NATIONAL BUREAU OF STANDARDS REPORT

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SOME PROPERTIES OF LIGHTWEIGHT AGGREGATE CONCRETES CONTAINING ENTRAINED AIR IN PLACE OF FINE AGGREGATE

by

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and
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Report to
U. S. Naval Civil Engineering
Research and Evaluation Laboratory
Department of the Navy

NBS

U. S. DEPARTMENT OF COMMERCE
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NATIONAL BUREAU OF STANDARDS

Contents

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Abstract

Lightweight concretes were prepared in which the fine aggregate was replaced entirely by entrained air, or consisted of a siliceous sand and the coarse aggregates were pumices, expanded shales, an expanded slag, and a siliceous pea gravel. The concretes contained from 20 to 35 percent of entrained air, calcium chloride, and 5 to 6 bags of high-early-strength or normal portland cement per cu yd. Air-entraining (foaming) agents used were a proprietary resin widely used in structural concrete, a wetting-dispersing agent used in precast lightweight units, and a hydrolyzed protein foaming agent used in combating gasoline fires. Air entrained in concrete by means of the resin was the most stable to handling.

All no-fines mixes were analyzed by washing a sample of freshly mixed concrete over a sieve. Water-cement ratios of almost all of the mixes were in the range 0.4 to 0.5 by weight. Concretes containing high-early-strength cement and calcium chloride attained 53 to 57 percent of their 28-day compressive strengths in 24 hr; the 28-day compressive strength was more dependent upon the air content than upon aggregate type. Moduli of rupture (28-days) ranged from 1/3 to 1/5 of the compressive strengths in the range of 150 to 1500 psi compressive strength. The ratio of bond strength to compressive strength ranged from 1/2 to 1/4 in the same range of compressive strength. Static and dynamic moduli of elasticity showed good correlation but correlations between compressive strengths and moduli of elasticity were found only in concretes containing similar types of aggregates.

The absorption was lower and the shrinkage of these concretes was no higher than for concretes made previously with both coarse and fine lightweight aggregate; "saturation coefficients" were low - 0.2 to 0.4 - and resistance to freezing and thawing was better than for sand-gravel concrete without entrained air; otherwise, the resistance to freezing and thawing was lowest in mixes containing more than 30 percent of entrained air. The rise of water due to capillarity was generally less than one inch in 7 days.

The thermal conductivity was closely dependent upon density.

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1. INTRODUCTION

This work was initiated for the purpose of investigating the properties of lightweight aggregate concretes that might be used as the core materials in precast dense- and lightweight-concrete composite panels for wall and roof construction in small buildings. The investigation had the following more specific purposes:

1. The design and testing of concretes containing coarse lightweight aggregates, 20 to 35 percent of entrained air, and no-fine lightweight aggregate.

2. Comparison of the use of hydrolyzed protein type foaming agents used in combating fires with air-entraining agents more commonly used in concrete.

3. The acceleration of strength development to the maximum degree possible without applying heat and without adversely affecting the workability of the freshly-mixed material.

An earlier study (1)[1/] had shown that the fine aggregate could be replaced entirely by entrained air in mixtures made with portland cement and uniform-size gravel without adversely affecting workability or shrinkage, and with marked improvement in resistance to laboratory freezing and thawing, reduced capillary rise of water, and lowered thermal conductivity.

1/ Numerals in parentheses denote references listed at the end of this report.

The strength and elasticity were lowered markedly. It appeared that this type of mixture might be profitably investigated if coarse lightweight aggregate were used. Carlson (2) had shown in 1938 that, for mixtures having a constant water-cement ratio and made with uniform-size dense aggregate, the shrinkage was greatest in the mixes containing the smallest aggregate and least in those containing the largest aggregate. In this series of tests the shrinkage was more than 40 percent lower for a mixture with 3/8 to 3/4-in. aggregate than it was for one with the same volume of aggregate in the U. S. sieve size range No. 30 to No. 50 (0.012 to 0.023 in.). Further reasons for eliminating the fine lightweight aggregate lay in certain characteristics wherein these aggregates differ from dense aggregates: first, in the disproportionately high percentage of dust present in the fine lightweight aggregates, and second, in the fact that the bulk specific gravity of the lightweight aggregates increases as the particle size decreases with the specific gravity of the finest fractions and dust being well over two for some pumices while that for the coarser pumice fractions may be about one. It is seen that the finest fractions may contribute little toward lowering the density of a concrete mix and the presence of dust of relatively high specific surface may require an unduly high proportion of mixing water.2/

A final reason for eliminating the fine aggregate was related entirely to the technology of lightweight aggregate concrete: it made it highly convenient and desirable to analyze the fresh concrete by washing the aerated cement paste through a screen so that, for each batch, a comparison could be made between the design proportions, based on batch weights and specific gravities, and the results of an analysis which included an absorption determination for the aggregate.

The high and variable absorptions for some of the aggregates had accounted for large uncertainties in water-cement ratio, cement factor and air content in previous investigations. Since entrained air is usually one of the ingredients in the more conventional lightweight aggregate concretes, the present investigation afforded an opportunity to attempt to measure and control this variable more closely.

2/ Since the study was initiated it has appeared that a beneficial effect might accrue from the presence of lightweight aggregate dust in concrete. Expanded shale and expanded slate dusts appear to be "pozzolanic," i.e., to react with the free lime liberated during the hydration of portland cement. There is reason to expect that pumice and expanded slag dusts as well might be highly pozzolanic.

2. SCOPE OF THE INVESTIGATION

The coarse lightweight aggregates chosen for study were California pumice, New Mexico pumice, expanded shale (Haydite), sintered shale (Lelite), and expanded slag (Waylite). An additional pumice (from Santorin, Greece) and an additional expanded shale, Rocklite, were used in a relatively small number of batches; a few batches were made with a siliceous pea gravel from White Marsh, Md. A siliceous sand from the same source was used with a number of the coarse lightweight aggregates.

The coarse aggregates were used as supplied by the producer in most cases. Concretes were made with several different percentages of entrained air in the range 20 to 35 percent with most of the aggregates and a high early-strength cement; additional mixes were made with similar percentages of entrained air, using a normal portland cement. Calcium chloride was used as an accelerator of strength development in all mixes and three different types of air-entraining agents were used with most mixes. The slump requirement was set at 5 ± 2 inches.

The proportions of cement to saturated, surface-dry aggregate, by absolute volume, were approximately 1 to 5 except for a few of the mixes.

Tests performed were as follows:

<u>Proportions and density of plastic and hardened concrete</u>

(a) Density of plastic concrete,
(b) Slump,
(c) Air content-estimate of stability of entrained air,
(d) Analysis of plastic concrete-cement factor,
(e) Absorption of aggregate from analysis,
(f) Calculation of proportions from batch weights and specific gravities of ingredients,
(g) Density and calculated air content of all specimens.

<u>Strength</u>

(a) Compressive strength (1, 7, and 28 days) of 6- by 12-in. cylinders,
(b) Modulus of rupture (7 and 28 days) of 3- by 4- by 16-in. prisms,
(c) Bond strength and bond stress-slip relationships of 6- by 6- by 12-in. horizontally-cast pull-out specimens with 7/8-in. round, deformed reinforcing bars.

Elasticity

(a) Stress-strain relationships and secant moduli of elasticity for 28-day compressive strength cylinders,
(b) Dynamic (resonance) moduli of elasticity (longitudinal and flexural), and rigidity (torsional) and Poisson's ratio of 6- by 12-in. cylinders and 3- by 4- by 16-in. prisms at age of 28 days.

Moisture characteristics

(a) Absorption (24 hr, 73 F and 5-hr boil) and saturation coefficient of broken halves of modulus of rupture prisms,
(b) Capillary rise of water in broken halves of modulus of rupture prisms,
(c) Shrinkage of 2- by 2- by 12-in. prisms due to drying at 73 F, 50 percent relative humidity for 180 days,
(d) Resistance to freezing and thawing, change in dynamic moduli, and durability factor of 3- by 4- by 16-in. prisms.

Thermal conductivity

Guarded hot plate test of 1- by 8- by 8-in. plates.

3. MATERIALS, MIXING, AND FABRICATION

3.1 Cements, Aggregates, Foaming Agents and Accelerators

A high-early-strength cement and a normal portland cement meeting the requirements of Federal Specification for portland cement, SS-C-192 (Type III and Type I, respectively) were used. These cements were obtained from a local supplier and had been manufactured at Union Bridge, Md.

Lightweight aggregates were used in intermediate or coarse gradations only; these were expanded shale (Haydite) from St. Louis, Missouri; sintered shale (blend of Lelite "coarse" and "intermediate" gradations); foamed slag (Waylite) from Bethlehem, Pennsylvania; New Mexico pumice, and California pumice. A small number of mixes was made with an additional expanded shale (Rocklite) from Ventura, California, and a single mix was made with pumice from Santorin, Greece. Dense aggregate used consisted of a siliceous pea gravel (nominally No. 4 to 3/8 in.), and a siliceous sand from White Marsh, Md.

On the basis of previous work (1) and additional study preliminary to the present investigation, three air-entraining, or, as they shall be termed here, "foaming" agents were used. These were chosen from a group of over 20 agents of various types, most of which were wetting agents or detergents, which were used in small, hand-mixed and machine-mixed batches. The selection was based upon the apparent stability and "controllability" of the proportion of entrained air. The agents chosen were of differing types:

1. Agent "V" a proprietary neutralized resin widely used in pavement concrete, prepared for use as a 5 percent aqueous solution.

2. Agent "M", a foaming agent used in combating gasoline fires; this agent was a hydrolyzed degenerated waste protein derivative of fish scales and cattle hooves.

3. Agent "F", which consisted essentially of a sodium salt of an alkylnaphthalene sulfonic acid. This agent could be classed as a wetting agent; it has received some use in "foamed", lightweight concrete products and in fire protection.

The apparently high stability of agent "M" in preliminary tests, and the successful use of a similar agent (a hydrolyzed keratin) in producing cellular concretes in Great Britain (3) indicated that this type of agent, not previously used in concrete in this country, should be rather thoroughly examined.

Inasmuch as low-strength concretes cannot usually be removed from forms at a very early age and since "precast" concrete sometimes requires handling at very early ages, an accelerator was required. Strength accelerators used in small preliminary batches were commercial flake calcium chloride; a mixture of chlorides of calcium, aluminum, barium, iron, and sodium (of which calcium chloride constituted 70 percent of the mixture by weight); triethanolamine; triethylamine; sodium hydroxide; and high-alumina cement. While some of these agents produced marked acceleration of initial set, calcium chloride and the salt mixture appeared to be the most effective in accelerating the development of 24-hr strength when used with high-early-strength cement. Calcium chloride was as effective as the salt mixture and more economical and easier to use. The other agents, when used in amounts producing a notable effect, generally produced premature stiffening. Therefore, calcium chloride was used in all mixes in the amount of 2 percent, by weight of cement.

3.2 Preparation and Proportioning of Aggregates

In view of some uncertainties in the proportions of lightweight aggregate concretes in previous investigations the batching was done on a dry basis. The dry weight of a given type of aggregate was held constant for a series of batches; the dry weight of aggregate was chosen as the amount which would provide a ratio of 1 part of cement to 5 parts of aggregate, by absolute volume. Since the extended soaking periods to which lightweight aggregate had been subjected in earlier work almost never obtain in practice, it was decided to store the aggregate[3/], prior to mixing, for 4 to 5 hr in a covered container with all of the estimated water of absorption and about 75 percent of the gaging water. The aggregate was periodically agitated to give the water access to all of the aggregate in the container. The values used for specific gravity and absorption of the aggregate were not those obtained by the A.S.T.M. method, which are listed in Table 1. Values for specific gravity were obtained in preliminary tests of aggregate by water displacement of a known dry weight of material after 4-hr immersion in a 2 liter graduate. As will be shown later, the absorption values used were those of aggregate reclaimed from the density sample of concrete 4 to 5 hr after the beginning of the soaking period and were generally appreciably smaller than the corresponding values obtained by the A.S.T.M. methods. The differences were of such magnitude that considerable errors would arise in the calculation of proportions and water-cement ratios for concretes containing aggregates soaked for only 4 hr, if the higher A.S.T.M. 48-hr values were used.

3.3 Mixing Procedure; Slump and Density Measurements

The mixing was done in a tilt-drum mixer of 3 cu ft capacity. The weights of ingredients were chosen to provide approximately 2 cu ft of concrete having an approximate cement factor of 5 to 6 bags per cu yd when the air content was in the desired range of 20 to 35 percent. The mixer was not prepared with priming batches since successively mixed batches might differ widely in air content. The walls of the mixer were moist prior to mixing. The wet aggregate together with the water in which it had been stored for about 4 hr (estimated water of absorption and 3/4 of gaging water) were introduced to the mixer first, followed by the calcium chloride dissolved in

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3/. The moisture in the aggregate prior to weighing was determined by means of a "fry-test" and the batch weight corrected for this moisture, usually a very small amount.

water. Mixing was begun and the cement was added while the mixer was rotating. Water was then added until all of the aggregate particles were covered with cement paste. This required about one minute from the time that the cement had been added. The foaming agent was next added 4/ and mixing continued for three minutes. During this time water was added as needed to provide, as judged visually, the desired air content and workability. With experience this could be done reasonably accurately. The mixer was then turned off for a two-minute period and then mixing was resumed for a final two-minute period.

A slump test was made for each batch immediately following mixing; the slump values are tabulated in Table 2. The workability was generally excellent, except for a few mixes in which the slump was three inches or less. Slumps as low as these values were caused by a loss of air from the mix due to the handling and the rodding procedure used in the slump test, and indicated some instability in the entrained air.

Two density determinations were made upon the plastic concrete, the first ("No. 1" in Table 3) simultaneously with the slump determination and the second ("No. 2" in Table 3) 10 minutes later upon material remaining after the fabrication of the test specimens. The density determinations were made in a 0.1 cu ft cylindrical container. The container was filled in two layers and each layer was rodded 25 times in the manner used in fabricating 6- by 12-in. test cylinders. The second layer was struck off flush with the top of the container, and the weight of the sample determined, from which the density, in pounds per cubic foot, was calculated.

3.4 Fabrication of Test Specimens

Specimens were fabricated from mixes estimated to have the desired air contents. Generally, more than one mix was made with each aggregate-cement-foaming agent combination, in order to obtain concretes of more than one air content. It may be seen in Table 2 that variations in air content were obtained by varying the quantity of foaming agent (when all other factors remained the same). Most of the batches were of sufficient size to permit the casting of the following specimens:

4/ One method tried consisted in adding a mixture of calcium chloride, foaming agent, and water together; this resulted in very poor stability of entrained air. This experience has been corroborated by others and the manufacturers of some of the agents caution against the practice.

Three 6- by 12-in. cylinders
One 6- by 6- by 12-in. pull-out
Four 3- by 4- by 16-in. prisms
Two 2- by 2- by 12-in. prisms
Two 1- by 8- by 8-in. plates
One 6- by 12-in. cylinder, designated "x-cylinder"

The specimens were cast in the order listed. For low air contents one of the 3- by 4- by 16-in. prisms or the x-cylinder, or both, were eliminated. The purpose of the x-cylinder, which was generally of lower air content (since it was cast last) than the three other cylinders, was to provide indications of the effect of loss of entrained air upon strength. The 2- by 2- by 12-in. prisms were provided with metal end-inserts to facilitate length change measurements.

In a few cases smaller (half size) batches were made to provide compressive strength cylinders only.

All molds were water-tight. The cylinders were molded in accordance with the method of A.S.T.M. Standard C192-49. Both sizes of prisms and the pull-out specimens were cast with the long axes horizontal, and for the 3- by 4- by 16-in. prism the 4-in. dimension was vertical; the plates were cast with one 8-in. dimension vertical. All specimens (other than the cylinders) were cast in two layers and each layer was rodded and spaded around the edges sufficiently to consolidate the concrete. The rod used was the standard 5/8-in. bullet-nose rod, except in the case of the smaller 2- by 2- by 12-in. prisms and 1- by 8- by 8-in. plates; for these specimens a 1/4-in. rod was used. All specimens were screeded and trowelled smooth immediately after casting, whereupon they were covered with waxed paper until removed from the molds at the age of 20 to 24 hr.

4. AIR CONTENT AND CEMENT FACTOR

4.1 Calculation of Air Content

The air content was calculated gravimetrically, as follows:

$$\text{Percent of entrained air} = (W_c - W_d)/W_c \times 100$$

where W_d is the density determined for the plastic concrete, or from the weights of test specimens, and W_c is the "no-air" density calculated from the batch proportions and the absolute volumes of the batch ingredients. The air contents, determined in this way, are given in two columns of Table 2; the air content for the plastic concrete is the value calculated using the mean weight per cu ft of density samples No. 1 and No. 2; a value for the hardened concrete is also given for each mix and was calculated using the average density of three 6- by 12-in. cylinders when removed from the molds less than 24 hr after mixing. It was assumed that means taken to seal and cover the molds prevented the escape of water from the concretes during the initial 24-hr period. Table 3 gives information in detail on the density and calculated air content obtained from the No. 1 and No. 2 density determinations for the plastic concrete, and for all of the specimens of various dimensions on the basis of their 24-hr weights. In figure 1, the densities of the 6- by 12-in. cylinders when removed from the molds are plotted against the air contents calculated from those densities. Considering only a single type of aggregate at a time, it is seen that there was a linear relationship between air content and density in the range of 20 to 35 percent of entrained air. Among the mixes without fine aggregate, the pumices are grouped together near the bottom of the graph and the gravel mixes are, naturally, at the other extreme. At a given air content, the Waylite mixes were lighter, and the Lelite and Rocklite mixes heavier, than the Haydite mixes. The slopes of the linear relationships increased with density. Replacing 25 percent of the volume of the lightweight aggregate by sand naturally increased the density. The New Mexico pumice mixes with sand were almost as heavy as the no-fines Haydite mixes of the same air content.

4.2 Stability of Entrained Air

Table 3 reveals a decrease in air content and a corresponding increase in density during the 10-min period between determination No. 1 and No. 2. The mean of these two values, considered as an average air content of the plastic concrete, generally agreed well with the values calculated for the 6- by 12-in. cylinders. However, among the various types of specimens, the air content decreased significantly (and the density increased) as the specimen size became smaller. The small shrinkage prisms (2- by 2- by 12-in.) and conductivity plates (1- by 8- by 8-in.) generally showed the lowest air contents and the highest densities. The information contained in Table 3 then indicates, if comparisons are made, the relative stability of the entrained air to handling, i.e., scooping, rodding, spading, etc. An important attribute of virtually all of these concretes was that, despite the fact that they were trowel-finished immediately after casting, there was generally no further loss of air after finishing, i.e., the top surfaces did not subside or "sag." The loss of air, it is believed, would be far less serious than the degree of loss indicated in Table 3 if these concretes were to be used in construction since the size of the members would undoubtedly be larger than the sizes of some of these specimens and the amount of handling would be far smaller. From Table 3 the relative instability of the entrained air may be judged in three ways: (a) The magnitude of the difference between the air contents for plastic concrete samples No. 1 and No. 2; (b) The magnitude of the differences in air contents among the various specimens of different sizes; (c) The magnitude of the difference between the air contents of the 6- by 12-in. cylinders and the single "X" 6- by 12-in. cylinder cast after all other specimens were cast (when sufficient concrete remained).

Comparisons of air contents of the specimens of various sizes cast from selected individual mixes of comparable air contents, expressed as a percentage of the No. 1 air content of the plastic concrete, are indicated as follows:

Aggregate	Foam-ing agent	Type of cement	Air content as percent of No. 1 air content				
			cylinder	pull-out	r-prism	s-prism	conductivity plate
Pumice N	M	III	94	88	86	73	--
Haydite	M	III	90	84	84	71	64
Lelite	M	III	80	68	68	65	61
Gravel	M	III	90	83	85	78	--
Mean			88	81	81	72	63
Pumice N	F	III	83	82	69	62	62
Haydite	F	III	93	87	88	78	73
Lelite	F	III	82	81	73	70	63
Gravel	F	III	92	--	78	79	--
Mean			88	83	77	72	66
Pumice N	V	III	99	97	95	92	94
Haydite	V	III	95	92	89	92	82
Lelite	V	III	82	77	79	78	73
Gravel	V	III	100	--	96	96	--
Mean			94	87	90	90	83

Although the usual "rodding" and "spading" techniques were the only methods of consolidation here employed, later experience has indicated that placement by vibration might result in lower losses of entrained air. Agent "V", the proprietary neutralized resin widely used for air-entrainment in concrete, generally provided the most stable air entrainment. Agents "M" and "F" provided air entrainment of about the same stability but of significantly lower stability than that provided by agent "V". Agent "F" could not provide a satisfactorily pre-controlled air content when used with certain aggregates, particularly Waylite, with which no useful air content could be obtained. Agent "M" was less stable with Waylite than with other aggregates; agents of the type represented by "M" are unstable in the presence of wetting agents; upon investigation it was found that water in which Waylite had been soaked had some sulfonate or sulfate characteristics, probably due to sulfur compounds present in the original slag from which the Waylite was produced.

Instability of entrained air is not necessarily a serious fault; if the air voids retain a spherical shape and if the degree of loss is fairly constant from one batch to the next, corrections may be made by simply designing for that degree of loss. If, however, the instability results in a change in shape of the ideal spherical air bubble to one that is flattened, i.e. ovoid, then the strength properties will be affected. If the spherical voids decrease in vertical dimensions and increase in horizontal dimensions, the strength in the vertical direction will be decreased because of a diminution in the mean size of the inter-void columns of solid material comprising the concrete.

Much is yet to be learned in the use of hydrolyzed protein foaming agents. These agents do not behave, in a concrete mixer, in the same way that better known air-entraining agents behave. The amounts used, it is now known, should be a function of the water content of a mix, since there is an optimum concentration of foaming solution (foaming agent/water) that will produce the most stable foam. These agents were superior in stability to all others in preliminary tests in which neat pastes were subjected to rapid beating in a Hobart kitchen-type mixer; air contents in these pastes were in the range of 45 to 70 percent.5/

5/ An alternative method, not available at the NBS at the time of this study, has since shown that the amount of foaming agent required in mixes without aggregate may be reduced 70 to 85 percent without sacrifice of stability. This method consists in generating foam from water, foaming agent, and compressed air, and injecting the foam into a pre-mixed

4.3 Analyses of Concretes; Cement Factor

The value used for the specific gravity of the cements in calculating absolute volumes was 3.20. The values for the bulk specific gravities of the aggregates were determined by the displacement of water after soaking for 4 to 5 hr. These values appear in Table 1 in the column following that giving the values determined according to A.S.T.M. Method C128-42 (modified for lightweight aggregate). Comparing the two sets of values for specific gravity, it is seen that in most cases the 4-hr value used is lower than that provided by the A.S.T.M. method, which requires a much longer soaking period of 48 hr. The differences appear to be due to the appreciably lower absorption values (also given in Table 1) after 4 to 5 hr of soaking. These values are listed as the absorption values determined "from analyses" in Table 1.

Each of the absorption values listed is a mean for several determinations; a determination was made for each mix. 6/ These absorption determinations were made upon the aggregate retained on a No. 8 screen after washing the No. 1 concrete density sample upon the screen. The aggregate was dried to the "saturated, surface-dry" condition, weighed, oven-dried at 220 F for 24 hr, and weighed again. The loss in weight upon oven-drying was divided by the oven-dry weight to give the absorption value. The mean values in Table 1 represent as many as 8 or 9 separate determinations (in the cases of Pumice NM and Haydite). Individual values were generally within ± 2 percent of the listed mean values, even in the case of the relatively high absorption values for the pumices. The individual values were used in calculating the weights of saturated, surface-dry aggregate and the net water content from the batch weights of dry aggregate and water used in each mix. 7/

5/cont. slurry in a horizontal paddle-type (plaster) mixer. The foam remains stable upon blending with the slurry. It is possible that this method could be successfully employed with lightweight aggregate concretes for air contents in the range of 20 to 35 percent (cement paste air contents in the range of 40 to 70 percent).

6/For mixes that contained sand no analysis was made. Absorption values used for the lightweight aggregate were the average values obtained from analyses of the "no-fines" mixes, which are given in Table 1.

7/Naturally, this could be done only after the absorption determination had been completed, which was more than 24 hr after mixing. As explained previously, the aggregate was batched dry in amounts estimated to provide the desired weight of saturated, surface-dry aggregate.

The determination of the weight of saturated, surface-dry aggregate retained on the No. 8 screen after washing density sample No. 1 upon that screen permitted an analysis to be made of the concrete. First, a correction for loss of aggregate through the screen had to be applied. The amount passing the No. 8 sieve, as determined in the conventional sieve analysis (Table 1), was not used, but instead, a mean value was obtained by washing at least two samples of each aggregate upon the same screen used for washing the concrete samples. These mean values appear in Table 1 as "Percent washed through No. 8." These values are generally appreciably lower than the corresponding values from the sieve analyses, due probably, to the much gentler sieving of the washing procedure. The determination of the cement factor from the analysis of the density sample (with the understanding that, for a 0.1 cu ft sample, all weights apply to one cu ft when multiplied by 10) was as follows:

(a)	Weight of sample	=	weight per cu ft of concrete
(b)	Corrected weight of s.s.d. aggregate retained on No. 8 screen after washing sample	=	weight of s.s.d. aggregate per cu ft of concrete
(c)	(a) - (b)	=	weight of cement paste per cu ft of concrete
(d)	$(c)/(W/C + 1) = \frac{c}{W/C + 1}$	=	weight of cement per cu ft of concrete
	W/C	=	water-cement weight ratio
(e)	(d) x (27/94)	=	cement factor, bags per cu yd of concrete

The cement factor as calculated in (e), above, may be made applicable to any density value subsequently determined (as, for example, that for the 6-by 12-in. test cylinders) by multiplying the cement factor by the subsequently determined density and dividing by the No. 1 density value, (the density of the sample analyzed). The cement factor values calculated in this way are listed in Table 2 under the column headed "cement factor, from analysis." These values and companion values, also listed, calculated in the usual way from batch weights, are based upon the density values calculated from the weights of 6- by 12-in. test cylinders upon removal from the molds prior to the age of 24 hr.

