	104
	Compound			95	104	99
AU-10	Moist	40	82	72	86	95
	Compound			88	83	90
GR-1	Moist	46	54	58	69	87
	Compound			60	70	102
GR-2	Moist	54	62	65	74	72
	Compound			78	80	74
GR-3	Moist	61	66	70	85	82
	Compound			74	94	104
GR-4	Moist	57	67	68	77	87
	Compound			76	76	82
GR-5	Moist	19	14	--	43	64
	Compound			--	48	63
GR-6	Moist	--	33	46	52	58
	Compound			80	44	60
GR-7	Moist	37	52	57	82	80
	Compound			79	66	71
GR-8	Moist	43	50	68	60	66
	Compound			61	69	82
GR-9	Moist	64	56	46	79	76
	Compound			65	66	53
GR-10	Moist	40	44	65	79	102
	Compound			84	43	75
GR-11	Moist				64	74
	Polyethylene	67	74	46	42	61

* Continuous Moist Room Curing

** Moist Cured 1 Day, Treated with Liquid Membrane Curing Compound and Air Dried Indoors.

Extensibility of Concrete

Batch Designation	Specimen Number	Ultimate Strain in/in x 10^6	Ultimate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
AU-1	(A)	105	327	37	3.11	Load applied at 1 day of age and increased at rate of 8.9 psi per day	Moist room
	(B)	107	205	5	1.92	Load applied at 12 hours of age and increased as required to maintain specimens at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	133	266	12	2.00	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-2	(A)	90	213	22	2.37	Load applied at 1 day of age and increased at rate of 9.7 psi per day	Moist room
	(B)	125	135	6	1.08	Load applied at 12 hours of age and increased as required to maintain specimens at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	160	339	25	2.12	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors

Extensibility of Concrete

Batch Desig- nation	Specimen Number	Ultimate Strain in/in x 10^6	Ulti- mate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
AU-3	(A)	155	288	32	1.86	Load applied at 1 day of age and increased at rate of 9.0 psi per day	Moist room
	(B)	Specimen broke while loading					
	(C)	Specimen had loose gage points					
AU-4	(A)	152	365	46	2.40	Load applied at 1 day of age and increased at rate of 7.9 psi per day	Moist room
	(B)	Specimen broke while loading					
	(C)	105	247	8	2.35	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-5	(A)	100	176	9	1.76	Load applied at 1 day of age and increased at rate of 19.5 psi per day	Moist room
	(B)	Specimen broke while loading					
	(C)	70	208	5	2.97	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-6	(A)	130	295	16	2.27	Load applied at 1 day of age and increased at rate of 18.4 psi per day	Moist Room

Batch Desig- nation	Specimen Number	Ultimate Strain in/in x 10^6	Ulti- mate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
AU-6	(B)	110	277	7	2.52	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	120	232	6	1.93	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-7	(A)	130	400	24	3.08	Load applied at 1 day of age and increased at rate of 16.7 psi per day	Moist room
	(B)	120	355	5	2.96	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	90	252	3	2.80	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-8	(A)	140	330	17	2.36	Load applied at 1 day of age and increased at rate of 19.4 psi per day	Moist room
	(B)	60	240	7	4.0	Load applied at 4 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors

Extensibility of Concrete

Batch Designation	Specimen Number	Ultimate Strain in.in x 10^6	Ultimate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
AU-8	(C)	70	180	5	2.57	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-9	(A)	140	372	21	2.66	Load applied at 1 day of age and increased at rate of 17.7 psi per day	Moist room
	(B)	70	271	4	3.88	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	110	248	4	2.25	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
AU-10	(A)	Specimen broke while loading					
	(B)	Specimen broke while loading					
	(C)	100	234	3	2.34	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors

