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A Study of the Concrete Making Properties of Idealite Lightweight Expanded Shale Aggregate

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CONCRETE MAKING PROPERTIES OF IDEALITE LIGHTWEIGHT EXPANDED SHALE AGGREGATE - AHLSKOG

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A STUDY OF THE CONCRETE MAKING PROPERTIES OF IDEALITE LIGHTWEIGHT EXPANDED SHALE AGGREGATE

by

John J. Ahlskog

A Thesis
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Civil Engineering

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This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 29, 1961
Date

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For their financial assistance, I am indebted to the Ideal Cement Company. The Albuquerque Gravel Products Company and the Robert E. McKee Construction Company gave much assistance and co-operation during the course of this investigation.

I am especially grateful to Benjamin F. Snow for his help, constructive criticisms, and moral support.

For his direct assistance and advisement, a very personal acknowledgement is due to Professor William C. Wagner, the Chairman of the Civil Engineering Department at the University of New Mexico.

To Elaine, whose spiritual help and love enabled me to do this research, I owe my undying gratitude.

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I. THE PROBLEM

1. Lightweight Structural Concrete

The value of lightweight aggregate for structural concrete purposes has long been recognized as an effective means for reducing the dead weight of a composite structure. The use of structural components whose strength is equal to or better than that of conventional members can reduce design problems and ultimate construction costs.

A reduction in the dead weight of a reinforced concrete structure automatically means a reduction in design moments and shears; consequently, less reinforcing steel and less concrete area is necessary to construct a sound structure.

Lighter concrete will decrease erection and handling difficulties and thereby reduce labor costs.

The widespread use of prestressed concrete members in the past few decades has increased the benefits which can be gained by using lightweight aggregate concrete. The advent of precasting plants has increased the benefits even more. It stands to reason that handling and transporting a beam or girder will be cheaper if the

member's weight is reduced. Conceivably within the next ten or twenty years, precast structural concrete members will be fabricated, stockpiled, and catalogued in modular shapes analgous to the manner in which rolled steel sections are available at the present time.

Lightweight aggregate lends itself perfectly to the precast structural concrete field and will promote the widespread use of concrete members in place of steel members.

2. Advantages of Idealite

Among the many commercially produced lightweight aggregates, Idealite seems to exhibit many desirable qualities. According to the available literature, the expanded shale group of lightweight aggregates are capable of producing concrete with excellent structural characteristics, and one researcher found that expanded shale aggregate produced in rotary kilns resulted in the lowest weight aggregates of the ten groups that he studied.[1] While having low creep and shrinkage values, Idealite has been found to give strengths equal to or better than that of conventional sand and gravel concretes. Idealite concretes are also reported to have excellent workability properties.[2]

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[1] Shideler, J.J., "Lightweight Aggregate Concrete for Structural Use," ACI JOURNAL, October 1957, Proc. Vol. 54, p. 327.

[2] "Properties of Idealite Expanded Shale Lightweight Aggregate," Prepared by Greatwestern Aggregates, Inc., Denver 2, Colo., Revised 1957, p. 14.

Concrete made from most lightweight aggregates will have a lower modulus of elasticity than do ordinary concretes. This can be advantageous in the design of reinforced concrete members. Because of the higher "n" value, more of the member's load is thrown to the reinforcing steel, and less concrete is required to resist a given moment.

3. Disadvantages of Idealite

The use of Idealite as a lightweight concrete aggregate does have several drawbacks. Because it is a commercially produced aggregate, its cost is many times that of conventional aggregates, and care must be taken before using it as a solution to all structural concrete problems. The extra aggregate costs must effect a proportional savings elsewhere to justify the usage of Idealite. As is the case in many lightweight aggregates, Idealite concrete has a lower modulus of elasticity than does ordinary concrete.[3] This means that beams made from Idealite concrete will have correspondingly greater deflections. Many engineers feel that concretes made from lightweight aggregates have greater creep strain values than conventional concrete. This would make it extremely difficult to design prestressed or posttensioned members made from lightweight aggregate concrete. Shideler claims that many concretes made from

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[3] Ibid.