4.4 Other Proportions

The nominal proportions are given in Table 2 as "Parts of aggregate to one part of Portland cement" (by absolute volumes). These proportions are based upon the volume of cement and the calculated volume of saturated, surface-dry aggregate present in the mixer at the end of the mixing period. The proportions would be changed slightly in many cases if based upon analyses since the cement factor calculated from analysis was usually appreciably lower than that based on batch weights, due to the loss, by adhesion to the mixer walls, of a greater proportion of cement paste than of aggregate. The quantity of entrained air, recalculated on the basis of the analysis, would also be changed slightly in a number of cases, due to the fact that the calculated "no-air" weight, based on the proportions determined from analysis, was different from the value calculated from batch weights. In 90 percent of the mixes the difference between air contents calculated both ways did not exceed one percent, and in only one mix did the difference exceed two percent.

Analyses were not performed for mixes in which fine aggregate (siliceous sand) was used; therefore, cement factor values calculated in the usual way are the only ones listed for these mixes in Table 2.

5. CURING AND SCHEDULE OF TESTS OF SPECIMENS

The curing and testing of the specimens were performed at 73 F and uncontrolled humidity (except where noted) according to the following schedule:

Type of specimens[a]	Days in molds	Days moist cured	Days in water	Days in air	Age (days) when tested	Number of speci-mens tested [b]
cylinders, 6- by 12-in.	1	6	--	21[d]	1,7,28	1
x-cylinder, 6- by 12-in. (compressive strength)	1	6	--	21	28	1
r-prisms, 3- by 4- by 16-in. (modulus of rupture)	1	6	--	21[d]	7,28	1
r-prisms, 3- by 4- by 16-in. (freezing and thawing)	1	6	3[c]	42[e]	50	1 or 2
pull-out, 6- by 6- by 12-in. (bond strength, slip)	1	6	--	21	28	1
s-prisms, 2- by 2- by 12-in. (drying shrinkage)	1	--	6	180[f]	7 to 187	2
plates, 1- by 8- by 8-in. (thermal conductivity)	1	6	--	30	40[g]	1

a/ Absorption and capillarity test specimens were the broken halves of modulus of rupture prisms and were subjected to oven-drying at 220 F for 48 hr prior to testing at ages exceeding 50 days.
b/ From each mix, at each age.
c/ After drying period.
d/ For specimens tested at 28 days only.
e/ Average length of drying period (± 14 days).
f/ Relative humidity 50 ± 5%.
g/ Oven-dried at 220 F for 48 hr prior to testing.

6. DESCRIPTION OF TESTS AND DISCUSSION OF TEST RESULTS

6.1 Compressive Strength

The 6- by 12-in. cylinders were capped with a high-strength, rapid-hardening plaster of paris preparatory to testing for compressive strength. Of the three cylinders cast from each batch immediately after mixing, one was tested at the age of 24 hr, one at 7 days, and one at 28 days. The x-cylinder, cast from the concrete remaining from each batch after all other specimens had been cast, was tested at the age of 28 days.[8] The cylinders were tested by loading at a rate of 500 psi per min in a hydraulic testing machine. Compressive strengths at 1, 7, 28 days are listed in Table 4, and are plotted against air content in figures 2a, 2b, and 2c.

The mean compressive strengths, expressed as percentages of the mean 28-day strengths, are summarized in the following Table:

8/ Static and dynamic elasticity properties were also determined for the 28-day cylinders in the course of, or prior to, testing for compressive strength. For descriptions of these tests, see sections 6.4.1 and 6.4.2.

Aggregate	Cement	Number of mixes	Percent of 28-day strength at age indicated		
			Compressive strength		Modulus of rupture
			1 day	7 days	7 days
Pumice	III	8	57	105	117
Haydite) Rocklite) Lelite) Waylite)	III	15	53	90	109
Gravel	III	3	55	123	104
Pumice, sand	III	7	54	85	100
Haydite) Rocklite) sand	III	4	55	92	103
Gravel, sand	III	2	69	97	114
Pumice	I	6	35	92	79
Haydite) Waylite)	I	2	31	78	100
Gravel	I	1	39	85	100
Gravel	I	1	--	88	--

(The modulus of rupture data in the Table will be discussed in section 6.2). It may be seen that the summarized data for the concretes (all of which contained calcium chloride) are divided, for convenience, into three aggregate groups: all of the pumices are in one group, Haydite, Rocklite, Waylite, and Lelite are in another group, and siliceous coarse aggregate is in the third group. Each of the aggregate groups is further divided into three groups: concretes containing high-early-strength (Type III) cement and no-fine aggregate are in one group, those containing high-early-strength cement and sand are in another group, and those containing normal portland (Type I) cement and no-fine aggregate are in a third group for each aggregate type. For a total of 37 mixes made with high-early-strength cement (Type III) the one-day compressive strength was a remarkably constant percentage of the 28-day strength - 53 to 57 percent on a group basis. Only for the sand-gravel mixes was the one-day percentage notably different among the high-early-strength cement mixes. The 7-day strength ranged from 85 percent, for the pumice-sand mixes, to 123 percent of the 28-day strength, for the no-fines gravel mixes when high-early-strength cement was used. In general, the 7-day strength approached, or exceeded the 28-day strength for mixes made with high-early-strength cement.

For mixes containing normal portland cement (Type I), the one-day compressive strength averaged 31 to 39 percent, and the 7-day strength averaged 78 to 92 percent of the 28-day compressive strength, on a group basis.

Examination of figures 2A, 2B, and 2C reveals no well-defined departure from a general air content-strength relationship, except for the expected relatively low one-day strengths of the mixes containing normal portland cement, and the unexpected relatively low strengths at all ages for mixes containing agent F. The dispersion of strengths at a given air content appears large. However, considering the 28-day values only, a change of one percent in the value for the percentage of entrained air would be accompanied by an average change of about 100 psi in compressive strength. This relationship is in agreement with previously obtained data (1). While the degree of precision with which the percentages of entrained air were determined is not known, it may be seen that, should the uncertainty in the values for air content be as high as ± 2 percent, much of the scatter could be accounted for. Some dispersion is to be expected in plotting strength values for individual specimens, in view of the relatively high coefficients of variation obtained by other investigators among specimens within batches of low-strength concretes (4). Nevertheless, the plotting of strength data in a single graph for concretes made with different types of aggregate of widely varying characteristics does not appear to indicate systematic differences in strength due to aggregate characteristics. It is probable that, within the range of air contents considered here, the strength of the cement paste is the strength determinant. Some departures from a hypothetical relationship should be expected for similar concretes subjected to extended periods of drying, due to differences in drying rates as influenced by the nature of the aggregate.

6.2 Modulus of Rupture

Two of the 3- by 4- by 16-in. prisms cast from each batch were tested for modulus of rupture, one at the age of 7 days, and the other at the age of 28 days. The testing was done by third-point loading and with a span of 15 in. in a hydraulic testing machine at a rate of 100 lb load per min. The 3-in. dimension was the depth of the specimen. After testing, the broken halves were stored in air at 73 F, humidity uncontrolled, for later use in absorption and capillarity tests. Modulus of rupture values for 7 and 28 days are listed in Table 4.

The 28-day modulus of rupture values are plotted against compressive strength in figure 3. Figure 3 indicates ratios of compressive strength to modulus of rupture ranging from 3, at the lowest strengths, to 5 for compressive strengths near 1500 psi. Some of the pumice concretes had inordinately low values for modulus of rupture; taking the pumice concretes alone, the relationship of compressive strength to modulus of rupture was not well defined. This is in accord with data previously obtained by Kluge, et al (5). Comparison of the 7- and 28-day modulus of rupture values may be done in the same way as for the compressive strength values. In the Table in the preceding section on compressive strengths, the 7-day modulus of rupture data are listed as percentages of the 28-day values. It is seen that for only one of 9 groups into which the data were divided, namely, the pumice concretes made with normal portland (Type I) cement, was the average 28-day modulus of rupture greater than the 7-day value. In all other groups the 7-day values ranged from equality with, to 17 percent greater than, the 28-day values. As in the case of the compressive strengths, the acceleration caused by the use of high-early-strength cement, or calcium chloride, or both, and the drying of the specimens for 21 days prior to the 28-day test, apparently caused little further development of strength after 7 days.

6.3 Bond Strength and Bond Stress-Slip Data

The bond test specimens were horizontally cast 6- by 6- by 12-in. pull-outs with embedded 7/8-in. round, deformed bars meeting the requirements of A.S.T.M. Standard A305-49. The length of embedment was 12 in. through the center of gravity of cross-section of the pull-out specimen. In testing, the specimen was seated vertically on a rubber belting cushion 1/4-in. thick, which rested upon a base plate attached to a spherical bearing block. The base plate was separated into two segments and the bearing block had a 1-in. hole in its center to permit the protrusion of the reinforcing bar to the gripping jaws. At the loaded end (bottom) two dial gages were bolted to a steel bar which was firmly attached to the concrete by bolts screwed into inserts which were embedded in the concrete at the time of casting. The spindle points of the dial gages were in contact with the smooth surface of a steel yoke fastened to the reinforcing bar by three set screws at a point 1-in. below the bottom 6- by 6-in. concrete face of the specimen. The yoke was free to move vertically with the reinforcing bar, away from the concrete. As the load was applied the average of the two dial readings indicated the movement of the point on the reinforcing bar at which the yoke was attached, in relation to the bottom concrete surface of the specimen. To obtain the value for slip at the loaded end of the specimen, these average readings were corrected for elongation of the bar between the concrete surface and the yoke connection point.

The slip of the reinforcing bar at the free-end (top) of the specimen was measured directly by a dial gage supported upon a frame set in plaster of paris upon the top 6- by 6-in. concrete face of the specimen. The spindle point of this gage rested upon the smooth end-surface of the reinforcing bar, which protruded about 1 in. from the concrete surface.

The pull-out specimens were tested in a hydraulic testing machine and the load was applied at a rate of 500 lb per min. Initial dial gage readings were taken at a load of 250 lb and thereafter at increments of 250 lb until failure. The dial readings were taken without interrupting the continuous application of the load.

The bond strengths and maximum observed slip values are listed in Table 4; bond strengths are plotted against compressive strengths in figure 4.

A notable feature of the bond stress-slip data is the fact that the maximum observed slip values for the free and the loaded ends are considerably smaller than values obtained in similar tests of dense concrete (6); the values are also notably smaller than those obtained in tests of concretes containing fine and coarse lightweight aggregate and having comparable compressive strengths. The ratios of compressive to bond strength indicated by figure 3 range approximately from 2 to 4, with the lower ratio corresponding to the lowest strength in the range of bond strengths of 60 to 300 psi. These values are in general agreement with previous data for no-fines pea-gravel concretes containing 25 to 30 percent of entrained air (1). The relative low slip values indicate that there is an abrupt rather than a gradual failure, and that initial slip occurs very slowly until the onset of failure when slippage occurs too rapidly to be measured. These results are indicative of an effect of the absence of fine aggregate in producing brittleness.

6.4 Static and Dynamic Elasticity Determination

6.4.1 Stress-Strain Determinations

Strain measurements were made upon about 40 representative 6- by 12-in. cylinders during the testing for compressive strength at the age of 28 days. Two electric resistance bonded wire strain gages having 6-in. gage lengths (SR-4 300 ohm "A-9") were bonded to opposite sides of each cylinder. The gages were connected electrically in parallel and two similar gages bonded to a steel bar and also connected in parallel served as a compensating resistance in a wheatstone bridge circuit. The average strain for both specimen gages was read directly in microinches per in. by means of an a.-c. bridge type strain indicator. Strain readings were made at convenient increments of loading without interrupting the continuous application of the load to the point of failure. Representative stress-strain curves are shown for two different strength levels in figure 5. A "secant modulus" of elasticity was determined as the slope of a secant to the stress-strain curve, drawn through the origin and the point on the curve corresponding to a strain of 0.0005. The secant modulus values are listed, with values of the maximum observed compressive strain, in Table 5.

The stress-strain curves of figure 5 indicate large differences among concretes made with different lightweight aggregates, but of similar compressive strengths. The curves for gravel concretes show the greatest curvature and those for the pumice concretes show the least curvature; at a given strength, the secant modulus of elasticity was highest for concretes containing gravel, and lowest for concretes containing pumice. The effect of replacing 25 percent of the coarse pumice by an equal volume of sand was to increase the slope of the stress-strain curve and the secant modulus. The maximum observed compressive strain ranged, for 800 psi concretes, from 0.0012, for gravel aggregate, to 0.0026 for pumice aggregate; for 400 psi concretes the values ranged from approximately 0.0009 for gravel to 0.0018 for pumice.

6.4.2 Dynamic (Resonance) Moduli of Elasticity and Rigidity

The apparatus used in determining the dynamic elastic properties consisted essentially of an electrical resistance-tuned oscillator continuously variable in the range 20 to 20,000 cps (± 1%) which, through a power-amplifier, energized an electro-mechanical driver. The driver consisted of a permanent-magnet speaker with a brass driving rod cemented to the voice coil. The driver and a counterweight were attached at the underside of the test so that adjustment of the counter-weight permitted the vertical protrusion of the driving rod upward through a hole in the surface of the table. The free end of the brass rod was thereby brought into contact with the test specimen which was in this way subjected to forced vibration. The sensing element was a piezoelectric crystal pickup cartridge, connected through a voltage (high gain) amplifier to the vertical deflection plates of a cathode-ray oscillograph. (The oscillator was connected not only to the driver, but also to the horizontal plates of the oscillograph). The needle of the pickup was placed in contact with the specimen by attachment of the pickup to the specimen with a rubber band. Resonance frequencies were indicated by Lissajous patterns of maximum height on the screen of the cathode-ray tube. The Lissajous patterns were also used to detect, by indications of phase changes occurring as a specimen was probed along its side or end surfaces, the nodal points and corresponding modes of vibration.

Virtually all of the 6- by 12-in. cylinders and 3- by 4- by 16-in. prisms remaining after tests at earlier ages were tested dynamically at the age of 28 days. Fundamental resonance frequencies of longitudinal, flexural, and torsional vibration were determined for both types of specimen. A specimen was excited longitudinally by placing it upright with the bottom end resting upon a sheet of sponge rubber covering the test table; the specimen was driven at the bottom end and the pickup was placed at the other end. Flexural vibration was excited by laying the specimen upon the sponge rubber in such a way that the driving rod was in contact with a point equidistant from each end and, for the prisms, equidistant from each side. The prisms were tested with the 3-in. dimension vertical, parallel to the direction of vibration. Torsional vibration was also excited with the specimens in a horizontal position; the cylinders were driven eccentrically at one end and the prisms were driven at one of the corners. The pickup was also attached at the ends of specimens driven flexurally and torsionally. Elasticity data were calculated from the resonance frequencies and weight of each specimen using the following equations:

For 6- by 12-in. cylinders:

$$\text{Dynamic } E_l \text{ (longitudinal)} = 0.0044\ Wn_l^2$$

$$\text{Dynamic } E_f \text{ (flexural)} = 0.0117\ Wn_f^2$$

$$\text{Dynamic } G \text{ (torsional)} = 0.0044\ Wn_t^2$$

For 3- by 4- by 16-in. prisms:

$$\text{Dynamic } E_l = 0.0138\ Wn_l^2$$

$$\text{Dynamic } E_f = 0.1144\ Wn_f^2$$

$$\text{Dynamic } G = 0.0178\ Wn_t^2$$

where E is the modulus of elasticity, G the modulus of rigidity (shear modulus), W the weight of the specimen in pounds, n the frequency in cycles per sec, and the subscripts l, f, and t refer to longitudinal, flexural, and torsional vibration, respectively. Poisson's ratio μ , was calculated as $(E/2G)-1$. Values for dynamic E_l, E_f, and G and μ are listed in Table 5. In figure 6, the dynamic E_l values are plotted against secant E values, and in figure 7 the dynamic E_l values are plotted against the 28-day compressive strengths. Figure 8 is a correction chart prepared for use when there are appreciable departures of Poisson's ratio from zero (for dynamic E_l) and from 1/6 (for dynamic E_f). The values listed in Table 5 and plotted in figures 6 and 7 were calculated assuming a value for Poisson's ratio of zero for longitudinal tests, and 1/6 for flexural tests; corrections of the type indicated in figure 8 have not been applied to these values.

Comparison of secant modulus of elasticity values and dynamic E_l (longitudinal) values for the 28-day compressive strength cylinders indicates an over-all mean ratio of static to dynamic values of approximately 2/3. The average ratio was 0.70 for concretes containing pumice, 0.58 for concretes containing gravel, and 0.62 for concretes containing Haydite, Waylite, Lelite, and Rocklite. An average ratio previously obtained for no-fines pea-gravel concretes containing 25 to 30 percent of entrained air was approximately 0.6 (1).

Ratios of uncorrected E_f to E_1 values for 6- by 12-in. cylinders and 3- by 4- by 16-in. prisms are given in the following Table:

Aggregate	Cement	Number of mixes		Ratio, E_f/E_1	
		cylinder	prism	cylinder	prism
Pumice C	III	2	1	0.81	0.78
Pumice C	I	3	3	0.80	0.82
Pumice C, sand	III	3	3	0.87	0.90
Pumice NM	III	2	2	0.77	0.80
Pumice NM	I	6	5	0.75	0.82
Pumice NM, sand	III	3	3	0.87	0.93
Pumice G	I	1	1	0.87	0.74
Haydite	III	8	8	0.91	0.87
Haydite	I	1	1	0.91	0.88
Haydite, sand	III	3	3	0.92	0.93
Waylite	III	3	3	0.87	0.85
Waylite	I	1	-	0.88	--
Lelite	III	5	5	0.87	0.84
Lelite	I	1	-	0.89	--
Rocklite	III	1	2	0.90	0.88
Rocklite, sand	III	1	1	0.92	0.94
Gravel	III	3	1	0.95	0.92
Gravel	I	2	1	0.95	0.92
Gravel, sand	III	2	2	1.00	0.97

The Table indicates that the widest disparity between E_1 and E_f occurs for concretes containing pumice aggregate, and the closest agreement occurs with concretes containing dense aggregates. Application of the Poisson's ratio correction factors of figure 8 would change the ratios insufficiently to explain the differences indicated in the foregoing Table. The reason for the differences probably lies in the effects of 21 days of drying upon the relative elasticity of concrete near the surface, as compared with concrete in the interior of a specimen. The drying of concrete generally causes a reduction in dynamic E, possibly as a result of widespread microscopic cracking of the cement paste matrix. In fact, the cracks developed during the drying of the pumice concretes of this study were easily visible, and in certain cases extended through pieces of the coarse aggregate. If material at the surface of a specimen is of lower dynamic E than that in the interior, the E_f value will be lower than the E_l value, because of the nature of the equations relating these properties to resonance frequencies and dimensions, despite the fact that both methods purport to yield dynamic E values in a direction parallel to the axis of a specimen. The flexural equation yields an incorrect value under the circumstances of these tests since, because it contains terms for the flexural rigidity (EI, in which I is the moment of inertia of a cross-section about the neutral axis), the material farthest from the neutral axis of a specimen is weighted most heavily in the equation. In addition, end effects are extremely large in flexural vibration. Another effect of drying would be low-modulus zones at each end of a specimen which would also have the effect of lowering the resonance frequency to a disproportionate degree. The values for E_l are presumed to be more nearly correct, since for a specimen differing in E through its cross-section, but uniform in cross-section along its length, the E_l values will not depend upon the position of the low-modulus zones in relation to the cross-section, but only upon the proportion of cross-section comprised by the different zones.

The torsion equation, in which the torsional rigidity term, GI_p (in which I_p is the polar moment of inertia), appears, would yield a value for G, the modulus of rigidity of a compound specimen, that was lower than the average G of the components weighted according to the proportion of cross-section area comprised by each component. However, large terminal effects would be absent in this case.

On the basis of the results of experiments conducted at the National Bureau of Standards, in which steel tubes filled with concrete were subjected to longitudinal, flexural, and torsional vibrations, and the calculated values of E_l, E_f, and G of the concrete component were compared with values obtained for plain concrete cylinders from the same batch, the following evaluation of the dynamic elasticity values is given:

1. The E_l values are approximately correct.

2. The E_f values are, in themselves, without merit for the lightweight aggregate concretes and should not be used for calculating the bulk modulus or Poisson's ratio.

3. The G values are unduly low (probably about 5 percent for the pumice concretes) but are acceptable as approximations of the dynamic modulus of rigidity values. When used in conjunction with E_1 to calculate Poisson's ratio, the value obtained is too high. For example, if G is low by 5 percent, Poisson's ratio may be high by more than 20 percent, assuming that the E_1 value is not in error.

The discussion in the preceding paragraphs indicates that the present values for dynamic E_f and μ are of questionable merit. The values are probably most useful for the gravel concretes, for which ratios of E_f/E_1 were higher than 0.95; the data for the pumice concretes (without sand) probably are in error to the greatest degree. Among the lightweight aggregate concretes, values for Poisson's ratio ranged from 0.30 to 0.40 (and in a few cases obviously incorrect values greater than 0.5 were obtained). It is suggested that, in future testing of lightweight aggregate concretes (especially those containing pumice or aggregates of lower density), the dynamic tests be made upon uniformly moist or uniformly dry specimens. The latter condition is preferred since it is the condition which ultimately obtains in many structural applications. Unfortunately, an inconveniently long period of time would be required to produce the uniformly dry condition. It should be expected that concretes made with very lightweight aggregates would exhibit widely differing properties in the wet and dry conditions.

The plotting of dynamic E_1 against the 28-day compressive strength of 6- by 12-in. cylinders in figure 7 indicates that there is no well-defined relationship between these two properties when wide variations in aggregate occur. It may be observed that pumice concretes of widely differing compressive strengths show relatively small differences in dynamic E, while at the other extreme, concretes with dense aggregates showed the greatest changes in dynamic E_1 for different compressive strengths.

6.5 Moisture Properties

6.5.1 Water Rise Due to Capillarity

The specimens used for the capillarity tests were 3- by 4- by 8-in. halves of the prisms broken in the modulus of rupture tests. A single specimen was tested for each mix. The specimens were stored in air at 73 F (humidity uncontrolled) for three to six weeks following the 28-day modulus of rupture tests, and were then oven-dried for 48 hr at 220 F and cooled to room temperature before the start of the capillarity tests. The test consisted in immersing the specimen upright with its plane end face immersed in water to a depth of 1/4 inch. The bottom face rested upon metal strips, permitting the water access to the submerged surface of the specimen. The water was circulated continuously. The temperature during the tests was 73 ± 3 F and the relative humidity was 85 ± 5 percent. Capillarity values were determined by observing the average rise of water along the sides of each specimen 1 and 24 hr and 7 days after the specimen was placed in water. These values are listed in Table 6.

The values for capillary rise of water are relatively low in relation to non-aerated sand-gravel concrete, for which values as high as 5 or 6 in. have been obtained in 7 days. The values for the present lightweight concretes were similar in magnitude to those previously obtained for no-fines dense-aggregate concretes containing 25 to 30 percent of entrained air. (1) In only 5 specimens of 49 tested did the 7-day rise exceed 1 in. in the present tests.

6.5.2 Absorption and Saturation Coefficient

Broken halves of modulus of rupture specimens, 3- by 4- by 8 in. were used for absorption and saturation coefficient determinations. A single specimen was tested for each mix. They were stored in air at 73 F (humidity uncontrolled) for three to six weeks following the 28-day modulus of rupture tests, and were then oven-dried at 220 F for 48 hr and cooled to room temperature before the start of the absorption tests. The specimens were then wholly immersed in water for 24 hr at 73 F, after which they were boiled in water for 5 hr and then allowed to cool for 16 hr while still wholly immersed. The specimens were weighed after oven-drying, cold soaking, and boiling, after reaching room temperature in each case. They were also weighed in water at 73 F after the 24-hr cold soaking. The absorptions were calculated as follows:

$$\text{Percent absorption, by weight, (24 hr cold)} = \frac{W_s - W_o}{W_o} \times 100$$

$$\text{Percent absorption, by weight, (5 hr boil)} = \frac{W_b - W_o}{W_o} \times 100$$

$$\text{Percent absorption, by volume, (24-hr cold)} = \frac{W_s - W_o}{W_s - W_w} \times 100$$

$$\text{Percent absorption, by volume, (5-hr boil)} = \frac{W_b - W_o}{W_s - W_w} \times 100$$

where the weights are W_o after oven-drying, W_s after 24 hr cold soaking, W_b after 5-hr boiling, and W_w is the weight in water after 24-hr cold soaking. 9/

The "saturation coefficient" was calculated as the ratio of the 24-hr cold absorption to the 5-hr boil absorption (by weight or volume). Absorption and saturation coefficient values are presented in Table 6. In figure 9, saturation coefficient data are plotted versus the air contents calculated from the densities based upon the weights of the specimens when removed from the molds. Data are also plotted from studies by Hornibrook, Freiberger, and Litvin in 1946 (7) on sand-gravel concretes with and without entrained air, and by Valore and Green in 1951 (1) on no-fines gravel concretes with 25 to 30 percent of entrained air. Average absorptions (by volume) are listed in the following Table:

9/ For those specimens having a density lower than that of water after 24-hr cold soaking the weight W_w was determined after the 5-hr boiling. If the density was still lower than that of water the volume, measured from the linear dimensions of the specimen and converted to an equivalent weight of water, was used as the denominator in calculating the absorptions by volume.