Extensibility of Concrete

Batch Designation	Specimen Number	Ultimate Strain in/in x 10^6	Ultimate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain $E \times 10^{-6}$ psi	Remarks on Load Application	Exposure
GR-1	(A)	98	379	41	3.87	Load applied at 1 day of age and increased at rate of 9.2 psi per day	Moist room
	(B)	150	302	7	2.01	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	60	295	8	4.92	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-2	(A)	110	325	36	2.95	Load applied at 1 day of age and increased at rate of 9.0 psi per day	Moist room
	(B)	90	275	5	3.06	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	60	280	9	4.67	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-3	(A)	95	256	30	2.70	Load applied at 1 day of age and increased at rate of 8.5 psi per day	Moist room
	(B)	60	159	3	2.65	Load applied at 12 hours of age and increased as required to maintain a specimen at a constant length	Treated with liquid curing compound and air dried indoors

Batch Desig- nation	Specimen Number	Ultimate Strain in/in x 10^6	Ulti- mate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
GR-3	(C)	109	292	10	2.68	Load applied at 2 days of age andincreased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-4	(A)	120	379	54	3.16	Load applied at 1 day of age and increased at rate of 7.0 psi per day	Moist room
	(B)	80	385	6	4.81	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	95	398	9	4.19	Load applied at 2 days of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-5	(A)	190	264	15	1.39	Load applied at 1 day of age and increased at rate of 17.6 psi per day	Moist room
	(B)	Specimen broke while loading					
	(C)	60	224	4	3.73	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-6	(A)	140	328	22	2.35	Load applied at 1 day of age and increased at rate of 14.9 psi per day	Moist room
	(B)	Specimen broke while loading					

Batch Desig-nation	Specimen Number	Ultimate Strain in/in x 10^6	Ulti-mate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
GR-6	(C)	80	160	7	2.00	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-7	(A)	Loose gage points	330	20		Load applied at 1 day of age and increased at rate of 16.5 psi per day	Moist room
	(B)	110	291	4	2.65	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	65	243	4	3.74	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-8	(A)	70	389	20	5.56	Load applied at 1 day of age and increased at rate of 19.8 psi per day	Moist room
	(B)	50	201	3	4.02	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	160	233	7	1.46	Load applied at 1 day of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors

Extensibility of Concrete

Batch Designation	Specimen Number	Ultimate Strain in/in x 10^6	Ultimate Stress psi	Age at Failure Days	Ratio of Ultimate Stress to Ultimate Strain E x 10^{-6} psi	Remarks on Load Application	Exposure
GR-9	(A)	70	229	15	3.27	Load applied at 1 day of age and increased at rate of 15.3 psi per day	Moist room
	(B)	170	234	6	1.38	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	Specimen Broke while Loading					
GR-10	(A)	70	240	64	3.42	Load applied at 1 day of age and increased at rate of 3.7 psi per day	Moist room
	(B)	90	211	5	2.34	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	150	270	7	1.80	Load applied at 1 day of age and increased as required to maintain a specimen at a constant length	Treated with liquid curing compound and air dried indoors
GR-11	(A)	Test Incomplete				Load applied at 1 day of age and increased at rate of ____ psi per day	Moist room
	(B)	80	253	8	3.16	Load applied at 12 hours of age and increased as required to maintain specimen at a constant length	Treated with liquid curing compound and air dried indoors
	(C)	Specimen had Loose Gage Points					

Static Modulus of Elasticity in Tension
$E \times 10^{-6}$ in lb./in.^{2}
(Secant Modulus Determined at ½ the Ultimate Stress)