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[3] Ibid.

lightweight aggregates have creep strain values equal to or less than those of corresponding sand and gravel concretes, particularly at early ages. He found that these lightweight aggregates exhibited more creep strain after a period of one year.[4] It would seem that research is needed to determine creep strain values for most lightweight aggregates, especially to determine the long term results. Idealite concrete exhibits creep strain values which are less than those of conventional concrete until a period of one year has elapsed.[5] Additional research is needed to determine the creep strain which occurs after periods longer in duration than one year.

One of the most pressing problems to be solved before using Idealite as a structural concrete is that of the determination of a competent, efficient, and simple mix design procedure. No concrete structure, whether plain, reinforced, prestressed, or precast, can be economically planned without a competent and accurate mix design as its basis.

3. Mix Design Problems

The design of a concrete mix using Idealite as an

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[4] Shideler, op. cit., p. 321.

[5] "Properties of Idealite Expanded Shale Aggregate," op. cit., pp. 11-12.

aggregate presented many special problems. The aggregate used was available from the manufacturer in three separate size fractions, and each of these fractions exhibited different absorption rates, different total absorption values, and different specific gravities. All of these variations contributed to the difficulty of determining and evaluating a mix design procedure.

The American Concrete Institute sums up the task of lightweight concrete mix design as follows, "The question of how much water is absorbed and how much water actually occupies space in the concrete is the principal difficulty in proportioning by absolute volume procedures.... The high rates of absorption and the fact that the absorption may continue at a high rate for several days make it difficult to determine correct values of absorption and specific gravity of the aggregate. Because of these complications the established relationships cannot be applied with the same confidence as for normal aggregates."[6]

The variations in the properties of the aggregate made it impossible to estimate accurately the final volume of a proposed mix until all of the ingredients were combined. In most presently used mix design methods, it is

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[6] ACI Committee 613, "Recommended Practice for Selecting Proportions for Structural Concrete," <u>ACI JOURNAL</u>, September 1958, Proc. Vol. 55, p. 306.

essential to know the ultimate yield of a combination of cement, water, and aggregate to estimate the ultimate strength, durability, workability, and economy of concrete mix; therefore, a trial mix program to determine the yield data for Idealite was suggested.

The densification of a concrete in the field is presently brought about using vibratory equipment. To closely correlate laboratory and field conditions, it seemed logical to use vibration equipment to densify laboratory test specimens.

Cement is the most expensive ingredient in practically all concrete mixes, and most authorities contend that the cement-water paste in a concrete mix is responsible for most of the shrinkage and resulting volume changes of the concrete structure. To minimize costs and to reduce shrinkage, as little cement paste as possible is therefore desirable in Idealite concrete mixes.

With the preceding difficulties in mind, a method for accurate mix design was formulated and tested with hopes that the resulting information would benefit the general public as well as the engineering profession by eliminating some of the unknown factors in Idealite expanded shale aggregate concrete mixes.

II. DESCRIPTION OF MATERIALS

1. Water and Cement

The water used in the laboratory work was obtained from the sources located in the Civil Engineering Concrete Laboratory at the University of New Mexico. It was assumed to be at a constant temperature, or nearly so. The cement used in the experimental work was type I portland cement obtained from the Ideal Cement Company. It was made at their Tijeras plant and was certified as meeting A.S.T.M. requirements for type I portland cement.[7]

2. Aggregates

The Idealite expanded shale aggregate used was obtained from the Robert E. McKee Construction Company stockpiles at Tijeras, New Mexico. It was surplus material from the construction of the Ideal Cement Plant located there.

The aggregate was manufactured at Laramie, Wyoming, and was shipped to New Mexico by rail.

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[7] "Standard Specifications for Portland Cement," 1958 Book of ASTM Standards, Part 4, (American Society for Testing Materials: Philadelphia, 1958), pp. 1-5.