Aggregate	Number of mixes		Absorption (%, by volume)	
	Type III cement	Type I cement	Type III cement	Type I cement
Pumice C	2	3	21.1	23.6
Pumice C, sand	3	-	12.8	--
Pumice N	5	2	16.3	18.8
Pumice N, sand	3	-	10.8	--
Pumice G	-	1	--	20.6
Haydite	4	1	13.6	15.0
Haydite, sand	3	-	9.3	--
Waylite	3	-	15.6	--
Lelite	5	-	12.1	--
Rocklite	3	-	13.0	--
Rocklite, sand	1	-	10.1	--
Gravel	3	1	11.3	10.0
Gravel, sand	2	-	13.2	--

The foregoing table does not indicate difference in absorption for concretes with different foaming agents, nor the fact that, for air contents over 30 percent, the absorption was, in many cases, higher for higher air contents. For air contents between 25 and 30 percent there was no apparent relation between absorption and air content. For five different aggregates with which different foaming agents were used, the average absorption was lowest for agent V in all cases, and highest for agent M for four of the five aggregates.

In general, the absorptions were low in relation to the porosity (if we may consider the 5-hr boil absorption (by volume) as a measure of porosity); this fact is illustrated by figure 9, which shows the saturation coefficient plotted against air content. Data from previous investigations on dense, sand-gravel concrete with air contents lower than 12 percent, (7) and no-fines gravel concretes with 25 to 30 percent of entrained air (1) are included in the figure. There appears to be a general, but rough, relationship between the two variables plotted, even for concretes made with aggregates of widely differing properties.

6.5.3 Effects of Freezing and Thawing

Freezing and thawing tests were performed upon 3- by 4- by 16-in. prisms dried in air for four to eight weeks following moist curing to the age of 7 days.10/ The specimens were then wholly immersed in water at 73 F for 72 hr before the start of the freezing and thawing tests. Absorption values were calculated from weights of the specimens determined before and after the 72-hr soaking period. The specimens were placed in rectangular copper cans in which, with a specimen in place, there was about 1/8-in. clearance around the sides of the specimen; sufficient water to cover the specimen was placed in each container. Specimens lighter than water were held down by metal weights. The specimens were subjected to automatic cycles of freezing and thawing in two groups of about 18 specimens in each group. The cycles consisted of the introduction of coolant liquid maintained at 0 ± 2 F into an insulated chamber in which the cans containing the specimens were placed. The cans were spaced far enough apart to permit the circulation of coolant between the cans. The coolant liquid was pumped out of the chamber after 1 1/2 hr and the thawing liquid, maintained at 50 ± 2 F, was pumped in. The thawing half of the cycle also was of 1 1/2 hr duration. The specimens underwent eight complete cycles of automatic freezing and thawing every 24 hours. 11/

The effects of freezing and thawing upon the specimens were measured by changes in the dynamic modulus of elasticity, E_1, determined immediately before the start of the first cycle and at various intervals thereafter. Dynamic

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10/ Thirty-one mixes were represented by individual specimens, two mixes were each represented by two specimens, and two mixes of "reference" sand-gravel concrete with no entrained air were each represented by two specimens. Of the reference mixes one was directly comparable in cement factor, and contained Type III cement and 2 percent of calcium chloride by weight of cement.

11/ The automatic freezing and thawing equipment normally was operated at a rate of twelve 2-hr cycles per day. On the basis of trials, prior to the start of the testing, it was found that a cycle of 3-hr duration was required to completely freeze and thaw a specimen containing pumice aggregate. The temperature at the center of the specimen was measured by means of an embedded junction of a thermocouple. The longer time required for the pumice concrete was due to the relatively low thermal diffusivity of the aggregate.

E_1, E_f, and G values were determined in the manner described in Section 6.4.2. Each specimen was removed from test after a reduction in E_1 of 30 to 50 percent, or, in cases where the decrease in E_1 did not reach 30 percent, after 100 cycles of freezing and thawing. Changes in dynamic E_1 are plotted against the number of cycles of freezing and thawing for each of 34 specimens in figures 10A and 10B. The air contents of the concretes, based upon the weights of the specimens upon removal from the molds, are indicated in the figures.

Figure 11 shows the "durability factor" of each specimen plotted against its air content. The durability factor was calculated as the ratio of the area under each curve (in figures 10A and 10B) within the rectangle of dimensions 0 to -30 (change in E_1) by 0 to 100 (cycles), to the entire area of the rectangle. The lower boundary of the rectangle was selected as 30 percent reduction in dynamic E_1 since this criterion of "failure" was found to be satisfactory in previous freezing-and-thawing testing at the National Bureau of Standards. Freezing and thawing test data are given in detail in Table 7, together with pertinent absorption data.

The freezing and thawing tests of the present investigation were relatively severe and results of the testing are to be regarded as relative only. No group of specimens, on the basis of the type of aggregate contained, appeared to fare in a significantly different manner from any other group. As shown in figure 10A, comparable sand-gravel concrete without entrained air (two specimens) "failed" in less than 20 cycles. Of the 14 other failures occurring before the one-hundredth cycle was reached, eight contained over 30 percent of entrained air; of 18 specimens that did not fail prior to 100 cycles, only one contained over 30 percent of entrained air.

One of the salient effects of the freezing and thawing action may be noted by comparing the last three columns of Table 7, in which are listed saturation coefficient data from the absorption tests (see also Table 6), comparable saturation coefficients calculated for the start of the freezing thawing tests, and the maximum values reached during the tests. The absorption values after 5-hr boiling were not determined upon the freezing and thawing specimens but were assumed to be the same as those determined upon the companion specimens tested for absorption. The maximum values of saturation coefficient (estimated) are considerably higher, in most cases, than the initial values which are based on three days of soaking of the specimens which were previously in an air-dry condition. The "build-up" in a saturation indicates that factors other than the initial saturation coefficient must be considered in relation to frost action.

Indications of deterioration by freezing and thawing were based upon changes in dynamic E_1 rather than upon changes in E_f or G, for reasons implicit in the earlier discussion of the dynamic moduli. For the present study, in which changes in dynamic E_1, E_f, and G were measured, an average decrease in E_1 of 25 percent was equivalent to a decrease in E_f of 32 percent, and a decrease in G of 33 percent. These values are averages and there were, in a few cases, large individual deviations from these values.

An unsatisfactory feature of the testing was the constraint imposed upon the specimens by the containers and by ice formed between the container walls and the specimen surfaces. Three of the specimens failed by transverse cracking near one end prior to reaching a decrease in dynamic E_1 of 30 percent. In view of the relatively low strength of these concretes, even at the start of the tests, it was believed that such failures were due principally to the external constraint. An automatic apparatus, which has been placed in operation at the NBS since these tests were made, in which the freezing is done in air and the thawing in water, is recommended for future testing of low-strength concretes.

6.5.4 Shrinkage Due to Drying

The 2- by 2- by 12-in. prisms were removed from water, in which they had been stored upon removal from the molds, at the age of 7 days and allowed to dry at 73 ± 2 F and 50 ± 5 percent relative humidity. Initial readings were made with a vertical comparator immediately upon removing the specimens from water and thereafter changes in length were measured for elapsed drying times of 1, 3, 7, 14, 28, 42, 90, and 180 days. The vertical comparator was equipped with a 0.0001-in. micrometer screw and a 0.0001-in. dial gage for zero-setting. Two specimens from each of 45 mixes were tested. The linear shrinkage is plotted against drying time in figures 12A, 12B, and 12C. Where specimens from more than one mix of a given composition were tested, the curves show the mean shrinkage with the number of mixes, indicated, despite differences in air content among mixes of otherwise similar composition. Shrinkage values for 28 and 180 days of drying are given for individual mixes in Table 6.

The shrinkage curves of figures 12A, B, and C indicate some differences in the shrinkage of concretes made with a given type of aggregate but with different foaming agents. As in the earlier study of gravel concretes containing 25 to 30 percent of entrained air (1), concretes containing agent V generally showed higher values of drying shrinkage than those made with other agents (Type III) cement and no-fines mixes only; agent V was not used with pumices (C or G).

When the entrained air is considered as a constituent of the cement pastes in these concretes, it can be shown that the paste content of the concretes ranged from about 45 to 55 percent; i.e., about one-half of the volume of the concrete was aerated cement paste and the other half was aggregate. Despite the relatively low aggregate content the shrinkage values were not greatly different from previously reported data. Green and Watstein (8) reported 120-day values for coarse-and-fine lightweight-aggregate concretes of comparable cement contents as indicated in the following Table, which includes values from the present study for concretes containing the same aggregates:

Aggregate	Average 120-day shrinkage, percent	
	Green and Watstein	present study (no fines)
Pumice C	0.11	0.09
Pumice N	--	0.09
Haydite	0.08	0.09
Waylite	0.07	0.08

The pumice concrete of Green and Watstein, for which a single value is listed in the foregoing Table, was made with a blend of pumices C and N. The value listed for the pumice N concrete of the present study does not include the single mix made with agent V, having a 120-day shrinkage of 0.15 percent. Except for this mix, the spread in average shrinkage values was not excessive among all of the concretes made with lightweight aggregates in the present study. Some of the values for pumice concretes, however, may be deceptive. The extensive formation of small shrinkage cracks, even in these relatively small specimens, had the effect, among the concretes of lowest strength, of arresting the development of shrinkage as ordinarily measured.

6.6 Thermal Conductivity

Twenty-four 1- by 8- by 8-in. plates were tested for thermal conductivity. The faces of these specimens were ground to remove the cast surface "skin" and reduce the thickness from 1 1/8 in. to 1 in. The specimens were oven-dried at 220 F for 48 hr prior to testing. The tests were made in a guarded hot-plate apparatus described in previous publications of the National Bureau of Standards (1, 5). The apparatus consisted essentially of an electrically heated hot-plate 8-in. square and a cold-plate of the same size cooled by pentane boiling at atmospheric pressure (97 F). The hot-plate was protected by a heated guard so that the heat generated was directed through the test specimen between the hot- and cold-plates. When a steady temperature state was obtained the electric power input to the hot-plate was measured and the temperatures of the hot- and cold-plate surfaces were determined by means of thermocouples. The thermal conductivity in btu per hr per sq ft of area per degree F temperature difference per in. thickness was calculated from these data and the dimensions determined for the test specimen. The tests were conducted with the warm side at 140 F and the cold side at 98 F. The thermal conductivity values are presented in Table 8, and in figure 13 the thermal conductivity values are plotted against the oven-dry densities of the specimens. In addition to data for the lightweight aggregate concretes of the present study, data are also plotted in figure 13 for a foamed cement paste, conventional sand-gravel concrete of comparable cement factor and without entrained air, and "no-fines" concretes (air gravel) containing 5 1/2 bags of cement per cu yd and 25 to 30 percent of entrained air.

The thermal conductivity data presented in figure 13 indicate a dependence upon density which has become, in recent years, well known. The relationship of the two variables appears to extend into the range of dense-aggregate concretes, with and without entrained air, on the one hand, and into the range of foamed cement paste on the other. In view of these results, tests of this type might conveniently be greatly curtailed in future investigations of portland cement concretes which the guarded hot-plate method of test was used, an unsatisfactory feature of the results is the fact that the specimens were necessarily in an oven-dry condition at the time of testing. The oven-dry condition is not representative of these materials in use.

7. SUMMARY

Some 60 mixes of "no-fines" lightweight aggregate concretes with 20 to 35 percent of entrained air, 5 to 6 bags of cement per cu yd, and 2 percent calcium chloride (by weight of cement) were prepared. Coarse aggregates were pumices from three sources, expanded shales of three types, an expanded slag and a siliceous pea gravel. About three fourths of the mixes were made with high-early-strength cement (Type III), and the remainder with normal portland cement (Type I). In about one third of the high-early-strength mixes, 25 percent of the lightweight aggregate (coarse) was replaced by an equal volume of siliceous sand. The "no-fines" high-early-strength mixes were prepared with three air-entraining (foaming) agents of different types: a hydrolyzed protein used in fire fighting, a dispersing-wetting agent, and a proprietary resin widely used for entraining air in concrete. Most of these mixes contained the protein-type agent.

Mix proportions were approximately 1 part of cement to 5 parts of aggregate, by volume. Mix design was based upon a soaking period of 4 hr for all aggregates, and absorptions and bulk specific gravities were determined for saturated surface-dry aggregate after soaking for 4 hr.

The resin foaming agent provided the most stable air entrainment in concrete subjected to handling or working; the protein and detergent types were less stable, but all mixes lost up to 35 percent of the entrained air when cast into specimens 1-in. thick. The loss in 6- by 12- cylinders averaged from 6 to 12 percent. The losses could satisfactorily be compensated by over-design and only the detergent type agent presented difficulties in pre-determining air contents.

Cement factors were based upon analyses of the fresh concretes for the no-fines mixes.

Compressive strengths were more closely related to air contents than to aggregate types. At 28 days the mean compressive strength was less than 200 psi for 35 percent of entrained air, about 400 psi for 30 percent, about 700 psi for 25 percent, and about 1300 psi for 20 percent, with some wide variations from these values. In the range of 20 to 30 percent of entrained air, a change of one in the air content percentage was equivalent to a change of 100 psi in compressive strength. Mixes made with the detergent agent or with Type I cement were low in compressive strength in

relation to all other mixes. The high-early-strength mixes containing lightweight aggregate attained mean compressive strengths, for each aggregate, in 24 hr equal to 53 to 57 percent of their 28-day strengths.

The relation between modulus of rupture to compressive strength for all mixes in the 28-day compressive strength range of 150 to 1500 psi was linear, and ratios of modulus of rupture to compressive strength ranged from 1/3 to 1/5 from the lowest to the highest strengths. Only the pumice concretes, as a group, departed from this relationship.

The ratio of the bond strengths of pull-out specimens with deformed reinforcing bars to compressive strengths in the 28-day compressive strength range of 150 to 1500 psi ranged from 1/2 to 1/4. Values for slip at loaded and free ends of the bar in lightweight aggregate pull-outs were much lower at failure than in concretes of comparable strength containing fine and coarse lightweight aggregates and lower percentages of entrained air.

Secant (static) and dynamic (longitudinal resonance) moduli of elasticity were closely related, but the mean ratios of secant to dynamic moduli was about 0.65. Dynamic moduli of elasticity calculated from flexural resonance frequencies were in error to an undetermined degree, apparently because of the effect of drying in producing anisotropy through the cross-section of the concrete. Moduli of elasticity were correlated with the compressive strengths of the concretes only for a single type of aggregate considered at one time. At a given compressive strength, the moduli of the pumice concretes were lowest, those for gravel concretes were highest, and those with other aggregates were intermediate between these two groups.

The absorption values (by volume) for the concretes of this study were appreciably lower than for concretes containing comparable lightweight aggregates (coarse and fine) as reported in earlier investigations. Replacement of 1/4 of the coarse lightweight aggregate by an equal volume of siliceous sand effected further decreases in absorption of 25 to 40 percent. Saturation coefficient values ranged from 0.2 to 0.5 as compared with 0.6 to 0.95 for structural sand-gravel concrete with and without entrained air.

Water rise due to capillarity averaged less than 1-in. in 7 days.

The resistance of the present concretes to a severe automatic freezing and thawing treatment was considerably greater than that of a non-aerated sand-gravel concrete, except for a number of lightweight concretes containing more than 30 percent of entrained air.

The drying shrinkage of these concretes was about the same as previously reported for comparable lightweight aggregate concretes made with fine and coarse aggregates, except for the pumice concretes. For the pumice concretes of the lowest strength, internal cracking appeared to diminish the measured shrinkage in relation to that reported in earlier studies.

Thermal conductivity values, when plotted against the densities of these lightweight concretes, became part of a well-defined relationship between these two properties existing over the range in densities of 20 to 140 lb/cu ft.

8. References

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4. Otto Graf, "Gas Concrete, Foam Concrete, Lightweight Lime Concrete," Konrad Wittwer, Stuttgart, Germany,(1949).

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8. William C. Green and D. Watstein, "The Structural Properties of Some Lightweight Aggregate Concretes," National Bureau of Standards Report No. 1166, for the Housing and Home Finance Agency, October 1, 1946.

Errata

Table 7, footnote a/, Figures 10a and 10b, captions.

The duration of the freezing and thawing periods is erroneously given as 3 hr each. The duration of a complete cycle of freezing and thawing was 3 hr of which the freezing period was 1 1/2 hr, and the thawing period was 1 1/2 hr.

Table 1. Physical Properties of Aggregates

Aggregates	Sieve Analysis, U.S. St'd Sieves (percent passing, by weight)					Percent washed through No.8	Absorption (by wt)		Bulk specific gravity		Unit weight d/	
	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8		ASTM method a/	from analysis b/	ASTM method a/	4 hr displacement c/	loose	jigged
							%	%			lb/cu ft	
Pumice	96	56	15	9	8	3	37.2	27	1.19	1.06	27.6	31.6
Pumice NM	--	100	68	3	2	2	57.8	35	1.11	0.95	22.8	26.0
Pumice G	98	75	24	10	9	5	51.4	34	0.96	1.06	--	--
Haydite	--	100	97	34	5	3	8.0	6	1.48	1.52	48.1	53.4
Waylite	--	100	87	19	10	2	22.0	14	1.62	1.35	30.5	35.3
Lelite	100	92	82	21	10	5	8.9	8	1.71	1.64	43.7	49.6
Rocklite	--	--	100	45	1	-	17.8	9	1.81	1.64	55.3	61.9
Gravel	--	100	91	19	3	-	0.3	0.5	2.62	2.60	---	---

a/ A.S.T.M. method C128-42. Absorption determined for saturated, surface-dry aggregate condition (C128-42 modified for lightweight aggregate).

b/ Aggregate retained after washing unit weight sample of plastic concrete through No. 8 sieve.

c/ Based on displacement of water after 4 hr immersion in 2 liter graduate.

d/ A.S.T.M. method C29-42.

Table 2. Proportions of Concretes
(All mixes contained 2% $CaCl_2$, by weight of cement)

Mix designation [a]	Cement type	Coarse aggregate	Fine aggregate	Air-entraining agent		Air content		Aggregate-cement ratio, by abs. vol.		Cement factor, [c] bags/cu yd of concrete		Water-cement ratio, by weight	Slump
				Type	Amount, by wt, cement	Plastic concrete [b]	Cylinders, 1-day	coarse	sand	from batch weights	from analysis [d]		
					(percent)	(percent)	(percent)						(in.)
PC3M-1	III	Pumice C	none	M	0.69	23.9 [e]	21.9	5.0	---	5.86	5.64	0.52	6.5
PC3M-2	III	do	do	M	1.04	29.3	29.4	5.2	---	5.40	4.88	0.52	6.5
PCS3M-1	III	Pumice C	sand W	M	1.24	23.7	23.3	3.6	1.2	5.99	----	0.48	7.0
PCS3M-2	III	do	do	M	1.54	26.9	26.5	3.6	1.2	5.74	----	0.48	7.0
PCS3M-3	III	do	do	M	1.85	29.3	29.6	3.6	1.2	5.46	----	0.49	7.5
PC1M-1	I	Pumice C	none	M	0.52	26.0	25.5	5.2	---	5.54	5.47	0.40	7.5
PC1M-2	I	do	do	M	0.52	27.5 [e]	26.8	4.1	---	6.39	5.97	0.45	8.0
PC1M-3	I	do	do	M	0.69	35.1	35.6	4.1	---	5.70	5.45	0.42	7.5
PN3M-1	III	Pumice M	none	M	0.69	25.3	25.7	4.9	---	5.85	6.02	0.43	4.5
PN3M-2	III	do	do	M	1.04	28.1	28.3	5.2	---	5.68	5.71	0.41	4.5
PNS3M-1	III	Pumice M	sand W	M	1.29	28.1	26.8	3.7	1.2	5.64	----	0.49	4.5
PNS3M-2	III	do	do	M	1.39	32.7	33.2	3.7	1.2	5.20	----	0.47	7.0
PNS3M-3	III	do	do	M	1.54	35.0	35.8	3.7	1.2	5.02	----	0.45	6.0
PNS3M-4	III	do	do	M	1.54	35.3	35.8	3.7	1.2	4.93	----	0.49	5.5
PN3F-1	III	Pumice M	none	F	0.76	20.6	20.0	4.8	---	6.25	6.08	0.56	3.0
PN3F-2	III	do	do	F	0.99	25.3	25.4	4.8	---	5.81	5.50	0.50	4.0
PN3F-3	III	do	do	F	1.09	32.2	35.5	4.8	---	4.84	5.04	0.48	6.0
PN3V-1	III	Pumice M	none	V	0.32	27.7	27.8	4.9	---	5.49	5.38	0.51	5.5
PN1M-1	I	Pumice M	none	M	0.35	30.0	28.5	4.9	---	5.64	5.81	0.43	7.0
PN1M-2	I	do	do	M	0.69	36.3	36.4	4.9	---	5.02	4.97	0.45	8.0
PG1M-1	I	Pumice G	none	M	0.43	27.5	26.8	5.0	---	5.48	5.47	0.51	7.0
G3M-1	III	Gravel W	none	M	0.69	26.0	26.9	4.9	---	5.73	5.60	0.43	6.0
GS3M-1	III	Gravel W	sand W	M	1.00	22.8 [e]	20.8	3.7	1.2	6.21	----	0.43	6.5
GS3M-2	III	do	do	M	1.54	30.5	30.3	3.7	1.2	5.53	----	0.43	6.5
G3F-1	III	Gravel W	none	F	0.45	27.0 [e]	25.2	4.9	---	6.00	5.39	0.40	5.0
G3V-1	III	Gravel W	none	V	0.21	27.0 [e]	27.1	4.9	---	5.68	5.50	0.46	6.0
G1M-1	I	Gravel W	none	M	0.35	24.2 [e]	19.2	4.9	---	6.46	----	0.39	5.5
G1M-2	I	do	do	M	0.60	23.7	23.4	4.9	---	6.12	----	0.38	5.0

(Continued on next page)

Table 2. Proportions of Concretes (Continued)

Mix designation a/	Cement type	Coarse aggregate	Fine aggregate	Air-entraining agent		Air content		Aggregate-cement ratio, by abs. vol.		Cement factor, c/ bags/cu yd of concrete		Water-cement ratio by weight	Slump
				Type	Amount, by wt, cement	Plastic concrete b/	Cylinders, 1-day	coarse	sand	from batch weights	from analysis d/		
					(percent)	(percent)	(percent)						
H3M-1	III	Haydite S	none	M	0.69	20.5	20.0	5.2	---	6.09	6.44	0.42	2.0
H3M-2	III	do	do	M	0.69	30.9	30.8	5.2	---	5.35	4.66	0.39	4.0
H3M-3	III	do	do	M	0.74	33.2	32.3	5.1	---	5.24	4.60	0.43	3.0
H3M-4	III	do	do	M	0.78	34.8	34.0	5.0	---	4.87	4.35	0.48	4.5
HS3M-1	III	Haydite S	sand W	M	0.80	23.3	21.4	3.9	1.3	5.86	----	0.51	5.0
HS3M-2	III	do	do	M	1.05	28.7	28.1	3.9	1.3	5.39	----	0.50	5.5
HS3M-3	III	do	do	M	1.54	32.0	32.4	3.9	1.3	5.22	----	0.43	7.0
H3F-1	III	Haydite S	none	F	0.55	28.6	27.9	5.0	---	5.42	5.18	0.49	4.5
H3F-2	III	do	do	F	0.73	34.8	35.3	5.1	---	4.85	4.58	0.50	4.0
H3V-1	III	Haydite S	none	V	0.21	31.3	32.1	5.1	---	5.15	4.46	0.46	3.5
H3V-2	III	do	do	V	0.27	33.7	33.0	5.0	---	5.00	4.49	0.51	4.5
H1M-1	I	Haydite S	none	M	0.35	31.0	27.2	4.0	---	6.54	5.90	0.44	8.0
W3M-1	III	Waylite	none	M	0.43	27.1	27.0	4.5	---	5.59	5.01	0.43	4.0
W3M-2	III	do	do	M	0.74	33.1	32.7	4.6	---	5.48	5.02	0.45	3.0
W3V-1	III	Waylite	none	V	0.21	33.3	34.0	4.9	---	5.19	5.11	0.44	4.0
W1M-1	I	Waylite	none	M	0.35	30.0	26.2	5.1	---	6.14	5.78	0.39	3.0
L3M-1	III	Lelite	none	M	0.52	26.0	24.2	5.0	---	5.94	5.78	0.42	3.0
L3F-1	III	Lelite	none	F	0.79	28.1	26.5	4.9	---	5.73	5.05	0.46	3.0
L3F-2	III	do	do	F	0.46	28.5	26.5	4.9	---	6.01	5.14	0.48	2.5
L3V-1	III	Lelite	none	V	0.34	28.0	25.7	4.9	---	5.64	4.82	0.52	6.0
L3V-2	III	do	do	V	0.34	32.6	33.1	4.8	---	4.97	4.44	0.59	5.0
L1M-1	I	Lelite	none	M	0.35	26.6	23.1	4.9	---	6.04	5.82	0.43	5.0
R3M-1	III	Rocklite	none	M	0.93	22.7	22.9	5.2	---	5.78	5.14	0.44	5.0
R3M-2	III	do	do	M	0.93	26.9	27.0	5.3	---	5.40	5.18	0.47	5.0
R3M-3	III	do	do	M	0.93	27.9	27.6	6.1	---	5.84	5.08	0.42	6.0
RS3M-1	III	Rocklite	sand W	M	1.24	27.5	27.2	4.3	1.5	5.10	----	0.43	6.0

a/ Letters preceding first numeral designate aggregate: PC, PN, and PG are pumices: G, gravel; H, Haydite; W. Waylite; L, Lelite; R, Rocklite; and S, Sand: First numerals, 3 or 1 indicate cement type, M, F, and V designate air-entraining agents. (All mixes contained 2% $CaCl_2$ by weight of cement).
b/ Average for two determinations made immediately following mixing and 10 minutes later.
c/ Based on unit weight for 6- by 12-in. cylinders when removed from molds.
d/ Unit weight sample washed through No. 8 sieve.
e/ Single value from unit weight immediately following mixing.