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	2.79	3.63	3.66	4.19	3.80
	Compound**			3.33	4.35	3.26
AU-2	Moist	----	2.10	2.98	----	3.81
	Compound			3.27	----	2.97
AU-3	Moist	2.32	3.27	2.17	2.67	2.77
	Compound				2.91	2.81
AU-4	Moist	1.83	2.93	3.83	3.49	3.90
	Compound			3.66	3.56	4.31
AU-5	Moist	1.02	1.84	3.82	4.45	4.49
	Compound			2.67	3.25	3.39
AU-6	Moist	1.73	2.99	3.38	4.55	4.75
	Compound			2.83	3.94	4.87
AU-7	Moist	3.54	3.90	4.08	4.76	5.05
	Compound			3.44	5.03	5.00
AU-8	Moist	2.24	2.67	2.68	4.13	3.71
	Compound			2.83	3.57	2.93
AU-9	Moist	2.26	2.98	3.85	4.25	4.71
	Compound			3.60	4.16	4.65
AU-10	Moist	1.26	1.92	3.91	4.69	4.96
	Compound			2.88	3.66	3.83
GR-1	Moist	2.85	4.61	4.80	5.71	5.59
	Compound			4.91	5.00	5.76
GR-2	Moist	2.08	3.73	5.22	4.93	5.50
	Compound			4.17	4.29	5.69
GR-3	Moist	2.50	3.11	3.31	3.15	4.86
	Compound			3.96	3.29	3.98
GR-4	Moist	3.97	4.91	5.02	5.42	5.88
	Compound			5.28	5.49	6.07
GR-5	Moist	1.17	4.40	----	5.96	6.55
	Compound			----	4.50	4.83
GR-6	Moist	----	4.20	4.33	6.15	6.73
	Compound			2.33	5.67	5.65
GR-7	Moist	1.42	----	5.52	5.98	7.08
	Compound			3.49	6.09	6.18
GR-8	Moist	4.07	4.28	5.99	5.16	6.29
	Compound			4.79	4.11	4.43
GR-9	Moist	2.83	4.06	4.66	5.23	5.49
	Compound			4.21	5.01	3.93
GR-10	Moist	1.97	2.65	4.12	5.71	5.95
	Compound			3.82	----	5.01
GR-11	Moist				4.53	4.98
	Polyethylene	3.47	----	5.70	6.13	4.91

* Continuous Moist Room Curing
** Moist Cured 1 Day, Treated with Liquid Membrane Curing Compound and Air Dried Indoors

Static Modulus of Elasticity in Tension
$E \times 10^{-6}$ in lb./in.^{2}
(Secant Modulus Determined by Ratio of Ultimate Stress to Ultimate Strain)

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	1.51	3.19	3.16	3.66	3.68
	Compound**			3.60	3.53	3.23
AU-2	Moist	----	2.02	2.45	----	2.85
	Compound			2.79	----	2.71
AU-3	Moist	1.61	1.72	2.02	2.70	2.76
	Compound				2.62	2.70
AU-4	Moist	1.81	2.77	2.96	3.18	3.50
	Compound			3.03	3.37	3.69
AU-5	Moist	0.88	2.07	2.96	4.55	4.28
	Compound			2.62	3.25	3.07
AU-6	Moist	1.46	2.91	2.91	4.04	4.46
	Compound			2.85	3.75	4.14
AU-7	Moist	2.12	3.22	2.91	4.08	3.59
	Compound			2.84	3.96	4.16
AU-8	Moist	1.89	2.53	2.65	4.37	3.20
	Compound			2.76	3.25	2.99
AU-9	Moist	1.70	3.06	3.39	4.08	3.94
	Compound			3.20	3.80	3.43
AU-10	Moist	1.08	1.77	3.54	4.30	4.47
	Compound			2.82	3.31	3.22
GR-1	Moist	2.50	3.92	4.31	4.52	5.09
	Compound			4.51	4.95	4.47
GR-2	Moist	1.85	3.21	4.19	4.78	5.39
	Compound			4.09	4.36	4.45
GR-3	Moist	1.61	2.89	3.04	3.27	4.56
	Compound			3.44	3.32	3.33
GR-4	Moist	3.29	4.48	5.33	4.93	5.23
	Compound			4.87	4.71	5.13
GR-5	Moist	1.74	4.43	----	6.98	5.16
	Compound			----	4.17	4.60
GR-6	Moist	----	3.24	4.34	6.15	6.98
	Compound			2.46	4.66	4.42
GR-7	Moist	2.08	4.40	5.11	5.98	5.75
	Compound			3.92	4.24	5.28
GR-8	Moist	3.63	4.68	4.65	5.42	5.98
	Compound			4.57	4.57	3.41
GR-9	Moist	2.73	4.70	5.91	4.81	5.00
	Compound			4.39	4.39	5.66
GR-10	Moist	1.80	4.41	5.08	5.32	4.75
	Compound			4.10	----	3.79
GR-11	Moist				4.53	4.66
	Polyethylene	2.70	2.62	5.43	6.79	5.00