3. Aggregate Manufacture

Briefly, the aggregate manufacturing process involves mining the shale from the soft shale deposits located near Laramie, Wyoming. The shale is then ground and screened into three separate portions from which the fine, the medium, and the coarse fractions of Idealite will be made. Then the shale is passed through rotary kilns where the high temperatures cause the moisture and gases within the shale to expand rapidly. This creates a "popcorn" effect and causes the shale particles to expand. A network of minute voids within the kilns also causes the outer surface of each particle to melt slightly. As the particles are removed from the kiln and cooled, the outer surfaces solidify and form a relatively hard and impervious coating.

After the expanded aggregate cools, it is again divided into three size fractions ranging from the U.S. sieve size designations $\frac{3}{4}$" to #4, #4 to #16, and minus #16 material. The aggregate is then ready for sale to the customer.

4. Aggregate Physical Appearance

The individual aggregate particles ranged from a

chocolate brown to a dull white in color and were generally rounded in shape. When broken open, the internal structure of each particle was porous and sponge-like internally but had a thin shell-like coating. Externally, each particle had a generally sealed surface with few visible cracks.

III. PARAMETERS

1. Slump Was Kept Constant

To restrict the number of variables present throughout the laboratory work, the standard slump test was used, and the slump of each mix was kept within a range of one to two inches.[8] At first glance, this slump range seemed to be too low to be typical of mixes with sufficient workability, but after considering several factors peculiar to lightweight aggregates and Idealite in particular, the low slump value seemed to be justified. First of all, a lightweight concrete will be more workable than ordinary sand and gravel concrete with the same slump value due to the weight factor alone. The lighter weight makes it physically easier for laborers and masons to work with Idealite concrete. A stiffer mix will be easier to place in the forms for this reason. Secondly, the available literature pointed out that a two-inch slump in Idealite concrete resulted in workability equivalent to a five-inch slump in ordinary concrete.[9] Subsequent laboratory work appeared to verify this claim.

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[8] Ibid., pp. 718-719.

[9] "Properties of Idealite Expanded Shale Aggregate," op. cit., p. 14.

2. Cement Content

Because cement is generally the most expensive constituent of any concrete mix, it is important to know the change in concrete quality which results from a variation in cement content; therefore, cement content was chosen as one of the essential mix parameters for a conclusive and comprehensive analysis of the concrete making properties of Idealite expanded shale aggregate.

3. Per Cent Fines

The cost of the fines in any aggregate group usually exceed that of the larger aggregate sizes. This would be true of Idealite in most localities due to the higher shipping cost of the fines. Idealite fines have a higher weight per cubic foot than do the larger aggregate particles. Since shipping costs are based on weights, the cost of Idealite fines at the job site would be proportionately higher at job sites located long distances from the Idealite manufacturing plant.

Because a given volume of fine particles has a greater amount of surface area to offer than the same given volume of coarse particles, any excess amount of fines in a concrete mix may require more cement to give a concrete equal in strength to that of a less "sandier" mix. Since the aggregate has more surface area, more

cement is needed to bind the aggregate particles together. On the other hand, the addition of fines to a mix may result in a reduced cement requirement when the fine particles act as ball bearings and lubricate the mix. This ease in mixing quality which an additional amount of fines can impart to a concrete mix can result in a more homogeneous concrete. A homogeneous concrete has greater strength than does a non-homogeneous concrete because there are no "weak spots" in it.

A concrete may demand more water to reach a given slump value if any excess fines are present. This excess water demand is caused by the added surface area which the fines offer. The film of water adhering to the surface of the finer particles may make itself available to the cement during the hydration process. This would increase the amount of water available to the hydrating cement particles and would weaken the ultimate strength of the concrete. It is desirable not to have any excess amount of fines in a concrete aggregate for this reason.

The use of a uniformly graded aggregate is very desirable because it reduces total concrete costs by decreasing the amount of cement paste required for a given set of design specifications. Uniformly graded aggregate cement is needed to [illegible] the [illegible] [illegible] [illegible]. On the other hand, the addition of fines to a [illegible] result in a [illegible] [illegible] [illegible] when the fine particles act as ball bearings and help the mix. This ease in mixing quality which an [illegible] [illegible] of fines can impart to a concrete mix can result in a more homogeneous concrete. A homogeneous concrete has greater strength than does a non-homogeneous concrete since there are no "weak spots" in it.