Table 3. Air Content and Density of Various Types of Specimens

Mix designation[a]	Percent air									Density of concrete specimens, (lb/cu ft)											
	Plastic concrete[b]			Concrete, one day old[c]						Cylinder		x-Cylinder		r-Prism			Pull-out	s-Prism		Cond. plate	
	No.1	No.2	mean	cyl.	x-cyl.[d]	r-prism	pull-out	s-prism	plate	1-day	28-days	1-day	28-days	1-day	28-days	oven dry	1-day	1-day	180-days	1-day	oven dry
PC3M-1	23.9	----	----	21.9	----	20.2	20.8	----	----	64.7	58.2	----	----	66.1	57.4	53.6	65.6	----	----	----	----
PC3M-2	31.2	26.9	29.3	29.4	25.3	26.9	27.5	22.8	----	58.8	52.4	62.2	55.4	60.9	53.0	49.8	60.4	64.3	55.0	----	----
PCS3M-1	25.0	22.4	23.7	23.3	20.6	22.6	23.6	20.0	18.4	76.5	71.6	79.2	75.0	77.2	72.2	66.4	76.2	79.8	----	81.4	65.5
PCS3M-2	28.2	25.6	26.9	26.5	22.7	24.8	25.0	21.2	22.6	73.3	68.9	77.1	72.6	75.0	70.0	64.8	74.8	78.6	70.0	77.2	----
PCS3M-3	31.0	27.6	29.3	29.6	27.0	27.2	28.4	23.5	24.4	70.0	65.6	72.6	67.8	72.4	66.3	62.5	71.2	76.1	70.3	75.2	----
PC1M-1	27.5	24.4	26.0	25.5	23.1	23.3	25.1	----	----	61.5	54.8	63.7	57.0	63.5	55.5	53.0	62.0	----	----	----	----
PC1M-2	27.5	----	----	26.8	----	25.6	25.6	23.6	24.0	62.8	56.6	----	----	63.8	56.0	52.8	63.8	65.4	58.1	65.2	53.4
PC1M-3	36.2	34.0	35.1	35.6	33.6	32.5	34.8	29.7	31.4	56.0	49.0	57.0	50.9	58.1	50.6	48.6	56.0	60.0	53.0	59.9	48.2
PN3M-1	27.4	23.1	25.3	25.7	----	23.1	23.5	20.9	20.6	59.1	52.9	----	----	61.2	52.9	48.0	60.9	63.2	53.7	63.0	47.8
PN3M-2	30.9	25.3	28.1	28.3	----	25.1	25.5	23.3	21.9	57.1	50.3	----	----	59.6	51.3	47.2	59.3	61.4	54.4	62.2	47.8
PNS3M-1	27.9	26.3	28.1	26.8	24.6	25.2	26.5	23.1	24.1	70.3	66.4	72.4	68.0	71.8	66.2	61.4	70.6	73.8	68.0	72.9	----
PNS3M-2	34.2	31.1	32.7	33.2	30.2	30.9	30.6	29.1	27.2	64.4	60.2	67.3	63.0	66.6	60.8	56.5	66.9	70.3	64.8	68.3	----
PNS3M-3	37.6	----	----	35.8	----	----	----	----	----	62.0	57.5	----	----	----	----	----	----	----	----	----	----
PNS3M-4	38.7	31.8	35.3	35.8	27.8	33.6	34.7	28.6	27.0	61.6	58.0	69.3	65.0	63.8	58.2	54.7	62.7	68.6	62.7	70.1	----
PN3F-1	20.9	20.3	20.6	20.0	----	----	----	----	----	63.2	57.3	----	----	----	----	----	----	----	----	----	----
PN3F-2	30.7	19.9	25.3	25.4	18.0	21.2	25.2	18.9	19.0	59.2	53.5	65.1	59.7	62.6	55.0	47.3	59.4	64.3	55.9	64.5	50.4
PN3F-3	37.7	26.7	32.2	35.5	22.8	28.0	31.7	22.8	24.8	51.3	45.3	61.4	55.4	57.2	50.0	47.1	54.3	61.4	53.4	59.8	46.7
PN3V-1	28.0	27.3	27.7	27.8	26.2	26.7	27.1	25.8	26.3	57.0	50.5	58.3	51.7	57.9	49.7	44.7	57.6	58.6	50.2	58.2	45.2
PN1M-1	31.5	25.9	28.7	28.5	23.9	26.7	27.5	25.6	27.6	56.3	48.4	59.8	52.2	57.7	48.8	46.4	57.1	58.6	51.5	57.0	45.8
PN1M-2	39.0	32.6	35.8	36.4	31.7	33.7	31.2	34.0	36.2	50.1	42.8	53.8	46.2	52.2	43.7	42.1	54.2	52.0	45.2	50.3	40.5
PG1M-1	28.3	26.6	27.5	26.8	23.7	26.6	25.1	----	25.1	60.5	50.9	62.2	53.0	60.9	49.0	45.2	60.0	----	50.6	60.0	44.4
G3M-1	30.0	22.0	26.0	26.9	25.4	25.4	25.0	23.4	----	108.5	106.0	110.7	108.5	110.3	108.0	104.5	111.4	113.7	113.1	----	----
GS3M-1	22.8	----	----	20.8	----	19.7	----	----	----	117.8	114.6	----	----	119.4	117.0	112.4	----	----	----	----	----
GS3M-2	32.0	29.8	30.5	30.3	27.2	27.6	29.8	26.8	24.9	103.9	102.5	108.6	107.0	107.9	107.7	100.4	104.7	109.1	108.0	111.9	----
G3F-1	27.0	----	----	25.2	----	21.1	----	21.3	----	112.2	110.0	----	----	118.3	----	111.3	----	118.0	118.4	----	----
G3V-1	27.0	----	----	27.1	----	26.0	----	25.8	----	107.8	105.9	----	----	109.3	----	103.0	----	109.6	110.1	----	----
G1M-1	24.2	----	----	19.2	----	15.8	15.9	14.6	15.3	120.8	119.7	----	----	125.8	122.9	120.1	125.7	127.6	124.0	127.5	122.6
G1M-2	23.7	----	----	23.4	----	----	----	----	----	115.4	113.3	----	----	----	----	----	----	----	----	----	----

(Continued on next page)

Table 3. Air Content and Density of Various Types of Specimens (Continued)

Mix designation[a/]	Percent air									Density of concrete specimens, (lb/cu ft)											
	Plastic concrete[b/]			Concrete, one day old[c/]						Cylinder		x-cylinder		r-prism			Pull-out	s-prism		Cond. plate	
	No.1	No.2	mean	cyl.	x-cyl.[d/]	r-prism	pull-out	s-prism	plate	1-day	28-days	1-day	28-days	1-day	28-days	oven dry	1-day	1-day	180-days	1-day	oven dry
H3M-1	24.0	17.0	20.5	20.0	----	22.0	21.9	16.5	16.5	82.5	79.2	----	----	84.9	81.5	76.7	84.9	89.4	85.1	89.4	81.1
H3M-2	34.3	27.5	30.9	30.8	26.1	28.8	28.7	24.4	22.0	71.6	68.7	76.6	73.2	73.8	69.9	64.3	73.9	78.4	75.4	80.8	73.0
H3M-3	35.2	31.2	33.2	32.3	25.7	26.6	31.3	26.0	19.1	69.7	68.2	76.4	73.9	75.5	73.2	68.7	70.7	76.1	77.6	83.2	----
H3M-4	37.2	32.3	34.8	34.0	29.4	33.1	34.6	27.9	25.6	67.5	65.4	72.2	69.2	68.4	64.6	61.7	66.9	73.8	70.6	76.1	70.2
HS3M-1	24.6	22.0	23.3	21.4	19.8	20.4	22.4	18.2	19.7	88.3	85.9	90.1	88.0	89.4	86.6	79.6	87.2	91.9	88.2	90.2	80.2
HS3M-2	30.0	27.4	28.7	28.1	25.7	26.9	30.1	24.2	24.6	80.9	79.2	83.7	81.0	82.3	79.6	74.3	78.7	85.3	82.4	84.9	----
HS3M-3	33.8	30.1	32.0	32.4	29.8	31.4	33.3	29.0	27.4	77.2	75.3	80.2	77.9	78.9	76.0	71.2	76.6	82.4	78.9	83.2	----
H3F-1	30.1	27.0	28.6	27.9	25.3	26.5	26.1	23.4	22.1	73.5	70.5	76.2	73.2	75.0	71.9	67.5	75.4	78.1	75.0	79.5	72.6
H3F-2	37.7	32.0	34.8	35.3	30.6	32.7	35.2	29.5	27.7	65.8	62.8	70.6	67.4	68.4	65.1	61.4	65.9	71.7	68.4	73.5	----
H3V-1	33.3	29.2	31.3	32.1	26.7	29.5	30.5	27.3	23.8	69.5	66.6	75.1	72.0	72.2	69.7	65.0	71.2	74.4	71.2	78.0	----
H3V-2	34.3	33.0	33.7	33.0	31.8	31.8	34.2	30.4	29.5	68.0	65.2	69.2	65.7	69.2	66.6	63.5	66.8	70.7	67.3	71.6	65.2
H1M-1	31.8	30.1	31.0	27.2	----	26.4	26.0	23.8	22.2	73.8	70.2	----	----	74.6	69.9	67.5	74.1	77.3	74.3	78.9	72.0
W3M-1	30.1	24.1	27.1	27.0	22.3	22.7	23.1	----	----	70.7	67.0	75.1	71.7	74.0	70.1	68.5	73.6	----	----	----	----
W3M-2	37.4	28.7	33.1	32.7	26.8	28.9	30.5	25.8	25.1	64.7	60.6	70.3	66.2	68.3	63.9	60.2	66.8	71.3	65.9	72.0	62.8
W3V-1	34.1	32.5	33.3	34.0	31.8	31.8	32.6	31.0	28.4	63.2	58.2	65.3	60.4	65.3	59.5	57.2	64.6	66.1	60.3	68.6	----
W1M-1	32.8	----	----	26.2	----	----	----	----	----	72.6	67.4	----	----	----	----	----	----	----	----	----	----
L3M-1	30.3	21.6	26.0	24.2	----	20.7	20.6	19.8	18.4	82.2	81.3	----	----	86.0	81.9	76.8	86.1	87.0	82.6	88.5	79.3
L3F-1	31.4	24.7	28.1	26.5	----	24.1	23.0	22.4	24.6	79.1	75.4	----	----	81.7	77.7	74.0	83.0	83.6	78.7	81.2	77.1
L3F-2	32.3	24.6	28.5	26.5	21.7	23.5	26.2	22.5	20.2	78.7	75.4	83.9	80.5	81.9	78.6	73.2	79.1	83.0	78.6	85.5	----
L3V-1	31.5	24.4	28.0	25.7	----	24.8	24.1	24.7	22.9	79.1	74.9	----	----	80.1	75.9	71.4	80.8	80.7	76.5	82.1	73.7
L3V-2	34.0	31.2	32.6	33.1	31.1	32.0	32.1	28.9	29.2	70.4	67.2	72.5	68.7	71.5	68.1	61.8	71.4	74.8	70.9	74.5	67.1
L1M-1	28.1	25.1	26.6	23.1	----	----	----	----	----	83.0	80.0	----	----	----	----	----	----	----	----	----	----
R3M-1	24.2	21.3	22.7	22.9	----	20.0	----	17.9	18.8	83.0	80.0	----	----	86.1	82.2	----	----	88.4	81.5	87.4	----
R3M-2	27.4	26.4	26.9	27.0	----	23.7	24.4	----	----	78.2	----	----	----	81.7	76.2	71.0	81.0	----	----	----	----
R3M-3	29.9	25.8	27.9	27.6	23.8	26.0	26.0	21.8	21.1	79.3	74.7	83.4	79.2	81.0	75.3	70.3	81.0	85.6	79.1	86.4	----
RS3M-1	28.6	26.3	27.5	27.2	25.6	25.2	26.7	23.3	23.3	85.0	81.1	86.9	83.3	87.4	83.1	77.2	85.6	89.6	84.8	89.6	----

a/ See footnote a/ to Table 2. (All mixes contained 2% $CaCl_2$ by weight of cement).
b/ Based on unit weight determinations; No. 1 made immediately following mixing, and No. 2 made 10 minutes later.
c/ Based upon weights of specimens when removed from molds.
d/ Made with concrete remaining after other specimens and No. 2 unit weight determinations were made.

Table 4. Compreesive, flexural, and bond strength, and bond etrees-slip characteristics of concreta.

Mix[a/] designation	Cement type	Aggregate	Density 28 da[b/]		Compr. strength[c/]			Modulus of ruptura c/		Bond[c/] strength 28 da	Bond stress for max. observad slip	Max. observad slip	
			cylinder	prism	1 da	7 da	28 da	7 da	28 da			free and	loaded and
			lb/cu ft	lb/cu ft	psi	psi	psi	psi	psi	psi	psi	10^{-3} in.	10^{-3} in.
PC3M-1	III	Pum. C	58.2	57.4	505	900	845	160	110	199	197	1.1	2.7
PC3M-2	III	" "	52.4	53.0	170	370	340	90	--	105	99	0.8	3.1
PC3M-2X	III	" "	55.4				395						
PCS3M-1	III	Pum.C, sand	71.6	72.2	575	790	885	175	190	214	205	2.5	5.4
PCS3M-1X	III	" " "	75.0				1200						
PCS3M-2	III	" " "	68.9	70.0	360	570	640	165	160	164	152	0.9	2.0
PCS3M-2X	III	" " "	72.6				950						
PCS3M-3	III	" " "	65.6	66.3	235	300	440	120	90	113	106	0.3	0.6
PCS3M-3X	III	" " "	67.8				565						
PC1M-1	I	Pum. C	54.8	55.5	130	380	460	75	100	127	121	0.9	4.4
PC1M-1X	I	" "	57.0				575						
PC1M-2	I	" "	56.6	56.0	210	565	580	95	115	141	136	1.5	2.3
PC1M-3	I	" "	49.0	50.6	55	115	125	--	40	67	61	0.4	2.2
PC1M-3X	I	" "	50.9				195						
PN3M-1	III	Pum. NM	52.9	52.9	590	1030	900	145	90	165	152	0.3	3.2
PN3M-2	III	Pum. NM	50.3	51.3	340	675	600	120	115	141	136	0.7	3.0
PNS3M-1	III	Pum. NM,sand	66.4	66.2	480	790	850	115	175	198	197	2.9	6.5
PNS3M-1X	III	" " "	68.0				1040						
PNS3M-2	III	" " "	60.2	60.8	165	345	385	110	85	99	91	0.4	0.5
PNS3M-2X	III	" " "	63.0				480						
PNS3M-3	III	" " "	57.5	--	80	150	195	--	--	--	--	--	--
PNS3M-4	III	" " "	58.0	58.2	80	145	195	55	45	84	83	0.6	3.4
PNS3M-4X	III	" " "	65.0				460						
PN3F-1	III	Pum. NM	57.2	--	665	1190	1190	--	--	--	--	--	--
PN3F-1X	III	" NM	57.5				1230						
PN3F-2	III	" "	53.5	55.0	280	505	495	160	115	133	121	0.5	1.5
PN3F-2X	III	" "	59.7				1140						
PN3F-3	III	" "	45.3	50.0	65	115	115	85	140	79	76	0.8	2.3
PN3F-3X	III	" "	55.4				670						
PN3V-1	III	Pum. NM	50.5	49.7	470	805	865	125	110	152	136	0.6	4.9
PN3V-1X	III	" "	51.7				910						
PN1M-1	I	Pum. NM	48.4	48.8	160	405	410	110	110	105	98	1.0	1.8
PN1M-1X	I	" "	52.2				805						
PN1M-2	I	" "	42.8	43.7	65	165	185	--	65	90	83	0.8	0.4
PN1M-2X	I	" "	46.2				310						
PG1M-1	I	Pum. G	50.9	49.0	170	435	480	70	80	125	121	1.0	1.8
PG1M-1X	I	" "	53.0				670						
G3M-1	III	Gravel	106.0	108.0	380	580	535	140	135	215	212	2.1	3.0
G3M-1X	III	"	108.5				680						
GS3M-1	III	" ,sand	114.6	117.0	910	1320	1340	295	295	--	--	--	--
GS3M-1X	III	" "	114.6				1370						
GS3M-2	III	" "	102.5	107.7	235	290	325	120	75	106	91	0.4	0.7
GS3M-2X	III	" "	107.0				580						
G3F-1	III	Gravel	110.0	--	255	495	380	140	--	--	--	--	--
G3V-1	III	Graval	105.9	--	255	545	410	125	--	--	--	--	--
G1M-1	I	Gravel	119.7	122.9	500	1095	1290	375	295	358	349	1.3	6.3
G1M-2	I	"	113.0	--	--	670	765	--	--	--	--	--	--
G1M-2X	I	"	113.6	--			810						

(Continued on naxt page)

Table 4. Compressive, flexural, and bond strength, and bond stress-slip characteristics of concrete. (Continued)

Mix[a] designation	Cement type	Aggregate	Density 28 da[b]		Compr. strength[c]			Modulus of rupture [c]		Bond [c] strength 28 da	Bond stress for max. observed slip	Max. observed slip	
			cylinder	prism	1 da	7 da	28 da	7 da	28 da			free end	loaded end
			lb/cu ft	lb/cu ft	psi	psi	psi	psi	psi	psi	psi	10^{-3} in.	10^{-3} in.
H3M-1	III	Hayd.	79.2	81.5	900	1395	1495	255	275	348	334	1.9	6.9
H3M-2	III	"	68.7	69.9	245	475	575	125	135	149	136	0.4	0.6
H3M-2X	III	"	73.2				835						
H3M-3	III	"	68.2	73.2	110	235	265	125	110	78	76	0.6	2.3
H3M-3X	III	"	73.9				620						
H3M-4	III	"	65.4	64.6	115	210	265	65	55	91	76	0.4	1.3
H3M-4X	III	"	69.2				485						
HS3M-1	III	Hayd. sand	85.9	86.6	740	1135	1320	265	255	277	273	1.6	6.0
HS3M-1X	III	" "	88.0				1555						
HS3M-2	III	" "	79.2	79.6	275	465	510	135	135	146	144	0.6	4.2
HS3M-2X	III	" "	81.0				715						
HS3M-3	III	" "	75.3	76.0	145	265	300	100	85	119	114	1.1	2.0
HS3M-3X	III	" "	77.9				390						
H3F-1	III	Hayd.	70.5	71.9	200	370	365	105	90	130	106	0.3	1.7
H3F-1X	III	"	73.2		--	--	505	--	--	--			
H3F-2	III	"	62.8	65.1	70	155	165	60	50	61	53	1.1	7.3
H3F-2X	III	"	67.4				325						
H3V-1	III	Hayd.	66.6	69.7	140	255	225	75	65	96	91	1.3	1.4
H3V-1X	III	"	72.0				465						
H3V-2	III	"	65.2	66.6	100	180	180	60	40	77	76	1.2	2.5
H3V-2X	III	"	65.7				180						
H1M-1	I	Hayd.	70.2	69.9	190	440	615	115	115	175	167	1.2	2.9
W3M-1	III	Wayl.	67.0	70.1	260	445	450	140	120	154	152	0.5	3.1
W3M-1X	III	"	71.7				780						
W3M-2	III	"	60.6	63.9	70	120	160	70	50	58	53	0.4	1.2
W3M-2X	III	"	66.2				430						
W3V-1	III	Wayl.	58.2	59.5	110	235	225	75	65	84	76	0.6	1.5
W3V-1X	III	"	60.4										
W1M-1	I	Wayl.	67.4	--	160	445	530	--	--	--	--	--	--
L3M-1	III	Lel.	81.3	81.9	435	645	925	160	195	265	258	0.0	2.3
L3F-1	III	Lel.	75.4	77.7	175	240	---	110	85	106	106	2.9	14.4
L3F-2	III	"	75.4	78.6	200	350	405	120	110	104	91	1.2	1.8
L3F-2X	III	"	80.5				655						
L3V-1	III	Lel.	74.9	75.9	425	665	760	170	130	213	197	1.2	2.7
L3V-2	III	Lel.	67.2	68.1	120	225	195	65	45	82	76	0.7	2.0
L3V-2X	III	Lel.	68.7				205						
L1M-1	I	Lel.	79.5	--	--	600	895	--	--	--	--	--	--
L1M-1X	I	Lel.	80.5				925						
R3M-1	III	Rockl.	80.0	82.2	680	1235	--	230	270	--	--	--	--
R3M-2	III	"	--	76.2	440	790	--	205	--	225	212	0.5	9.6
R3M-3	III	"	74.8	75.3	405	795	850	195	160	210	197	0.9	1.5
R3M-3X	III	"	79.2				1240						
RS3M-1	III	Rockl., sand	81.2	83.1	285	525	500	155	170	124	121	0.6	2.8
RS3M-1X	III	" "	83.3				760						

a/ See footnote a/table 2. (All mixes contained 2% $CaCl_2$, by weight of cement).
b/ Cured moist to 7 days, and at 73°F in air of uncontrolled relative humidity from 7 to 20 days.
c/ All except 28-day specimens in moist condition when tested; 28-day specimens in air-dry condition at time of testing, following 21 days of dry storage.

Table 5. Secant modulus of elasticity and dynamic moduli of elasticity and rigidity of concrete.