* Continuous Moist Room Curing

** Moist Cured 1 Day, Treated with Liquid Membrane Curing Compound and Air Dried Indoors

Static Modulus of Elasticity in Compression
$E \times 10^{-6}$ in lb./in.^{2}
(Secant Modulus Determined at 1000 psi Stress)

Batch Designation	Curing	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	2.24	3.06	3.32	4.45
	Compound**		2.67	3.36	3.39
	Dry***				3.49
AU-2	Moist	2.75	3.78		3.33
	Compound		3.01		3.35
	Dry				3.33
AU-3	Moist	1.78	2.25	2.78	2.77
	Compound		1.96	2.60	3.09
	Dry				2.78
AU-4	Moist	3.14	3.50	4.00	4.15
	Compound		3.49	3.95	4.41
	Dry				4.29
GR-1	Moist	4.11	4.76	5.66	6.38
	Compound		4.51	4.95	5.88
	Dry				5.99
GR-2	Moist	4.76	4.48	4.99	5.83
	Compound		4.27	4.94	5.87
	Dry				5.87
GR-3	Moist	2.96	3.63	4.65	4.77
	Compound		3.74	4.04	4.31
	Dry				4.58
GR-4	Moist	4.85	5.75	6.02	6.31
	Compound		5.74	6.27	6.57
	Dry				6.41

* Continuous Moist Room Curing

** Moist Cured 1 Day, Treated with Liquid Membrane Curing Compound, and Air Dried Indoors

*** Moist Cured 7 Days, Air Dried Indoors

Dynamic Modulus of Rigidity in Torsion
$G \times 10^{-6}$ in lb./in.^{2}
ASTM Method C 215-55T

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	0.76	1.15	1.40	1.60	1.70
	Compound**			1.45	1.57	1.61
	Dry***					1.68
AU-2	Moist	0.61	1.06	1.28	1.50	1.62
	Compound			1.26	1.44	1.48
	Dry					1.57
AU-3	Moist	0.58	0.88	1.11	1.37	1.41
	Compound			1.08	1.30	1.40
	Dry					1.42
AU-4	Moist	0.84	1.37	1.53	1.82	1.88
	Compound			1.57	1.76	1.87
	Dry					1.88
AU-5	Moist	0.36	0.55	1.13	1.61	1.72
	Compound			1.15	1.54	1.61
AU-6	Moist	0.58	1.06	1.51	1.81	1.96
	Compound			1.57	1.31	1.88
AU-7	Moist	0.83	1.28	1.64	1.94	1.95
	Compound			1.61	1.80	1.84
AU-8	Moist	0.96	1.28	1.52	1.76	1.91
	Compound			1.42	1.71	1.71
AU-9	Moist	0.74	1.23	1.58	1.84	2.01
	Compound			1.59	1.80	1.80
AU-10	Moist	0.55	1.06	1.62	1.86	2.00
	Compound			1.52	1.81	1.75
GR-1	Moist	1.12	1.78	2.09	2.58	2.72
	Compound			2.03	2.30	2.36
	Dry					2.56
GR-2	Moist	0.98	1.66	1.96	2.37	2.43
	Compound			1.97	2.26	2.31
	Dry					2.41
GR-2	Moist	0.91	1.41	1.71	2.15	2.05
	Compound			1.70	1.88	1.86
	Dry					2.00
GR-4	Moist	1.24	2.02	2.47	2.75	2.75
	Compound			2.40	2.68	2.59
	Dry					2.76
GR-5	Moist	0.63	1.20	1.84	2.42	2.50
	Compound			1.78	2.24	2.56
GR-6	Moist	----	1.54	2.09	2.55	2.80
	Compound			1.93	2.27	2.10
GR-7	Moist	1.11	1.93	2.37	2.66	2.88
	Compound			2.19	2.46	2.32
GR-8	Moist	1.75	1.98	2.38	2.65	2.92
	Compound			2.43	2.37	2.35
GR-9	Moist	1.70	2.12	2.43	2.70	2.77
	Compound			2.34	2.52	2.48
GR-10	Moist	1.04	1.70	2.31	2.68	2.78
	Compound			2.21	2.50	2.42
GR-11	Moist				2.74	2.64
	Polyethylene	2.32	2.45	2.64	2.79	2.88