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The use of a uniformly graded aggregate is very desirable because it reduces total concrete costs by decreasing the amount of cement paste required for a given set of design specifications.

will result in a minimum void content in a concrete mix and will reduce the volume of cement paste necessary to bind the aggregate particles together. None of the cement is wasted just filling space as would be the case if the mix did not have a sufficient amount of fines present. It can be said that either an excess or a deficiency of fines in a given mix will be uneconomical.

From the above considerations, it can be seen that for the sake of economy and efficiency, one must know the optimum amount of fines to use in a concrete mix; therefore, the per cent fines to total aggregate was used as one parameter in the following investigation of the concrete making properties of Idealite expanded shale aggregate.

To gather laboratory data, the cement content of laboratory mixes was varied from four to eight sacks of cement per cubic yard in one sack increments, and the per cent fines to total aggregate on a dry volume basis was varied from thirty-five to sixty per cent in five per cent increments. By holding one variable constant while running the other through its full range, a total of thirty concrete mixes were made and tested.

IV. LABORATORY PROCEDURES

1. Limitations of Conventional Mix Design Procedures

The major difficulties confronting the engineer in the design of lightweight concrete can best be stated as follows, "In lightweight aggregate concretes, high absorption, extreme irregularities in shape, and low density are all important factors to be considered in the determination of the final grading."[10]

Traditionally, most concrete has been designed on the basis of water-cement proportioning where it is necessary to have the aggregate in a saturated-surface dry condition (a state reached when an immersed aggregate will neither add nor subtract from the volume of the water surrounding it). In most lightweight aggregates the large number of interconnected fissures and interstices existing in each aggregate particle account for the large absorption values. This alone does not affect mix proportioning, but the fact that the fissures are relatively large does. The capillary forces holding the absorbed water within a particle of lightweight aggregate tend

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[10] "Lightweight Aggregate Concretes," Housing and Home Finance Agency, (Washington: U.S. Government Printing Office, 1950), p. 18.

to be overcome by the earth's gravitational force in this case. This means that some of the absorbed water runs out of the individual aggregate particles, and they no longer remain in a saturated-surface dry state. As a result, it can be concluded that the saturated-surface dry state is not a static condition and therefore is not easily determined.

Kluge says the following about lightweight aggregate concretes, "Probably the generally accepted water cement ratio law for dense-aggregate concrete is equally applicable to any given lightweight-aggregate concrete, but the problem of determining the surface moisture available as mixing water from crushed presoaked aggregate is not simple. Attempts have been made to develop a simple and reliable procedure to determine the saturated-surface dry condition of various aggregates with little success.... It would therefore appear, considering the present state of our knowledge, that proportioning mixes or controlling concrete strengths by application of the water-cement ratio law, per se, is definitely impractical in the majority of cases."[11] However, the water-cement ratio law has always been an aid to the engineer. If he knows the water-cement ratio of a mix, an engineer can generally estimate the trends in compressive strength, flexural strength, durability, permeability, and to an extent,

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[11] Kluge, R.W., "Structural Lightweight Aggregate Concrete," <u>ACI JOURNAL</u>, October 1956, Proc. Vol. 53, p. 387.

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[11] Lloyd, R.F., "Structural Lightweight-Aggregate Concrete," ACI Journal, November 1955, Proc. Vol. [illegible], p. [illegible].

the workability of the concrete. A complete abandonment of the water-cement ratio law does not seem sensible for lightweight aggregate concrete. This is especially true for certain lightweight aggregates whose total absorption values do not vary significantly between size fractions. Idealite aggregate falls into this category.