Mix[a] designation	Density (lb/cu ft)[b] cylinder 28 days	Density (lb/cu ft)[b] r-prism[c] 28 days	Secant E[d] cylinder	Maximum observed compr. strain	Dynamic E cylinder E_1[e]	Dynamic E cylinder E_f[f]	Dynamic E r-prism E_1[e]	Dynamic E r-prism E_f[f]	Dynamic G[g] cylinder	Dynamic G[g] r-prism	Poisson's ratio cylinder	Poisson's ratio r-prism
			10^6 psi	10^6 in.	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi		
PC3M-1	58.2	57.4	0.36	2511	0.52	0.43	0.51	0.40	0.19	0.20	0.35	0.29
PC3M-2	52.4	53.0	--	--	0.36	0.28	--	--	0.13	--	0.36	--
PC3M-2X	55.4	--	--	--	0.40	0.33	--	--	0.15	--	0.35	--
PCS3M-1	71.6	72.2	0.57	1538	0.80	0.71	0.79	0.72	0.30	0.32	0.34	0.23
PCS3M-1X	75.0	--	--	--	0.90	0.77	--	--	0.35	--	0.30	
PCS3M-M2	68.9	70.0	0.46	1558	0.69	0.58	0.69	0.63	0.26	0.27	0.31	0.28
PCS3M-M2X	72.6	--	--	--	0.81	0.72	--	--	0.31	--	0.30	
PCS3M-3	65.6	66.3	0.36	1370	0.55	0.47	0.53	0.46	0.21	0.22	0.33	0.19
PCS3M-3X	67.8	--	--	--	0.64	0.55	--	--	0.24	--	0.32	
PC1M-1	54.8	55.5	0.29	1608	0.46	0.40	0.45	0.35	0.17	0.17	0.32	0.31
PC1M-1X	57.0	--	--	--	0.53	0.43	--	--	0.20	--	0.34	--
PC1M-2	56.6	56.0	0.31	2122	0.50	0.42	0.51	0.40	0.20	0.19	0.28	0.31
PC1M-3	49.0	50.6	--	--	0.23	0.19	0.21	0.19	0.09	0.10	0.37	
PC1M-3X	50.9	--	--	--	0.28	0.22	--	--	0.10	--	0.39	--
PN3M-1	52.9	52.9	0.42	2540	0.47	0.35	0.53	0.42	0.18	0.20	0.33	0.31
PN3M-2	50.3	51.3	--	--	0.45	0.36	0.49	0.40	0.17	0.18	0.33	0.33
PNS3M-1	66.4	66.2	0.58	1691	0.75	0.67	0.74	0.67	0.29	0.30	0.30	0.24
PNS3M-1X	68.0	--	--	--	0.81	0.74	--	--	--	--	0.28	--
PNS3M-2	60.2	60.8	0.32	1751	0.48	0.41	0.44	0.40	0.18	0.18	0.35	0.24
PNS3M-2X	63.0	--	--		0.60	0.53	--	--	0.23	--	0.33	--
PNS3M-3	57.5											
PNS3M-4	58.0	58.2	--	--	0.38	0.31	0.30	0.29	0.14	0.13	0.37	
PNS3M-4X	65.0	--	--	--	0.65	0.55	--	--	0.25	--	0.31	
PN3F-1	57.2	--	0.50	2782	0.59	0.42	--	--	0.20	--		
PN3F-1X	57.5	--	--	--	0.58	0.38	--	--	0.19			
PN3F-2	53.5	55.0	0.31	1740	0.49	0.39	0.51	0.42	0.17	0.19	0.40	0.32
PN3F-2X	59.7	--	--	--	0.63	0.54	--	--	0.24	--	0.31	--
PN3F-3	45.3	50.0	--	--	0.22	0.17	0.32	0.27	0.08	0.12	0.39	0.29
PN3F-3X	55.4	--	--	--	0.67	0.47	--	--	0.20	--		
PN3V-1	50.5	49.7	0.37	2523	0.48	0.35	0.44	0.36	0.16	0.17	0.49	0.29
PN3V-1X	51.7	--	--	--	0.44	0.33	--	--	0.16	--	0.37	--
PN1M-1	48.4	48.8	0.28	1400	0.39	0.33	0.37	0.38	0.13	0.17	0.35	
PN1M-1X	52.2	--	--	--	0.54	0.41	--	--	0.20	--	0.32	--
PN1M-2	42.8	43.7	0.12	1183	0.24	0.20	0.23	0.21	0.09	0.10	0.34	
PN1M-2X	46.2	--	--	--	0.36	0.29	--	--	0.13	--	0.39	--
PG1M-1	50.9	49.0	0.31	1748	0.43	0.38	0.43	0.32	0.17	0.16	0.28	0.35
PG1M-1X	53.0	--	--	--	0.53	0.46	--	--	0.20	--	0.31	--
G3M-1	106.0	108.0	0.65	1505	1.10	1.02	1.22	1.12	0.48	0.51	0.15	0.19
G3M-1X	108.5	--	--	--	1.32	1.26	--	--	0.57	--	0.15	--
GS3M-1	114.6	117.0	1.36	1337	2.02	1.98	2.10	2.04	0.86	0.87	0.17	0.20
GS3M-1X	114.6	--	--	--	2.09	2.10	--	--	0.89	--	0.18	--
GS3M-2	102.5	107.7	0.44	1079	0.82	0.79	1.04	1.00	0.35	0.45	0.16	0.15
GS3M-2X	107.1	--	--	--	1.15	1.21	--	--	0.52		0.11	
G3F-1	110.0	--	0.53	873	1.04	1.04	--	--	0.47	--	0.12	--
G3V-1	105.9	--	0.47	1055	0.94	0.88	--	--	0.40	--	0.18	--
G1M-1	119.7	122.9	1.37	1709	2.27	2.14	2.52	2.31	0.93	1.07	0.22	0.18
G1M-2	113.0	--	1.01	1296	1.64	1.58	--	--	0.70	--	0.18	--
G1M-2X	113.6	--	--	--	1.73	1.66	--	--	0.74	--	0.17	--

(Continued on next page)

Table 5. Secant modulus of elasticity and dynamic moduli of elasticity and rigidity of concrete. (Continued)

Mix[a/] designation	Density (lb/cu ft)[b/]		Secant E[d/] cylinder	Maximum observed compr. strain	Dynamic E				Dynamic G [g/]		Poisson's ratio	
	cylinder 28 days	r-prism[c/] 28 days			cylinder		r-prism		cylinder	r-prism	cylinder	r-prism
					E_1[e/]	E_f[f/]	E_1[e/]	E_f[f/]				
			10^6 psi	10^6 in.	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi		
H3M-1	79.2	81.5	0.94	2288	1.30	1.22	1.33	1.17	0.52	0.53	0.25	0.25
H3M-2	68.7	69.9	--	--	0.71	0.64	0.73	0.64	0.29	0.29	0.24	0.23
H3M-2X	73.2	--	--	--	0.96	0.89	--	--	0.38	--	0.26	--
H3M-3	68.2	73.2	--	--	0.46	0.41	0.64	0.59	0.19	0.26	0.20	0.20
H3M-3X	73.9	--	--	--	0.78	0.71	--	--	0.32	--	0.23	--
H3M-4	65.4	64.6	0.26	1200+	0.43	0.40	0.39	0.34	0.18	0.16	0.20	0.23
H3M-4X	69.2	--	--	--	0.68	0.63	--	--	0.27	--	0.24	--
HS3M-1	85.9	86.6	1.06	1616	1.49	1.38	1.41	1.31	0.59	0.56	0.26	0.26
HS3M-1X	88.0	--	--	--	1.55	1.46	--	--	0.61	--	0.26	--
HS3M-2	79.2	79.6	0.56	1178	0.89	0.81	0.87	0.81	0.35	0.36	0.27	0.23
HS3M-2X	81.0	--	--	--	1.04	0.94	0.94	--	0.41	--	0.25	--
HS3M-3	75.3	76.0	0.32	1177	0.59	0.54	0.60	0.55	0.23	0.24	0.28	0.24
HS3M-3X	77.8	--	--	--	0.74	0.67	--	--	0.30	--	0.22	--
H3F-1	70.5	71.9	0.36	1336	0.62	0.58	0.65	0.54	0.25	0.25	0.25	0.28
H3F-1X	73.2	--	--	--	0.77	0.70	--	--	0.30	--	0.29	--
H3F-2	62.8	65.1	--	1200+	0.34	0.30	0.39	0.34	0.14	0.15	0.22	0.27
H3F-2X	67.4	--	--	--	0.56	0.45	--	--	0.23	--	0.23	--
H3V-1	66.6	69.7	0.22	1294	0.42	0.39	0.53	0.45	0.17	0.20	0.23	0.29
H3V-1X	72.0	--	--	--	0.70	0.63	--	--	0.28	--	0.26	--
H3V-2	65.2	66.5	--	--	0.34	0.31	0.31	0.26	0.14	0.13	0.23	0.19
H3V-2X	65.7	--	--	--	0.38	0.34	--	--	0.15	--	0.25	--
H1M-1	70.2	69.9	0.48	2078	0.75	0.68	0.68	0.60	0.30	0.28	0.26	0.22
W3M-1	67.0	70.1	0.44	1089	0.71	0.62	0.75	0.63	0.26	0.28	0.36	0.32
W3M-1X	71.6	--	--	--	0.99	0.87	--	--	0.37	--	0.33	--
W3M-2	60.6	64.4	--	--	0.34	0.31	0.39	0.35	0.14	0.16	0.24	0.19
W3M-2X	66.2	--	--	--	0.62	0.55	--	--	0.23	--	0.36	--
W3V-1	58.2	59.5	0.19	1480	0.39	0.32	0.41	0.33	0.15	0.16	0.36	0.30
W3V-1X	60.4	--	--	--	0.48	0.40	--	--	0.18	--	0.33	--
W1M-1	67.4	--	--	--	0.75	0.66	--	--	0.29	--	0.32	--
L3M-1	81.3	81.9	0.78	1612	1.24	1.01	1.16	1.00	0.45	0.45	0.25	0.29
L3F-1	75.4	77.7	--	--	0.57	0.50	0.75	0.62	0.23	0.29	0.23	0.24
L3F-2	75.4	78.6	0.40	1168	--	--	0.78	0.63	--	0.30	--	0.29
L3F-2X	80.5	--	--	--	1.01	0.89	--	--	0.37	--	0.38	--
L3V-1	74.9	75.9	0.53	2139	0.89	0.80	0.85	0.73	0.35	0.33	0.26	0.27
L3V-2	67.2	68.1	--	--	0.39	0.34	0.36	0.30	0.15	0.15	0.32	0.26
L3V-2X	68.7	--	--	--	0.42	0.37	--	--	0.16	--	0.29	--
L1M-1	79.6	--	0.89	1361	1.20	1.07	--	--	0.46	--	0.31	--
R3M-1	--	82.2	--	--	--	--	1.28	1.09	--	0.49	--	0.32
R3M-2	--	--	--	--	--	--	--	--	--	--	--	--
R3M-3	74.7	75.3	0.63	1539	0.93	0.83	1.01	0.92	0.36	0.40	0.27	0.26
R3M-3X	79.1	--	--	--	1.15	1.05	--	--	0.45	--	0.28	--
RS3M-1	81.1	83.1	0.50	1136	0.89	0.82	1.01	0.95	0.35	0.42	0.26	0.20
RS3M-1X	83.3	--	--	--	1.08	0.99	--	--	0.43	--	0.26	--

a/ See footnote a/ to table 2. (All mixes contained 2% $CaCl_2$ by weight of cement).
b/ Specimen 28 days old; moist cured to 7 days; stored at 73°F, humidity uncontrolled to time of test.
c/ Flexural strength prism.
d/ Calculated as stress/strain for strain = 0.0005.
e/ Calculated from longitudinal resonance frequency (uncorrected).
f/ Calculated from flexural resonance frequency (uncorrected).
g/ Calculated from torsional resonance frequency (uncorrected).

Table 6. Moisture Properties of Concretes

Mix designa-tion[a]	Percent air: Plastic concrete[b]	Percent air: Specimen, 1-day[c]	Water rise due to capillarity[d]: 1 hr.	Water rise due to capillarity[d]: 24 hr.	Water rise due to capillarity[d]: 7-days	Estimated abs. F. and T. prisms[e]: by weight	Estimated abs. F. and T. prisms[e]: by volume	Absorption (oven-dry specimens): 24-hr soak, by weight	Absorption (oven-dry specimens): 24-hr soak, by volume	Absorption (oven-dry specimens): 5 hr. boil, by weight	Absorption (oven-dry specimens): 5 hr. boil, by volume	Sat. Coef.[f]	Drying shrinkage: 28-days	Drying shrinkage: 180-days	Percent air Shrinkage prism 1-day
			(in.)	(in.)	(in.)	%	%	%	%	%	%		%	%	
PC3M-1	23.9[g]	20.2	0.3	0.5	0.5	----	----	23.8	20.5	58.5	50.4	0.41	-----	-----	----
PC3M-2	29.3	26.9	0.3	0.4	0.5	20.7	17.0	27.2	21.7	72.2	58.7	0.37	0.078	0.089	22.8
PCS3M-1	23.7	22.6	0.3	0.3	0.3	14.4	15.4	12.1	12.9	41.5	44.2	0.29	0.076	0.099	20.0
PCS3M-2	26.9	24.8	0.3	0.4	0.5	17.6	17.8	11.2	11.6	50.2	52.0	0.22	0.073	0.097	21.2
PCS3M-3	29.3	27.2	0.3	0.4	0.4	17.7	17.5	13.3	13.4	53.7	53.9	0.25	0.070	0.086	23.5
PC1M-1	26.0	23.3	0.8	1.0	1.5	----	----	24.7	21.0	69.2	58.1	0.36	-----	-----	----
PC1M-2	27.5[g]	25.6	0.4	0.5	0.8	18.2	15.9	25.3	21.3	69.8	59.2	0.36	0.101	0.118	23.6
PC1M-3	35.1	32.5	0.5	0.8	1.0	----	----	24.9	28.5	55.1	63.0	0.45	0.071	0.075	29.7
PN3M-1	25.3	23.1	0.4	0.5	0.5	----	----	22.5	17.3	61.7	47.5	0.36	0.096	0.119	20.9
PN3M-2	28.1	25.1	0.3	0.3	0.4	19.7	15.3	24.3	18.4	74.5	56.3	0.33	0.088	0.106	23.3
PNS3M-1	28.1	25.2	0.1	0.3	0.4	17.1	16.8	10.4	9.8	51.0	50.2	0.20	0.079	0.105	23.1
PNS3M-2	32.7	30.9	0.5	0.5	0.5	18.3	16.6	11.5	9.9	64.8	56.4	0.18	0.078	0.102	29.1
PNS3M-4	35.3	33.6	0.4	0.4	0.9	24.0	20.5	14.6	12.8	66.8	58.6	0.21	0.066	0.077	28.6
PN3F-2	25.3	21.2	0.4	0.5	0.5	----	----	18.9	14.3	75.3	57.4	0.25	0.073	0.098	18.9
PN3F-3	32.2	28.0	0.6	1.0	1.3	21.5	16.2	22.8	16.6	81.0	58.8	0.28	0.058	0.081	22.8
PN3V-1	27.7	26.7	0.5	0.8	0.8	24.7	17.5	20.6	14.8	82.2	58.0	0.26	0.116	0.158	25.8
PN1M-1	28.7	26.7	0.4	0.9	2.0	20.8	15.9	25.7	19.1	78.7	58.5	0.33	0.085	0.104	25.6
PN1M-2	35.8	33.7	0.6	1.0	1.8	----	----	27.4	18.5	95.2	64.2	0.29	0.080	0.087	34.0
PG1M-1	27.5	26.6	0.5	1.3	1.3	30.7	22.1	28.4	20.6	85.4	61.9	0.33	0.086	0.106	----
G3M-1	26.0	25.4	0.1	0.3	0.3	7.1	12.0	7.7	12.9	21.3	35.7	0.36	0.048	0.059	23.4
GS3M-1	22.8[g]	19.7	0.3	0.5	0.5	----	----	4.4	7.9	16.5	29.7	0.27	-----	-----	----
GS3M-2	30.5	27.6	0.8	0.8	0.9	14.5	23.4	11.5	18.5	23.2	37.4	0.50	0.058	0.081	26.8
G3F-1	27.0[g]	21.1	0.5	0.5	0.5	----	----	7.6	13.5	17.8	31.8	0.42	0.042	0.056	21.3
G3V-1	27.0[g]	26.0	0.8	0.9	1.0	----	----	4.5	7.5	21.5	35.5	0.21	0.061	0.078	25.8
G1M-1	24.2[g]	15.8	0.3	0.4	0.5	----	----	5.2	10.0	11.9	22.9	0.44	0.046	0.060	14.6

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Table 6. Moisture Properties of Concretes (Continued)

Mix designa-tion a/	Percent air		Water rise due to capillarity d/			Estimated abs. F. and T. prisms e/		Absorption (oven-dry specimens)				Sat. Coef. f/	Drying shrinkage		Percent air shrinkage
								24-hr soak		5-hr boil					
	Plastic concrete b/	Specimen, 1-day c/	1 hr	24 hr	7-days	by weight	by volume	by weight	by volume	by weight	by volume		28-days	180-days	prism 1-day
			(in.)	(in.)	(in.)	%	%	%	%	%	%		%	%	
H3M-1	20.5	22.0	0.5	0.5	0.5	----	----	10.6	12.9	22.4	27.4	0.47	0.085	0.101	16.5
H3M-2	30.9	28.8	0.4	0.4	0.4	10.1	10.9	11.4	12.2	37.2	40.1	0.30	0.063	0.084	24.4
H3M-3	33.2	26.6	0.4	0.5	0.5	----	----	14.5	16.0	36.5	40.2	0.40	0.061	0.081	26.0
H3M-4	34.8	33.1	0.6	0.9	1.0	12.8	12.7	20.2	20.6	44.1	43.7	0.47	0.063	0.085	27.9
HS3M-1	23.3	20.4	0.4	0.6	0.6	----	----	7.2	9.2	21.0	26.8	0.34	0.069	0.094	18.2
HS3M-2	28.7	26.9	0.4	0.5	0.5	11.6	13.7	7.5	9.0	34.5	41.1	0.22	0.067	0.095	24.2
HS3M-3	32.0	31.4	0.6	0.9	0.9	----	----	8.6	9.8	40.4	46.2	0.21	0.072	0.106	29.0
H3F-1	28.6	26.5	0.2	0.4	0.5	13.2	14.1	9.4	10.2	42.1	45.6	0.22	0.069	0.100	23.4
H3F-2	34.8	32.7	0.5	0.8	0.8	15.8	15.4	16.8	16.5	44.1	43.4	0.38	0.062	0.089	29.5
H3V-1	31.3	29.5	0.4	0.5	0.6	11.5	12.0	8.9	9.2	42.9	44.6	0.21	0.066	0.093	27.3
H3V-2	33.7	31.8	0.6	0.9	0.9	12.6	12.6	11.1	11.3	47.1	47.9	0.24	0.076	0.104	30.4
H1M-1	31.0	26.4	0.3	0.5	0.6	11.4	12.4	13.8	15.0	40.7	43.7	0.34	0.089	0.110	23.8
W3M-1	27.1	22.7	0.4	0.5	0.8	----	----	12.6	13.9	46.2	50.7	0.27	-----	-----	----
W3M-2	33.1	28.9	0.1	0.5	0.8	15.6	15.1	22.4	21.7	57.5	55.5	0.39	0.054	0.065	25.8
W3V-1	33.3	31.8	0.1	0.3	0.4	12.6	11.6	12.1	11.1	65.3	60.0	0.19	0.072	0.094	31.0
L3M-1	26.0	20.7	0.3	0.4	0.5	----	----	11.8	14.5	28.2	34.7	0.42	0.055	0.069	19.8
L3F-1	28.1	24.1	0.4	0.8	0.9	----	----	12.3	14.6	35.7	42.3	0.35	0.032	0.047	22.4
L3F-2	28.5	23.5	0.3	0.5	0.5	14.0	16.1	9.6	11.3	38.6	45.3	0.25	0.057	0.069	22.5
L3V-1	28.0	24.8	0.5	0.5	0.6	14.0	15.8	9.6	11.0	37.9	44.0	0.25	0.061	0.080	24.7
L3V-2	32.6	32.0	0.1	0.5	0.5	15.3	15.4	9.1	9.3	48.8	50.5	0.19	0.079	0.100	28.9
R3M-1	22.7	20.0	0.3	0.5	0.8	----	----	11.5	13.9	25.7	30.9	0.45	0.068	0.095	17.9
R3M-2	26.9	23.7	0.3	0.5	0.9	----	----	10.8	12.4	36.7	41.8	0.30	-----	-----	----
R3M-3	27.9	26.0	0.3	0.4	0.4	21.6	22.9	11.3	12.7	35.5	39.8	0.32	0.054	0.082	21.8
RSM-1	27.5	25.2	0.3	0.5	0.8	14.0	17.2	8.2	10.1	35.8	44.3	0.23	0.061	0.093	23.3

a/ See footnote a/ to Table 2. (All mixes contained 2% $CaCl_2$, by weight of cement).
b/ Value is mean for 2 determinations, made immediately following mixing and 10 minutes later.
c/ Value is that calculated from weights of 3- by 4- by 16-in. prisms when removed from molds.
d/ Halves of prisms from flexural strength test; oven-dried at 220°F before capillarity test.
e/ Air-dried at 73°F, humidity uncontrolled, for several weeks; then soaked at 73°F for 72 hr. before freezing and thawing.
f/ Ratio of 24 hr. 73°F to 5 hr. boil absorption for halves of flexural strength prisms; oven-dried at 220° F before soaking.
g/ Single value obtained immediately following mixing.

Table 7. Results of Automatic Freezing-and-Thawing Tests.[a]

Mix designa-tion[b]	Percent air		No. of F.& T. cycles		Change in dyn. E_1	Durability factor DFE_1[d] (based on 100 cycles)	Absorption						Saturation coefficient[g]		
	Plastic concrete[c]	F.& T. prism 1-day	Total	for 30% drop in dyn. E_1			24 hr soak[e]		72 hr soak[f]		Max during F.& T.		24 hr soak (abs. spec.)	72 hr soak F.& T. prism	Max during F.& T.
							by wt	by vol.	by wt	by vol.	by wt	by vol.			
					%		%	%	%	%	%	%			
PC3M-2	29.3	26.9	100	---	-20.0	0.29	27.2	21.7	20.7	17.0	32.0	26.3	0.37	0.29	0.44
PCS3M-1	23.7	22.6	93[l]	93	-30.7	0.67	12.1	12.9	14.4	15.4	18.6	19.9	0.29	0.35	0.45
PCS3M-2	26.9	24.8	93[l]	---	-11.8	0.78	11.2	11.6	17.6	17.8	23.1	23.4	0.22	0.35	0.46
PCS3M-3	29.3	27.2	100	---	-15.5	0.60	13.3	13.4	17.7	17.5	25.1	24.9	0.25	0.33	0.47
PC1M-2	27.5[k]	25.6	100	---	- 9.8	0.68	25.3	21.3	18.2	15.9	27.2	23.7	0.36	0.26	0.39
PN3M-2	28.1	25.1	100	---	+ 1.9	1.00	24.3	18.4	19.7	15.3	30.6	23.7	0.33	0.26	0.41
PNS3M-1	28.1	25.2	100	---	- 5.5	0.88	10.4	9.8	17.1	16.8	20.0	19.7	0.20	0.34	0.39
PNS3M-2	32.7	30.9	100	---	- 8.5	0.84	11.5	9.9	18.3	16.6	31.5	28.5	0.18	0.28	0.49
PNS3M-4	35.3	33.6	52	33	-59.0	0.15	14.6	12.8	24.0	20.5	38.7	33.0	0.21	0.36	0.58
PN3F-3	32.2	28.0	78	78	-30.0	0.43	22.8	16.6	21.5	16.2	38.4	29.0	0.28	0.27	0.47
PN3V-1	27.7	26.7	100	---	- 7.2	0.72	20.6	14.8	24.7	17.5	33.8	23.9	0.26	0.30	0.41
PN1M-1	28.7	26.7	100	---	+ 1.1	1.00	25.7	19.1	20.8	15.9	36.7	28.0	0.33	0.26	0.47
PG1M-1	27.5	26.6	100	---	-15.4	0.60	28.4	20.6	30.7	22.1	39.0	28.1	0.33	0.36	0.46
GS3M-2	30.5	27.6	18	19	-29.2	0.08	11.5	18.5	14.5	23.4	18.1	29.1	0.50	0.63	0.78
G3M-1a	26.0	25.4	100	---	-14.8	0.79	7.7	12.9	7.0	11.8	9.2	15.6	0.36	0.33	0.43
G3M-1b	26.0	25.4	100	---	-12.8	0.81	7.7	12.9	7.2	12.1	9.2	15.6	0.36	0.34	0.43
Ref-1a[h]	---	---	64	62	-38.9	0.42	5.3[m]	11.8	5.0	11.2	5.1	11.4	0.89	0.83	0.85
Ref-1b[h]	---	---	64	59	-35.5	0.42	5.4[m]	12.1	5.3	11.8	5.4	12.1	0.91	0.90	0.91
Ref-2a[i]	---	---	24	18	-45.8	0.12	5.0[m]	11.4	4.7	10.7	4.9	11.2	0.88	0.82	0.86
Ref-2b[i]	---	---	32	9	-63.5	0.13	5.0[m]	11.4	4.8	11.0	4.9	11.2	0.93	0.89	0.91

(Continued on next page)

Table 7. Results of Automatic Freezing-and-Thawing Tests.[a] (Continued)

Mix designation [b]	Percent air: Plastic concrete [c]	Percent air: F.& T. prism 1-day	No. of F.& T. cycles: Total	No. of F.& T. cycles: for 30% drop in dyn. E_1	Change in dyn. E_1	Durability factor DFE [d] (based on 100 cycles)	Absorption: 24 hr soak [e] by wt	Absorption: 24 hr soak [e] by vol.	Absorption: 72 hr soak [f] by wt	Absorption: 72 hr soak [f] by vol.	Absorption: Max during F.& T. by wt	Absorption: Max during F.& T. by vol.	Saturation coefficient [g]: 24 hr soak (abs. spec.)	Saturation coefficient [g]: 72 hr soak F.& T. prism	Saturation coefficient [g]: Max during F.& T.
					%		%	%	%	%	%	%			
H3M-2	30.9	28.8	100	---	+ 4.6	1.00	11.4	12.2	10.1	10.9	17.9	19.4	0.30	0.27	0.48
H3M-4	34.8	33.1	76	60	-61.5	0.33	20.2	20.6	12.8	12.7	23.3	23.1	0.47	0.29	0.53
HS3M-2	28.7	26.9	100	87	-35.6	0.47	7.5	9.0	11.6	13.7	18.6	21.9	0.22	0.34	0.54
H3F-1	28.6	26.5	100	---	-24.7	0.62	9.4	10.2	13.2	14.1	26.6	28.4	0.22	0.31	0.62
H3F-2a	34.8	32.7	27	22	-45.5	0.08	16.8	16.5	13.1	12.9	32.1	31.6	0.22	0.30	0.73
H3F-2b	34.8	32.7	28	27	-31.8	0.10	16.8	16.5	18.5	17.9	32.1	31.0	0.38	0.42	0.73
H3V-1	31.3	29.5	64[l]	---	- 8.6	0.91	8.9	9.2	11.5	12.0	27.4	28.6	0.21	0.27	0.64
H3V-2a	33.7	31.8	40	33	-44.1	0.20	11.1	11.3	10.4	10.4	30.6	30.7	0.24	0.22	0.65
H3V-2b	33.7	31.8	28	19	-61.1	0.10	11.1	11.3	14.8	14.8	30.8	30.8	0.24	0.31	0.65
H1M-1	31.0	26.4	100	---	- 8.2	0.89	13.8	15.0	11.4	12.4	21.9	23.8	0.34	0.28	0.54
W3M-2	33.1	28.9	76	64	-61.9	0.26	22.4	21.7	15.6	15.1	32.2	31.1	0.39	0.27	0.56
W3V-1	33.3	31.8	98	81	-47.2	0.56	12.1	11.1	12.6	11.6	32.3	29.6	0.19	0.19	0.50
L3F-2	28.5	23.5	100	75	-46.3	0.33	9.6	11.3	14.0	16.1	19.8	22.8	0.25	0.36	0.51
L3V-1	28.0	24.8	100	---	- 5.0	1.00	9.6	11.0	14.0	15.8	19.1	21.5	0.25	0.37	0.50
L3V-2	32.6	32.0	52	37	-48.7	0.22	9.1	9.3	15.3	15.4	30.9	31.2	0.19	0.32	0.63
R3M-3	27.9	26.0	64[l]	---	- 4.2	0.96	11.3	12.7	21.6	22.9	26.0	27.6	0.32	0.61	0.73
RS3M-1	27.5	25.2	100	103	-29.1	0.58	8.2	10.1	14.0	17.2	18.0	22.1	0.23	0.39	0.50

a/ Eight cycles per day; each cycle consisted of freezing (of rectangular cans containing specimens immersed in water) in coolant at 0°F for 3 hr and thawing in bath at 50°F for 3 hr.
b/ See footnote a/ to Table 2. (All specimens except Ref. 1a and 1b contained 2 percent $CaCl_2$ by weight of cement).
c/ Average of two determinations based on unit weights made immediately following mixing and 10 min later.
d/ Area under curve, (when drop in E_1 is plotted versus number of cycles) divided by area for no drop in E; boundaries: -30% E_1 and 100 cycles.
e/ From absorption tests on halves of flexural strength prisms (oven dried prior to testing).
f/ From freezing and thawing prisms moist cured to 7 days, air dried for 3 to 6 weeks at 73°F, humidity uncontrolled, and soaked at 73°F for 72 hr.
g/ Ratio of 24 hr or 72 hr absorption to 5 hr boil absorption; latter value from companion specimens (unfrozen) used in absorption tests.
h/ Sand-gravel concrete, no intentional air, 6 bags normal portland cement per cu yd (no $CaCl_2$).
i/ Sand-gravel concrete, no intentional air, 6 bags high-early-strength cement per cu yd (2% $CaCl_2$)
k/ Single determination based upon unit weight of concrete immediately following mixing.
l/ Failed by cracking at ends, probably due to constraint by container.
m/ Determinations made on freezing and thawing specimens following oven drying *after* freezing and thawing.