*Continuous Moist Room Curing
**Moist Cured 1 Day, treated with Liquid Membrane Curing Compound & Air Dried Indoors
***Moist Cured 7 Days, Air Dried Indoors

Dynamic Poisson's Ratio
ASTM Method C 215-55T

Batch Designation	Curing	12 Hours	1 Day	2 Day	7 Day	28 Day
AU-1	Moist*	.25	.24	.27	.25	.25
	Compound**			.25	.22	.21
	Dry***					.20
AU-2	Moist	.30	.26	.26	.25	.24
	Compound			.25	.22	.21
	Dry					.22
AU-3	Moist	.35	.27	.28	.26	.23
	Compound			.28	.18	.21
	Dry					.21
AU-4	Moist	.33	.28	.28	.25	.24
	Compound			.24	.25	.20
	Dry					.22
AU-5	Moist	.24	.28	.33	.29	.26
	Compound			.27	.27	.20
AU-6	Moist	.31	.29	.28	.26	.27
	Compound			.30	.22	.22
AU-7	Moist	.24	.23	.26	.26	.27
	Compound			.24	.22	.22
AU-8	Moist	.31	.27	.26	.26	.27
	Compound			.25	.24	.21
AU-9	Moist	.36	.26	.26	.27	.24
	Compound			.25	.23	.19
AU-10	Moist	.29	.27	.26	.24	.28
	Compound			.24	.20	.20
GR-1	Moist	.27	.19	.21	.20	.20
	Compound			.19	.18	.15
	Dry					.15
GR-2	Moist	.26	.20	.20	.18	.20
	Compound			.20	.15	.16
	Dry					.16
GR-3	Moist	.23	.19	.17	.19	.19
	Compound			.19	.16	.17
	Dry					.18
GR-4	Moist	.26	.18	.18	.19	.23
	Compound			.20	.18	.18
	Dry					.18
GR-5	Moist	.27	.23	.21	.21	.22
	Compound			.17	.20	.17
GR-6	Moist	---	.18	.19	.30	.23
	Compound			.19	---	.20
GR-7	Moist	.24	.22	.23	.22	.25
	Compound			.19	.11	.16
GR-8	Moist	.19	.21	.22	.21	.21
	Compound			.19	.19	.19
GR-9	Moist	.22	.17	.22	.22	.22
	Compound			.20	.19	.20
GR-10	Moist	.23	.20	.20	.22	.22
	Compound			.20	.21	.18
GR-11	Moist				.19	.18
	Polyethylene	.20	.19	.20	.21	.18

*Continuous Moist Room Curing

**Moist Cured 1 Day, Treated with Liquid Membrane Curing Compound and Air Dried Indoors

***Moist Cured 7 Days, Air Dried Indoors