The conventional water-cement ratio of a concrete mix is defined as the ratio of the number of cubic feet of water, exclusive of the aggregate absorbed water, contained in a cubic yard of concrete to the number of cubic feet of cement in that same cubic yard of concrete. In the case of Idealite, one can assume that including the volume of the absorbed aggregate water with the rest of the water in the mix will not change the shape of the water-cement ratio curve. It will merely reposition the curve slightly on the co-ordinate paper. Admittedly, the new "gross" water-cement ratio would not be as exact in nature as the conventional water-cement ratio is. The difference in absorption values between the aggregate fractions would cause a variation in the volume of the aggregate water if the aggregate proportions were changed. This deviation would be small enough to be negligible, on the order of one or two per cent for Idealite, and would not distort the correlation between a water-cement ratio the workability of the concrete. [illegible] of the water-cement ratio has been [illegible] for lightweight aggregate concrete. This is [illegible] that for certain lightweight aggregates [illegible] values do not vary significantly between [illegible] Idealite aggregate [illegible] [illegible].

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and the quality of a concrete.

Committee 613 of the American Concrete Institute has stated that it makes little difference whether concrete aggregates are dry or have free surface moisture as long as the moisture content is known and accounted for at the time of mixing.[12]

The maximum density theory of proportioning has fallen into disfavor throughout much of the engineering profession because while the densest concrete requires the minimum amount of cement paste to fill its voids, it does not always result in the most workable mix. Hence, an excess amount of water may be required to impart the desired workability to this dense mix. This will raise the concrete's water-cement ratio and lower its ultimate compressive strength. In spite of this disadvantage, the maximum density theory is used because it gives the engineer an idea of the amount of fines he should use in his trial mixes to minimize cement content. For this reason, the maximum density approach was used to help determine the structural concrete making properties of Idealite expanded shale aggregate.

The method of fineness modulus proportioning was

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[12] ACI Committee 613, "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete," ACI JOURNAL, September 1958, Proc. Vol. 55, p. 306.

not considered to be applicable to Idealite because of the variation in specific gravities between the different aggregate sizes. The final void content, paste content, and workability of a concrete is determined by the volume occupied by each size fraction, not the weight retained on each sieve.[13] A fineness modulus value is determined on the basis of the weight of material retained on each standard sieve and will not be indicative of the average particle size for an aggregate whose specific gravity values vary between size fractions. In other words, when a variation in specific gravity exists, an aggregate particle's weight and size (or volume) are not directly proportional to each other.

To adapt either the maximum density or the fineness modulus method of proportioning to Idealite, it was apparent that some type of volumetric correction to account for the variation in specific gravity had to be made.

2. Absorption Tests

Since most lightweight aggregates are more porous than ordinary aggregates, both the rate of absorption and the magnitude of the absorption by the aggregate particles will be high.

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[13] Ibid., p. 307.

A high rate of absorption can be detrimental to a concrete mix if all of the constituents are blended together when the aggregate is in an unsaturated condition. Rapid absorption of water by the aggregate could draw cement particles into the aggregate interstices. This would mean that less cement would be available to bond the aggregate particles together and would decrease the ultimate compressive strength of the concrete. According to the American Concrete Institute, it is advisable to mix the aggregate with about two-thirds of the mixing water for a short period of time prior to the addition of the cement when the aggregate is in less than a saturated condition.[14] The determination of the aforementioned "short period of time" was the object of the rate of absorption tests.

It would seem logical that an oven-dry aggregate would absorb water faster and longer than a partially saturated one. An oven-dry aggregate would therefore "rob" a concrete mix of more cement particles than a partially saturated one would. For this reason, oven-dry aggregate samples were used to determine the duration of the necessary premixing period.

The pycnometer method was used to determine the relative amount of water absorbed by the aggregate during

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[14] Ibid., p. 306.

set periods of time. To use the pycnometer method, one-half gallon "Mason" jars with gasketed covex conical lids were employed. First, the oven-dry aggregate was put in the jar, the jars were filled with water, the lid was screwed on, and the remaining space in the jar and the conical lid was filled with water through the hole at the apex of the conical lid. The jars were weighed immediately, after five minutes, ten minutes, fifteen minutes, thirty minutes, one hour, two hours, and twenty-four hours had elapsed. Before each weighing, the jars were agitated to remove any entrapped air bubbles, and enough water was added to fill the jars up to the tops of their caps. Using this method, the increase in the weight of the jars plus the aggregate and water after each time interval represented the amount of water absorbed by the aggregate during each time interval. Since the aggregate would undoubtedly absorb some water before the initial weighing took place, the initial weight was not considered to be representative of the oven-dry state of the aggregate; therefore, the total absorption by the sample could not have been calculated from the data gained in this test.