Table 8. Thermal conductivity values from guarded hot plate test

Mix designation	Percent air: plastic concrete a/	Percent air: cond. specimens 1-day	Density oven-dry	Thermal conductivity
			lb/cu ft	btu/hr/ft^2/°F/in.
PCS3M-1	23.7 b/	18.4	65.5	2.24
PC1M-2	27.5	24.0	53.4	1.68
PC1M-3	35.1	31.4	48.2	1.45
PN3M-1	25.3	20.6	47.8	1.60
PN3M-2	28.1	21.9	47.8	1.59
PN3F-2	25.3	19.0	50.4	1.65
PN3F-3	32.2	24.8	46.7	1.44
PN3V-1	27.7	26.3	45.2	1.48
PN1M-1	28.7	27.6	45.8	1.40
PN1M-2	35.8	36.2	40.5	1.26
PG1M-1	27.5	25.1	44.4	1.37
G1M-1	24.2 b/	15.3	122.6	6.79
H3M-1	20.5	16.5	81.1	3.02
H3M-2	30.9	22.0	73.0	2.60
H3M-3	31.2	19.1	70.2	2.50
HS3M-1	23.3	19.7	80.2	3.26
H3F-1	28.6	22.1	72.6	2.49
H3V-2	34.8	27.7	65.2	1.93
H1M-1	31.0	22.2	72.0	2.47
W3M-2	33.1	25.1	62.8	1.80
L3M-1	26.0	18.4	79.3	3.07
L3F-1	28.1	24.6	77.1	2.71
L3V-1	28.0	22.9	73.7	2.70
L3V-2	32.6	29.2	67.1	2.07
Cellular c/	71.0	70.0	20.0	0.65

a/ Based on average density of two samples of plastic concrete, one taken immediately following mixing and the other 10 min later.

b/ Based on single density determination for sample taken immediately following mixing.

c/ Foamed cement paste.

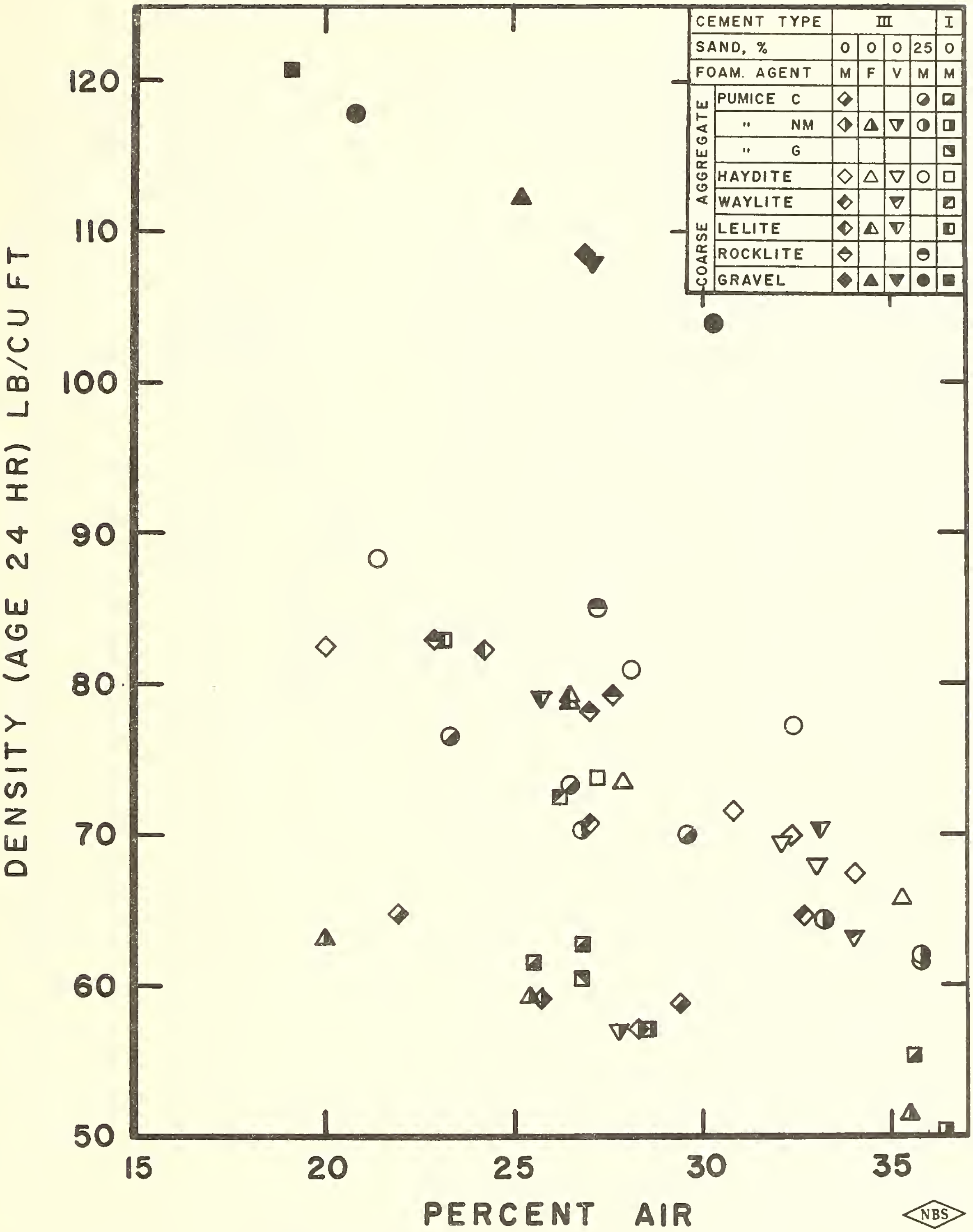

Fig. 1 - Density versus air content calculated from the weight of 6- by 12-in. concrete cylinders 24 hr old.

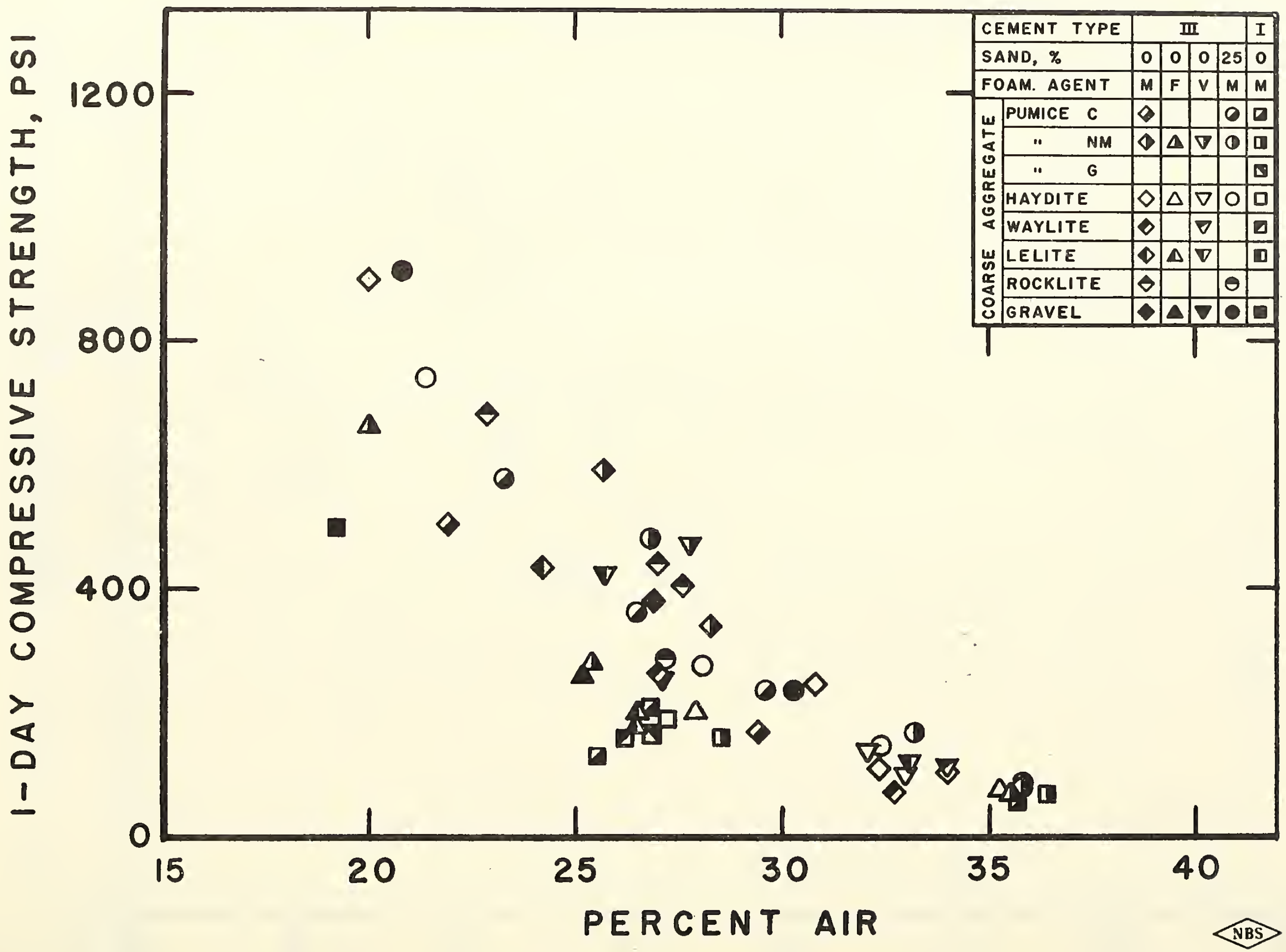

Fig. 2A - Compressive strength of 6- by 12-in. concrete cylinders at age of 24 hr versus air content based on the density of the cylinders.

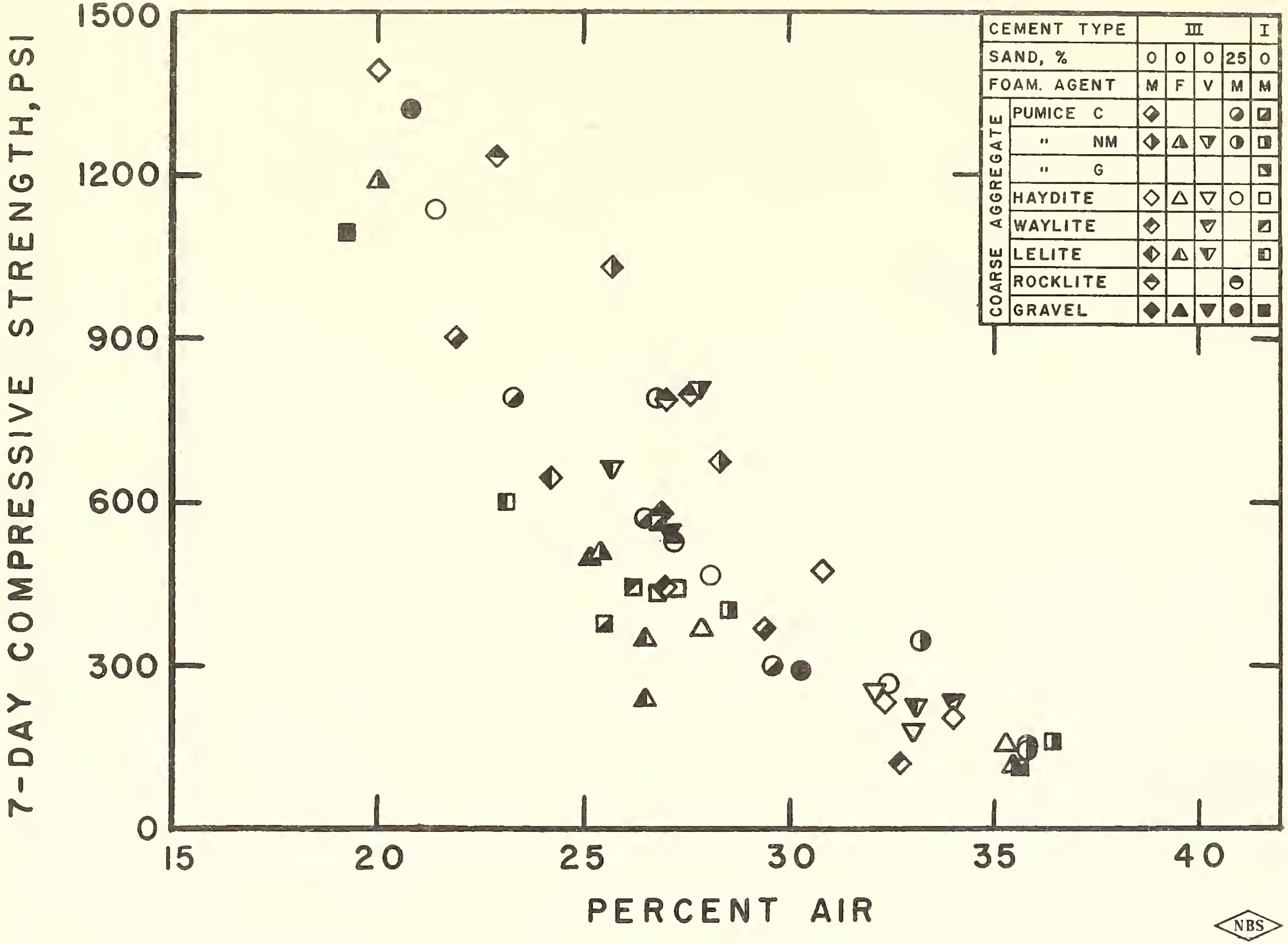

Fig. 2B - Compressive strength of 6- by 12-in. concrete cylinders at age of 7 days versus air content based on the density of the cylinders at age of 24 hr.

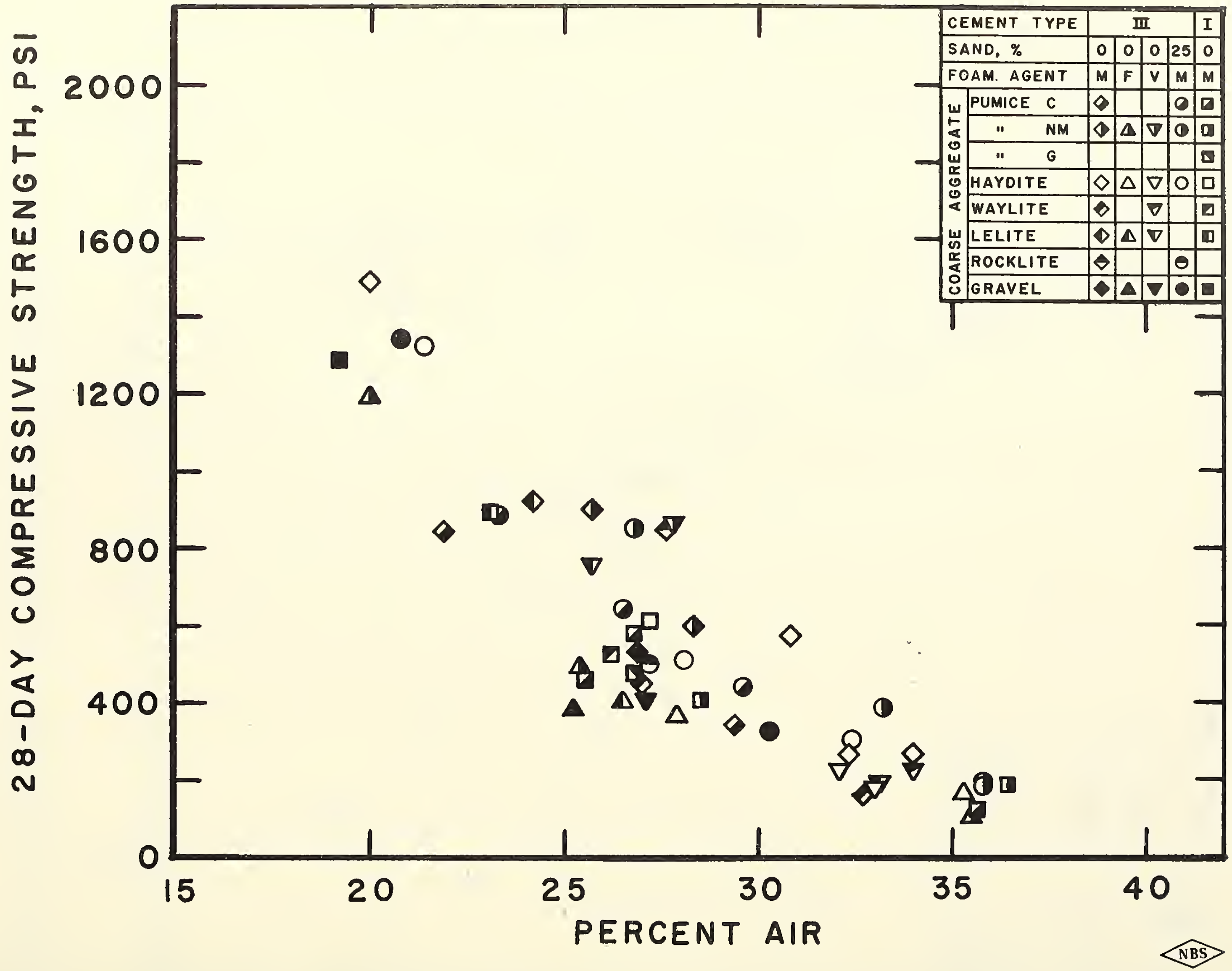

Fig. 2C - Compressive strength of 6- by 12-in. concrete cylinders at age of 28 days versus air content based on the density of the cylinders at age of 24 hr.

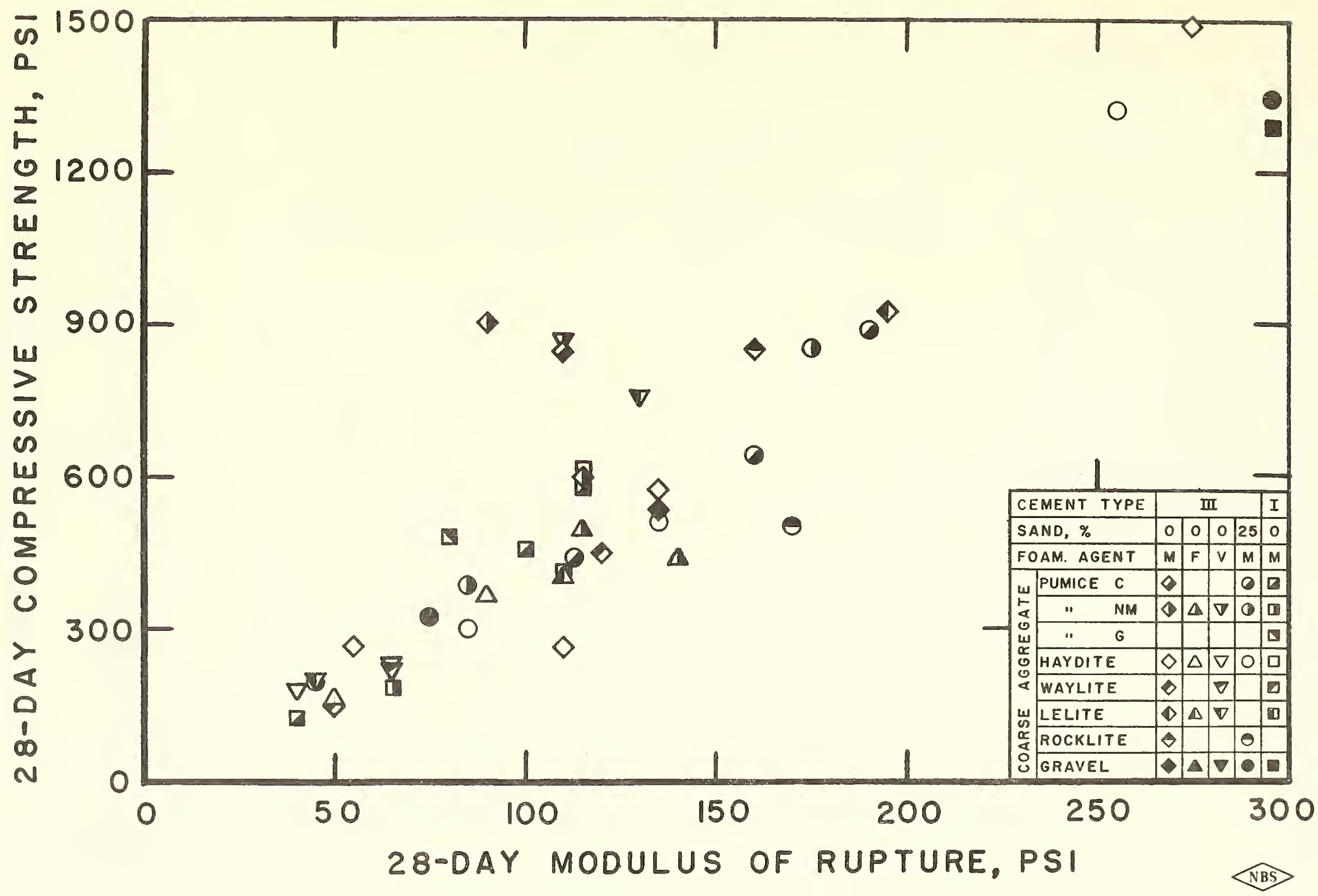

Fig. 3 - Compressive strength of 6- by 12-in. concrete cylinders at age of 28 days versus modulus of rupture of 3- by 4- by 16-in. prisms at the same age.

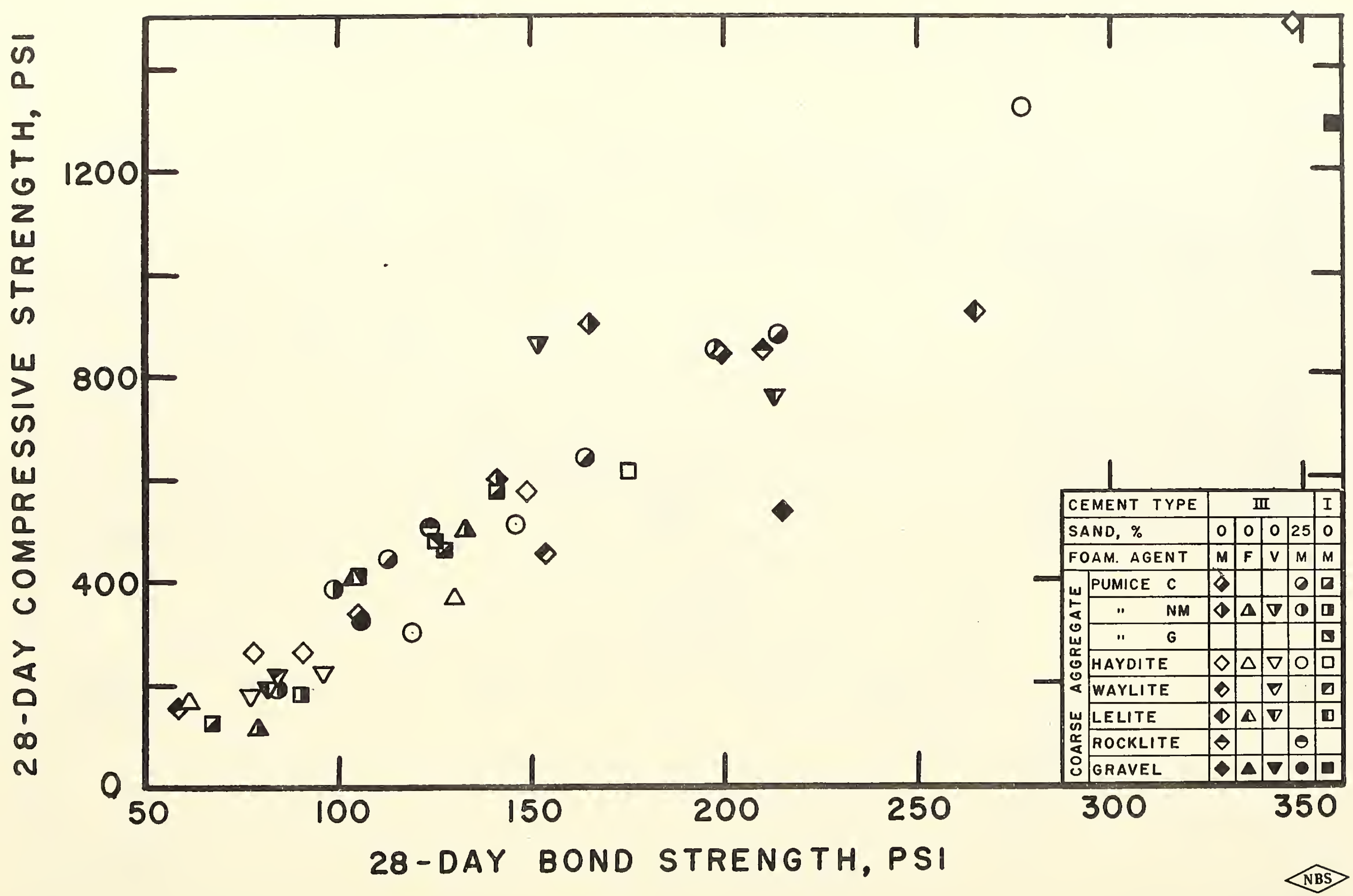

Fig. 4 - Compressive strength of 6- by 12-in. concrete cylinders at age of 28 days versus bond strength of 6- by 6- by 12-in. pullouts with 7/8-in. round deformed bars at the same age.

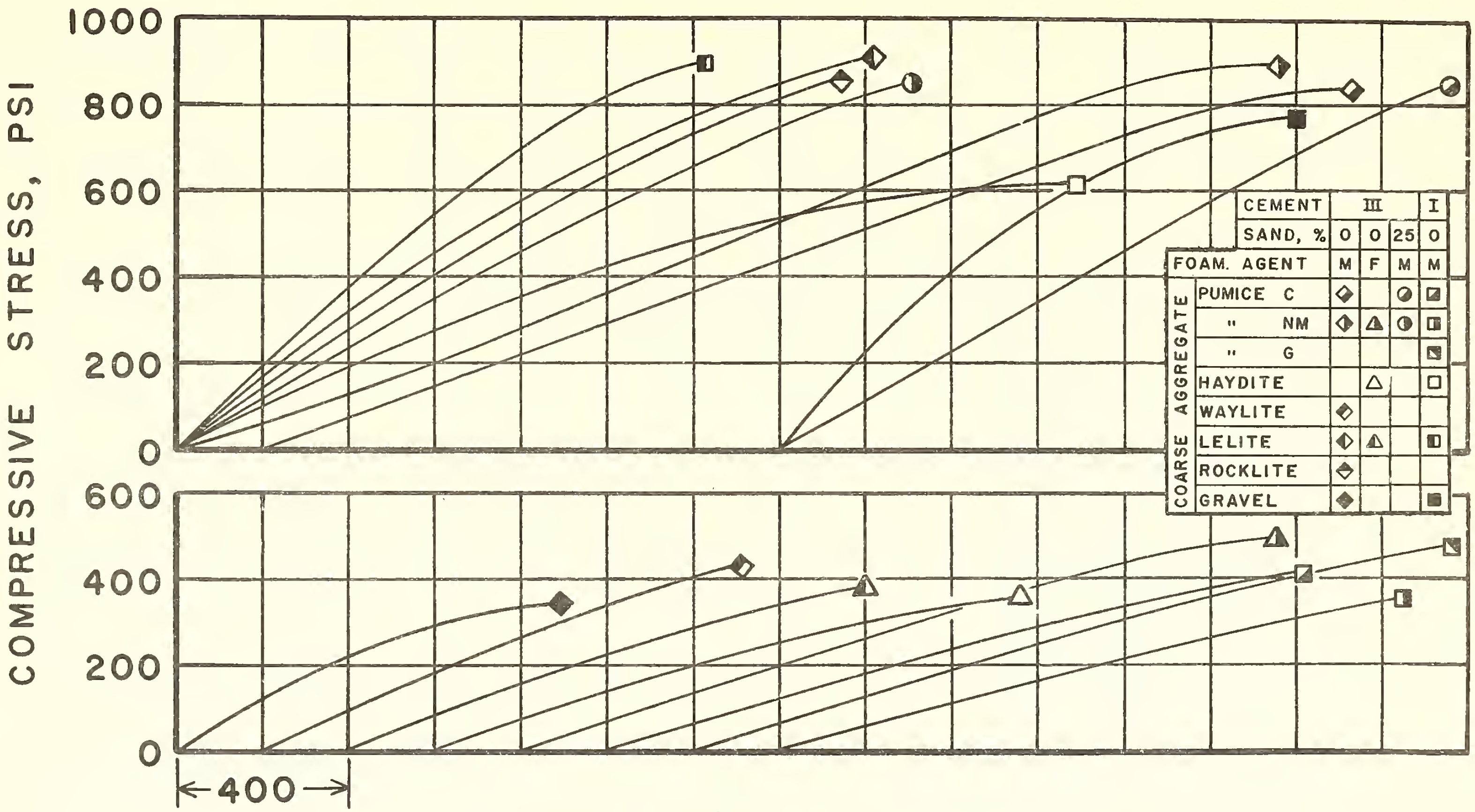

Fig. 5 - Typical stress-strain curves for 6- by 12-in. cylinders tested in compression at age of 28 days. (Note that the origins of some of the curves are offset).

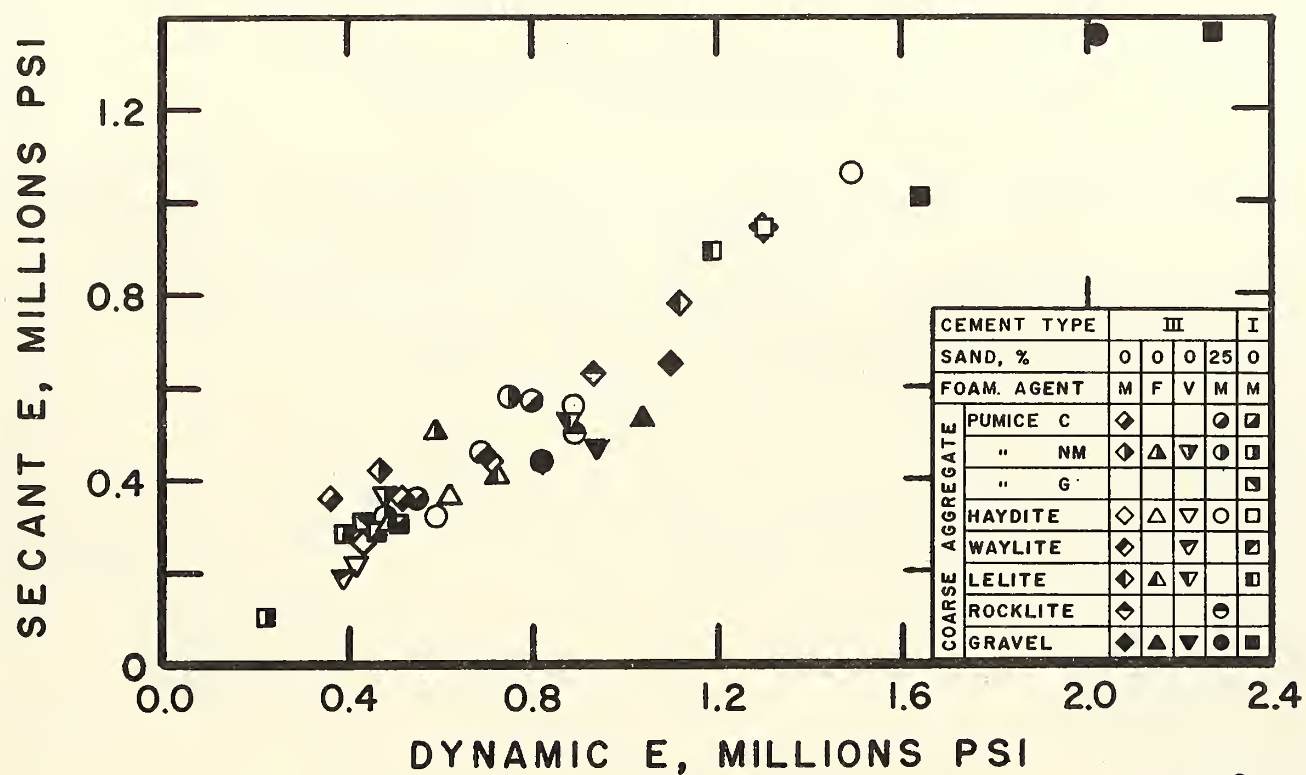

Fig. 6 - Dynamic E calculated from fundamental longitudinal resonance frequency measured at age of 28 days on 6- by 12-in. concrete cylinders versus secant E determined from stress-strain curves at a strain of 0.0005.

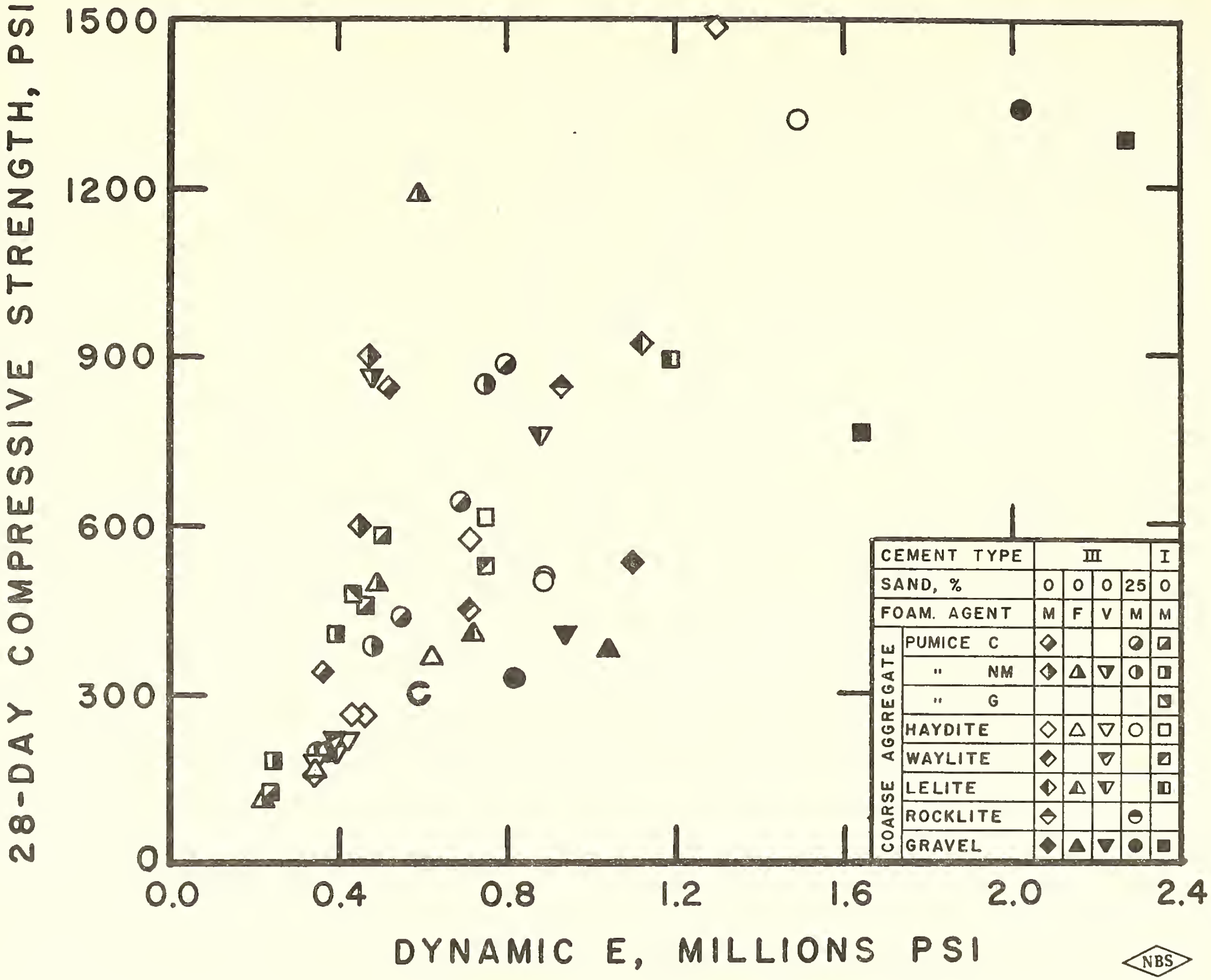

Fig. 7 - Compressive strength of 6- by 12-in. concrete cylinders at age of 28 days versus the dynamic E (longitudinal) determined at the same age upon the same cylinders.

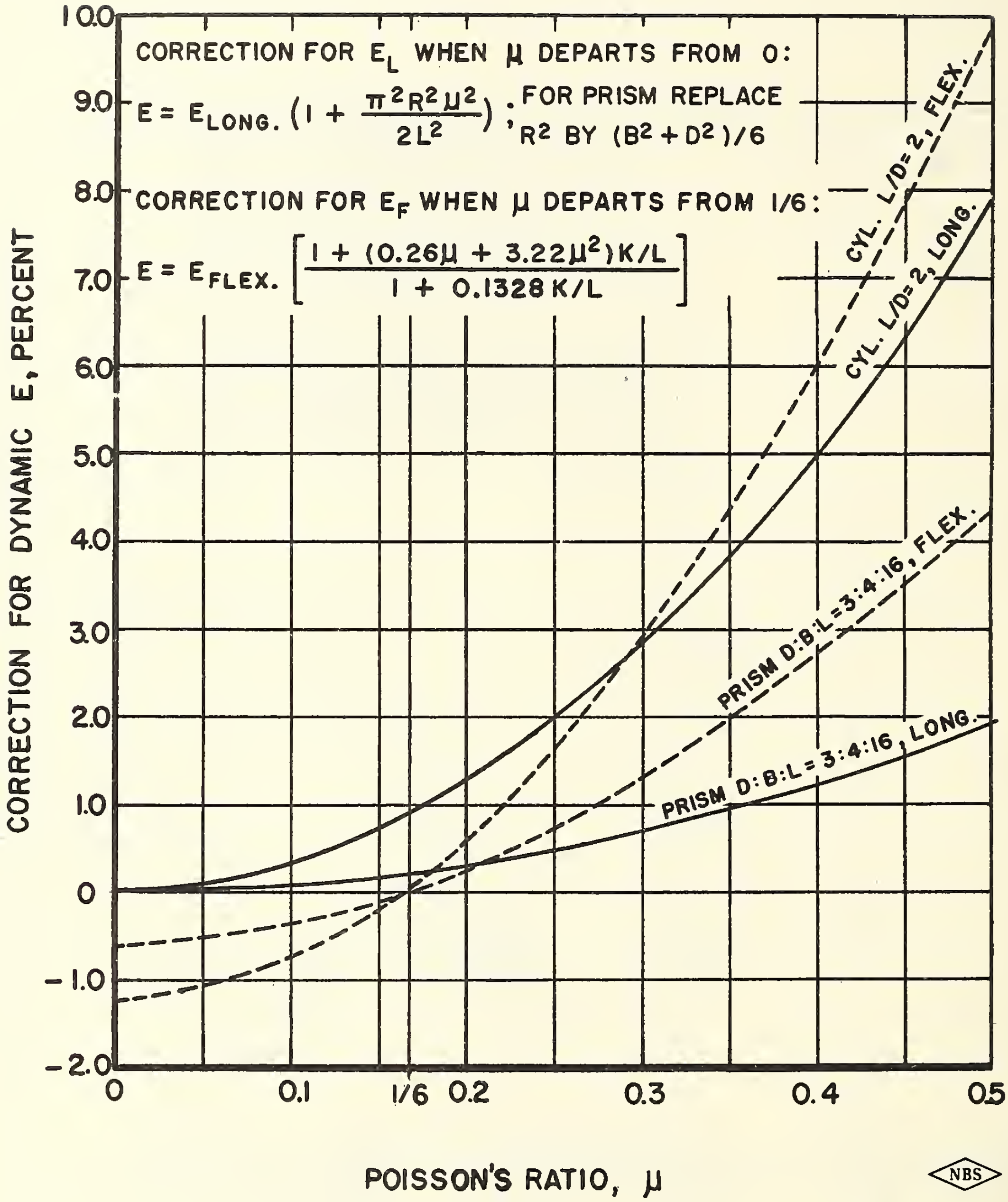

Fig. 8 - Corrections for dynamic E (longitudinal) when Poisson's ratio is different from 0, and for dynamic E (flexural), calculated according to Pickett's equation, when Poisson's ratio is different from 1/6. R is the radius of a cylinder, B is the breadth and D the thickness of a prism, L is the length, μ is Poisson's ratio and K is the radius of gyration of the cross-section of a prism about the neutral axis.

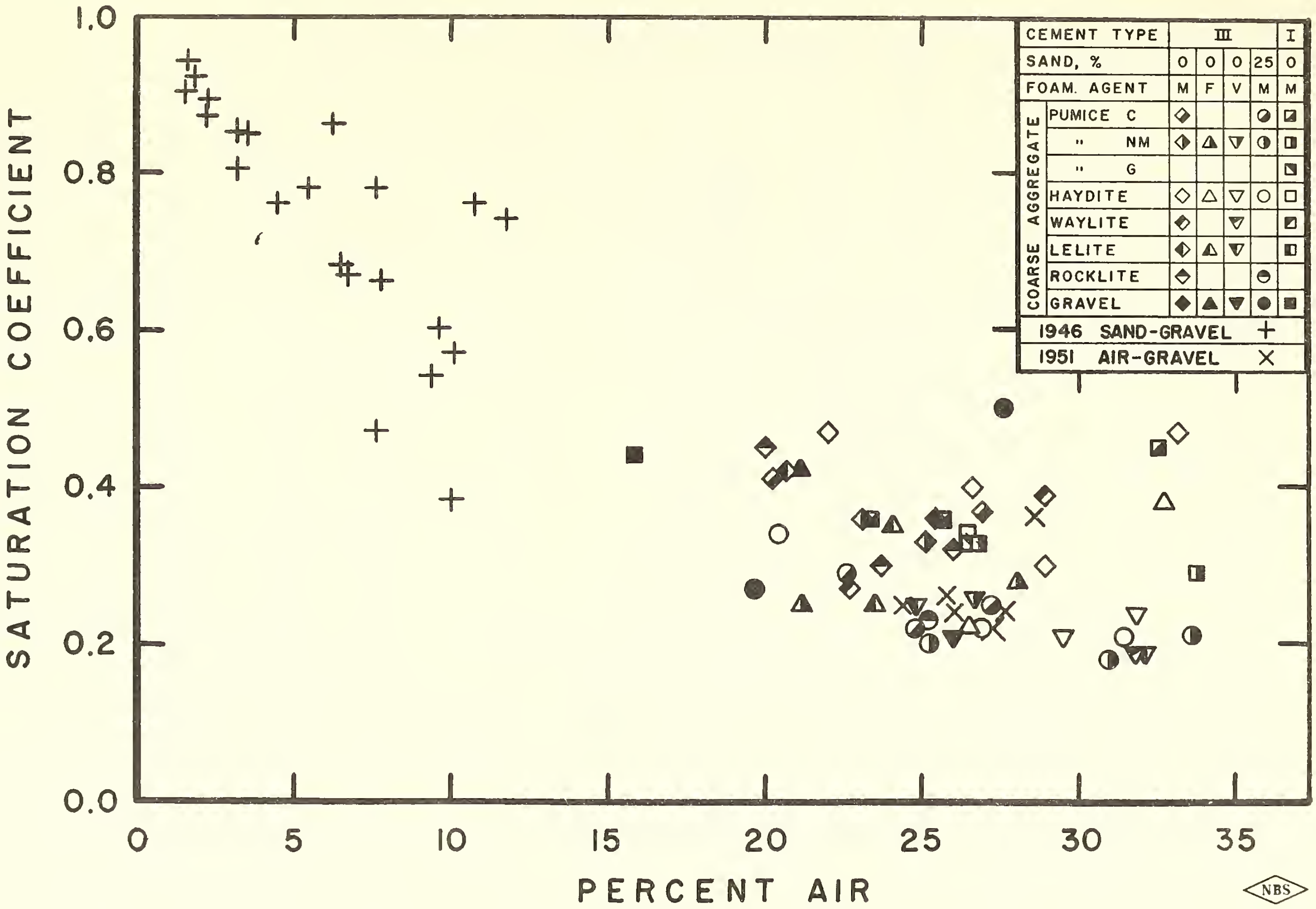

Fig. 9 - Saturation coefficient versus air content of halves of 3- by 4- by 16-in. prisms. The saturation coefficient is the ratio of the absorptions determined by soaking at 73 F for 24 hr and boiling for 5 hr; the air content is based upon the weight of the prisms at the age of 24 hr.

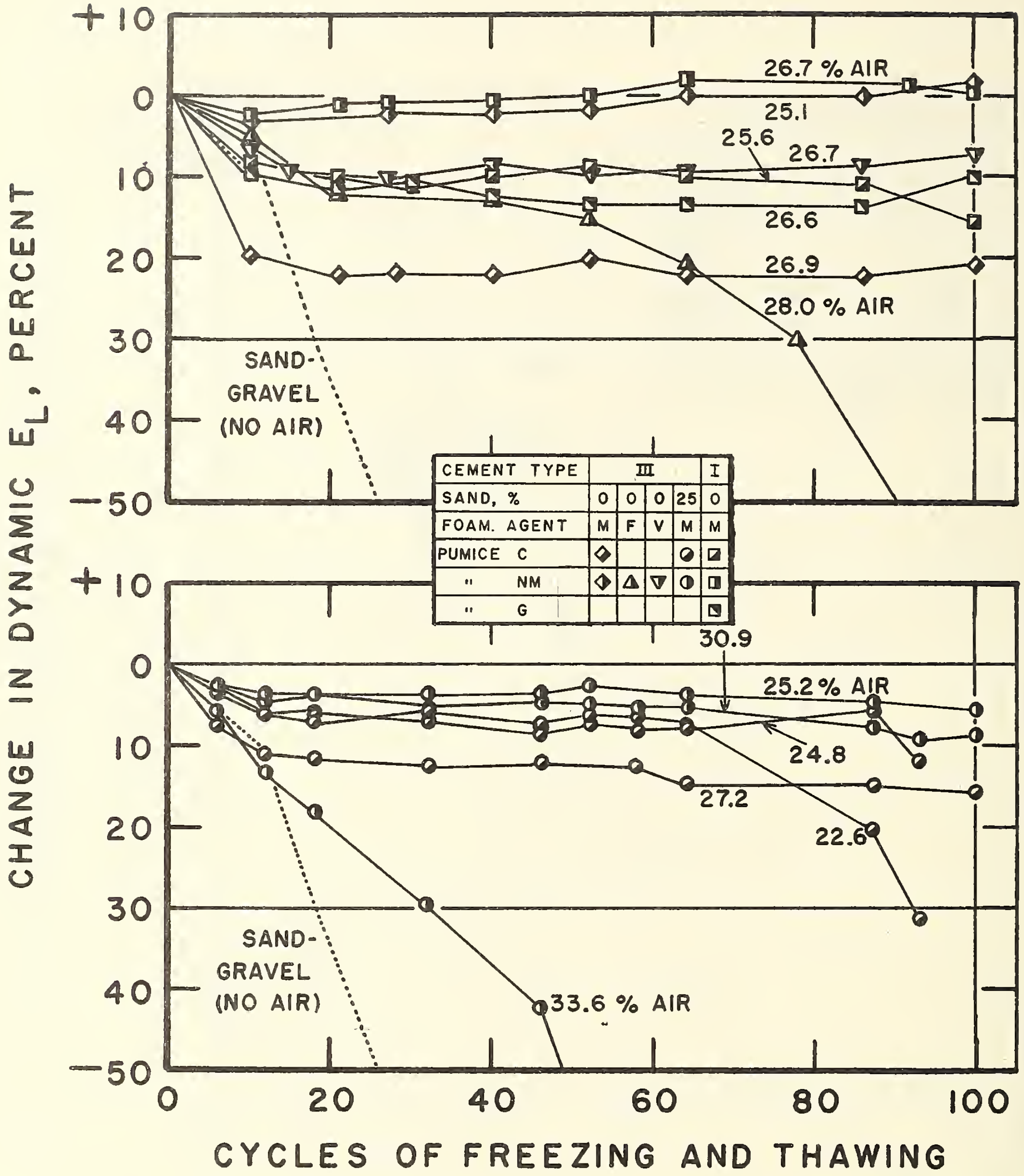

Fig. 10A - Change in dynamic E (longitudinal) versus the number of cycles of automatic freezing and thawing for 3- by 4- by 16-in. prisms of concrete made with various lightweight aggregates. Each cycle consisted of 3 hr immersion periods (of cans containing individual specimens covered with water) alternately in baths at 0 F and 50 F. Note indicated air contents which are based upon the weight of the prisms at an age of 24 hr. Note also, Figure 10A, dotted curves for a sand-gravel concrete containing 6 bags of Type III cement per cu yd, and no entrained air. All mixes contained 2% of calcium chloride, by weight of cement.

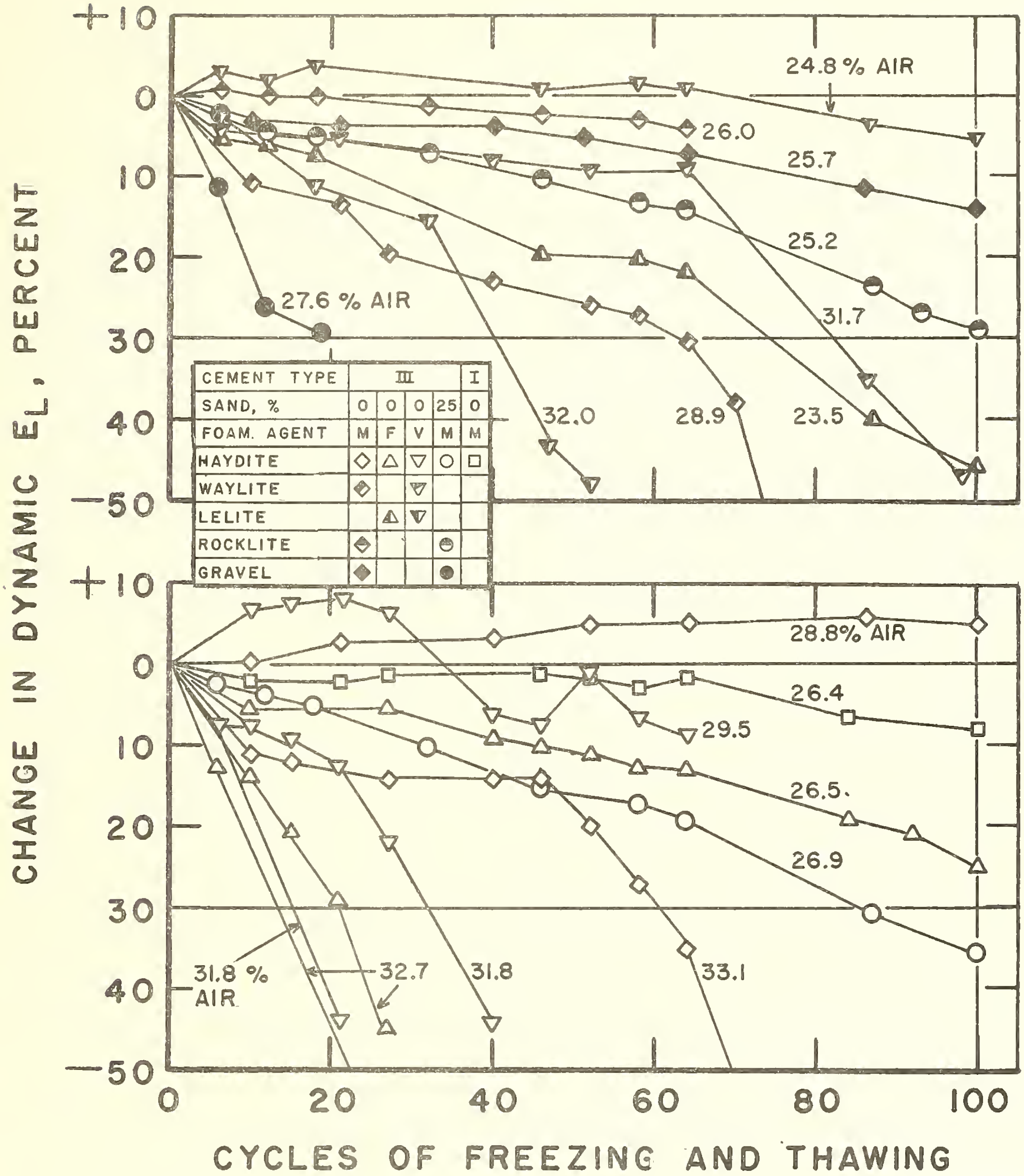

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Fig. 10B - Change in dynamic E (longitudinal) versus the number of cycles of automatic freezing and thawing for 3- by 4- by 16-in. prisms of concrete made with various lightweight aggregates. Each cycle consisted of 3 hr immersion periods (of cans containing individual specimens covered with water) alternately in baths at 0 F and 50 F. Note indicated air contents which are based upon the weight of the prisms at an age of 24 hr. Note also, Figure 10A, dotted curves for a sand-gravel concrete containing 6 bags of Type III cement per cu yd, and no entrained air. All mixes contained 2% of calcium chloride, by weight of cement.

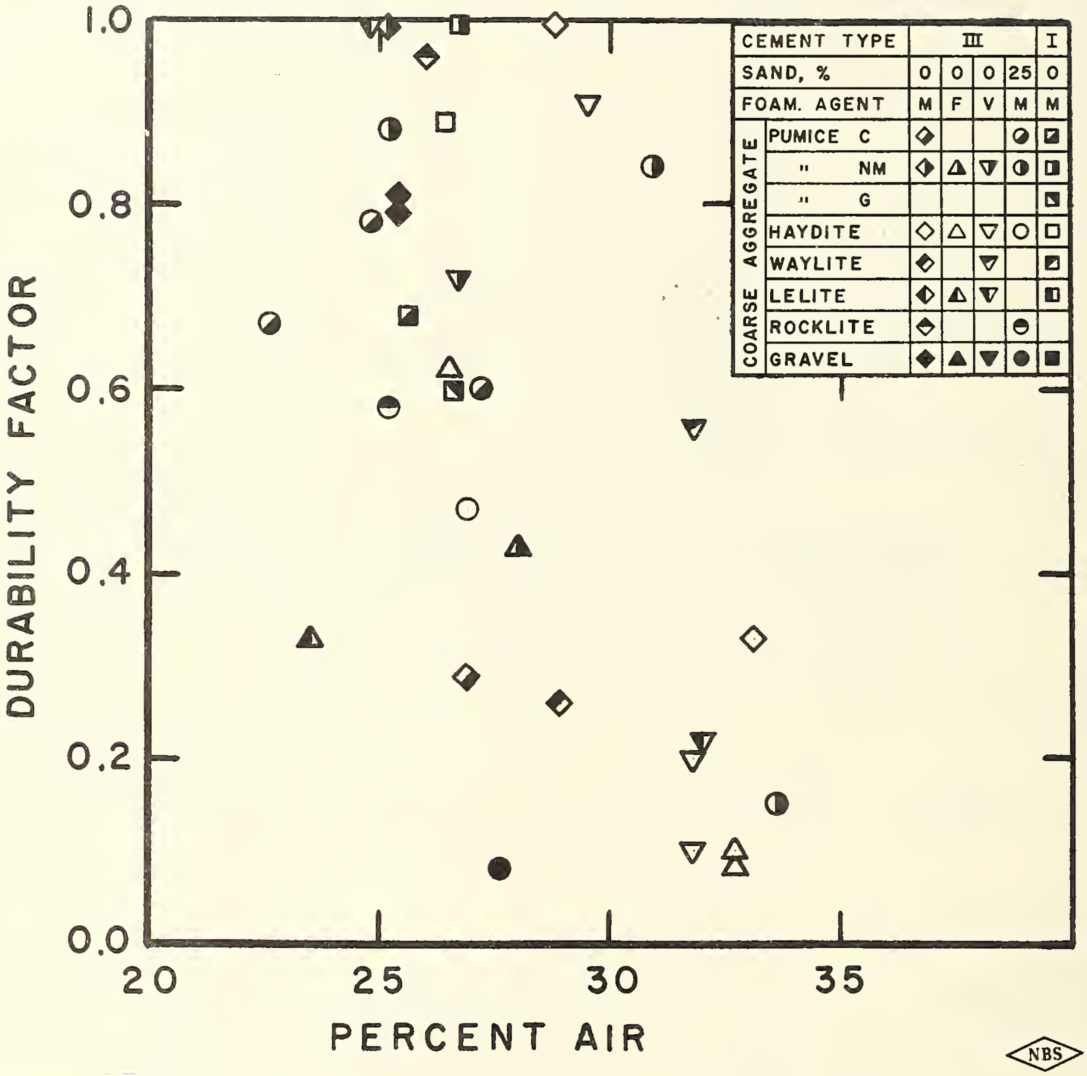

Fig. 11 - Durability factor, based on dynamic E (longitudinal), versus air content of the freezing and thawing specimens. The durability factor is the ratio of the area under the curve (Figure 10A, B) within the rectangle bounded by ordinates 0,30 and abscissal 0,100, to the entire area of the rectangle. The air content is based upon the weight of the specimens when 24 hr old.

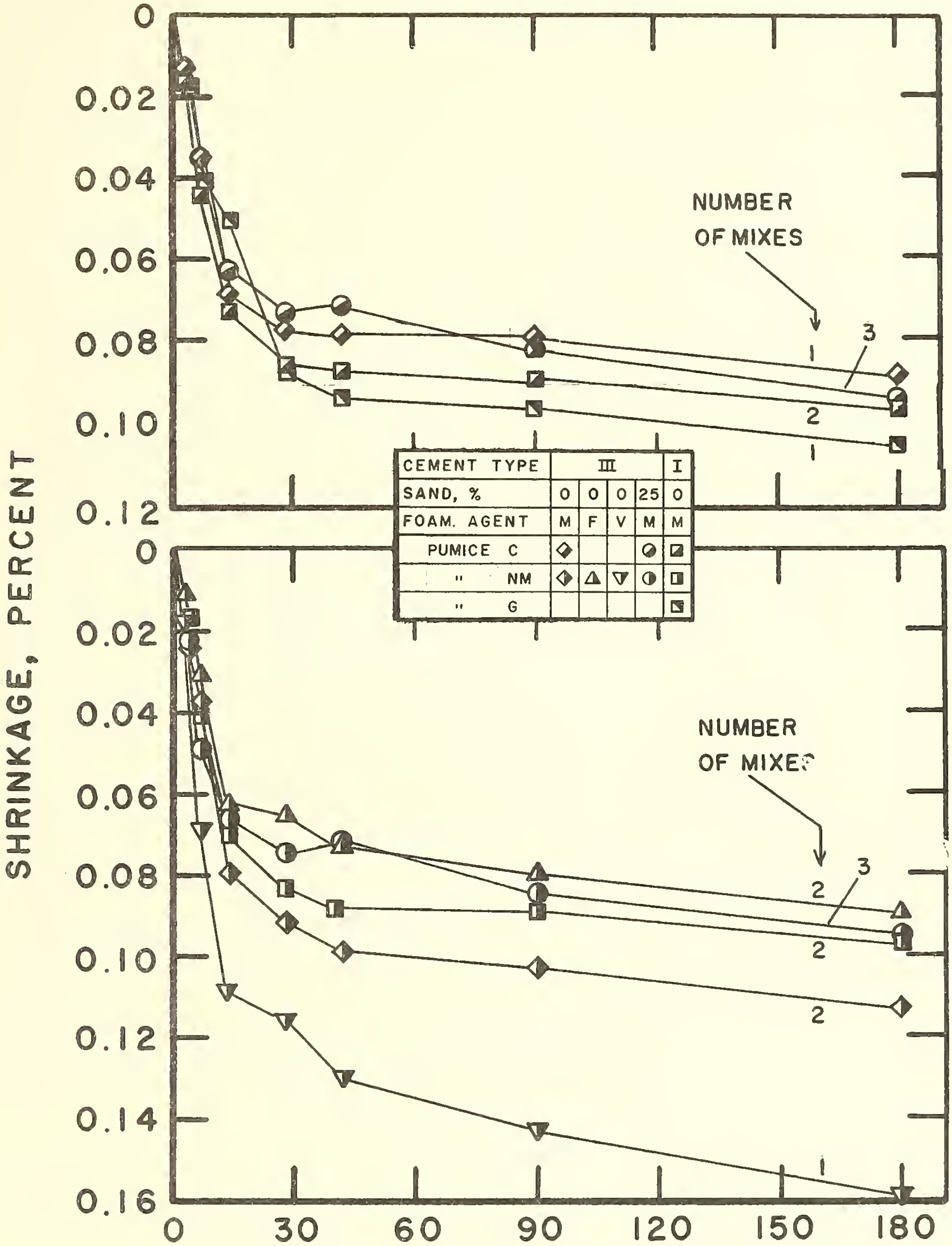

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Fig. 12A - Shrinkage versus drying time for 2- by 2- by 12-in. concrete prisms dried at 73°F, 50 percent relative humidity after storage in water at 73° F until 7 days old. (Note indication of number of mixes represented by each curve; two specimens were tested for each mix).

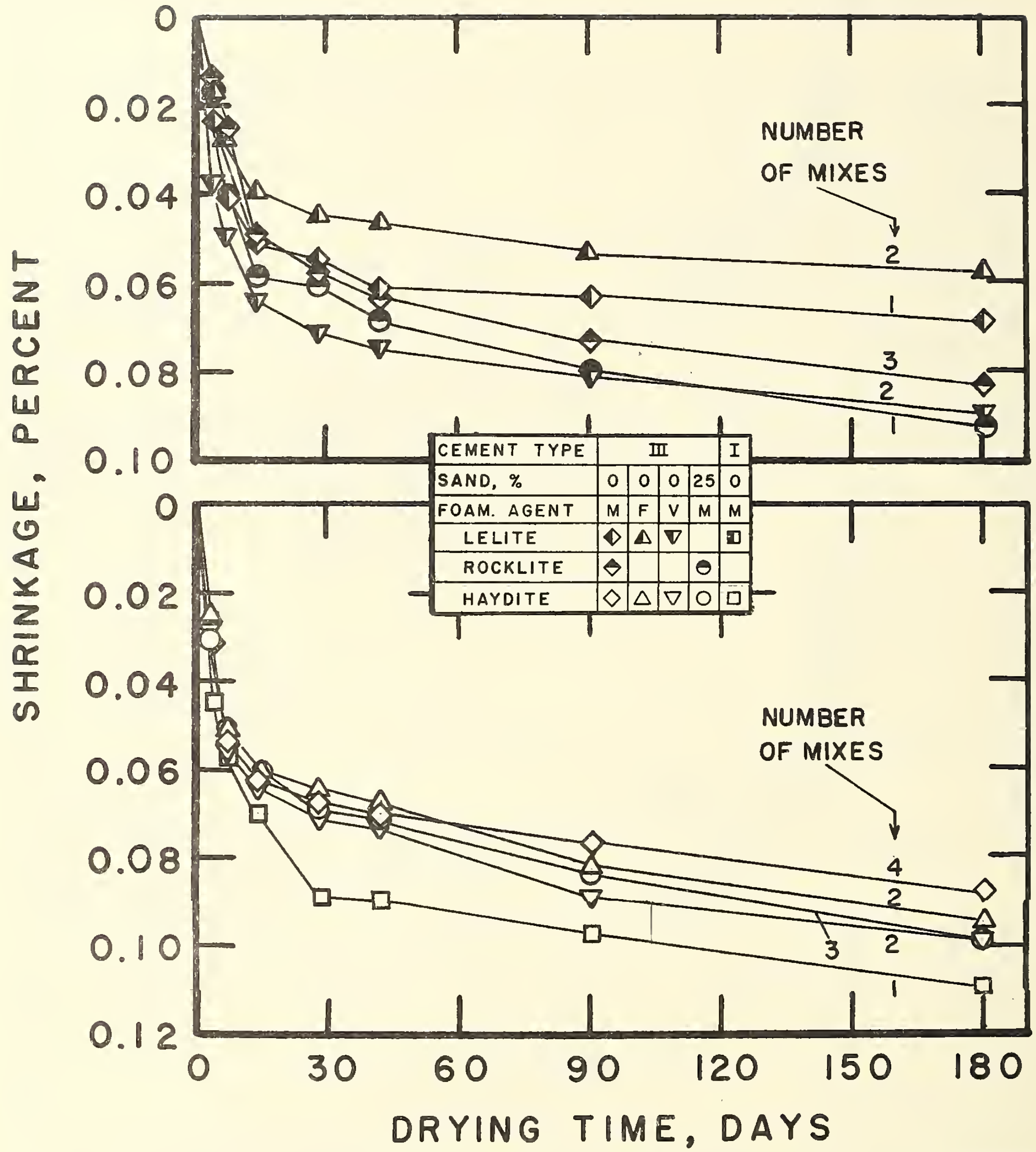

Fig. 12B - Shrinkage versus drying time for 2- by 2- by 12-in. concrete prisms dried at 73°F, 50 percent relative humidity after storage in water at 73°F until 7 days old. (Note indication of number of mixes represented by each curve; two specimens were tested for each mix.

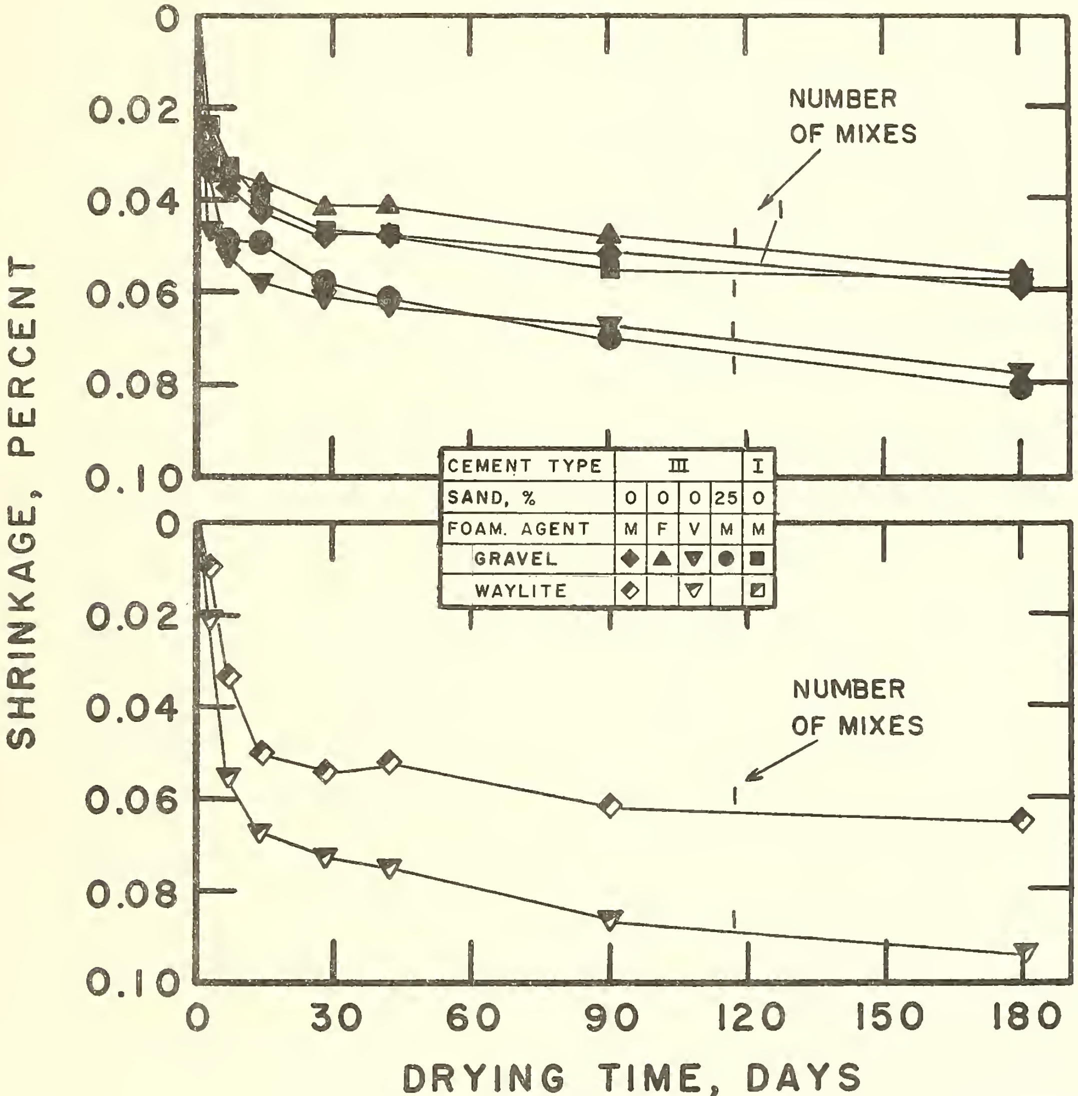

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Fig. 12C - Shrinkage versus drying time for 2- by 2- by 12-in. concrete prisms dried at 73° F, 50 percent relative humidity after storage in water at 73° F until 7 days old. (Note indication of number of mixes represented by each curve; two specimens were tested for each mix).

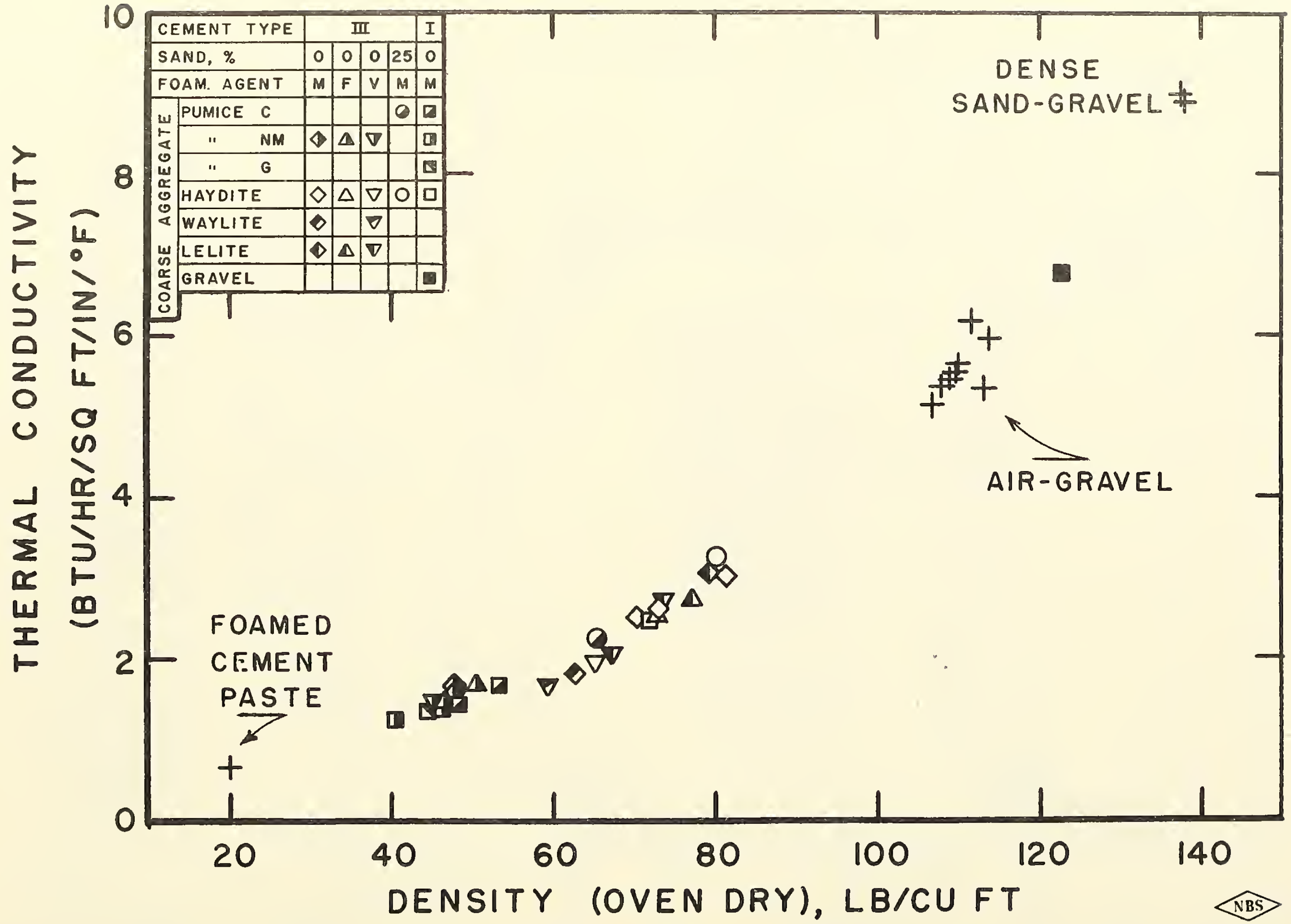

Fig. 13 - Thermal conductivity of 1- by 8- by 8-in. concrete plates, as determined in guarded hot-plate apparatus versus oven-dry (24 hr, 220 F) density.

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.00). Information on calibration services and fees can be found in NBS Circular 483, Testing by the National Bureau of Standards (25 cents). Both are available from the Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

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