This experiment proved that almost no water was absorbed by the specimen after the first ten minutes of soaking. It was then concluded that ten minutes would be a sufficient amount of time to mix unsaturated aggregate with water before adding any cement to the mix.

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This experiment proved that almost all water was absorbed by the specimen after the first ten minutes of soaking. It was then concluded that ten minutes would be a sufficient amount of time to [illegible] the aggregate with water before doing any [illegible] on the [illegible].

The determination of the actual weight of the water absorbed by the individual aggregate fractions was attempted, but it proved to be impossible to get consisitant results. Samples of each aggregate fraction were soaked for twenty-four hours and then removed from the soaking water. The fines were allowed to air dry until they flowed freely, and the coarser particles were dried with towels to remove any free surface moisture. After the free surface moisture was removed, the surface of the particles became moist again when the samples were allowed to stand for a few minutes. This indicated that water was coming from within the interior of the particles, and they were then not in a saturated-surface dry state. As a result, it was concluded that getting the aggregate in a saturated-surface dry state was virtually impossible.

3. Specific Gravity Tests

Because the aggregate was difficult to get in a saturated-surface dry condition and because the rate of absorption by the aggregate was difficult to determine, the specific gravities of the individual aggregate fractions were determined by using the "Chapman Flask" method after the aggregate was allowed to soak in water at room temperature for one-half hour.[15]

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[15] 1958 Book of ASTM Standards, Part 4, op. cit., pp. 556-560.

The results of the apparent specific gravity tests were:

Fines	1.80
Medium	1.36
Coarse	1.31

4. Sieve Analysis

A standard sieve analysis was run on the aggregate which gave the following results:

TABLE 1

SIEVE ANALYSIS OF IDEALITE AGGREGATE

U. S. Std. Sieve Size	Per Cent Passing		
	Coarse	Medium	Fine
3/4"	100.0	100.0	100.0
1/2"	82.0	100.0	100.0
3/8"	32.4	100.0	100.0
#4	1.8	68.6	97.3
#8	0.5	11.9	91.8
#16	0.4	2.2	60.4
#30	0.4	1.5	31.4
#50	0.0	1.1	19.0
#100	0.0	0.8	3.0
#200	0.0	0.7	2.0
Pan	0.0	0.0	0.0

Combining the aggregates on a dry weight basis as 30% coarse, 15% medium, and 50% fines, and comparing the resultant mixture with the A.S.T.M. tentative specifications for 1/2" maximum sized structural lightweight concrete aggregate, the following table results:[16]

TABLE 2

COMBINED IDEALITE AGGREGATE

U.S. Std. Sieve Size	Per Cent Passing	
	Combined Idealite	A.S.T.M. Combined Specifications
3/4"	100.0	100
1/2"	95.5	95 - 100
3/8"	83.1	-
#4	66.3	50 - 80
#8	49.0	-
#16	30.8	-
#30	16.2	-
#50	9.8	5 - 20
#100	1.7	2 - 15
#200	1.6	-

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[16] "1959 Supplement to Book of A.S.T.M. Standards, Including Tentatives," (Philadelphia: American Society for Testing Materials, 1959), p. 78.

Because the per cent fines to total aggregate was to be used as a parameter in subsequent laboratory work, the coarse and medium fractions of the aggregate were always combined on a dry weight basis as 70% coarse and 30% medium. Since this combination conformed to the A.S.T.M. tentative specifications better than any other, it was used for all of the later work and will henceforth be referred to as the "combined coarse aggregate."

4. Dry Compact Density

Before performing the maximum density tests on the combined aggregate, the dry compact unit weight of each of the two aggregate fractions, fines and combined coarse, was determined. A one-fourth of a cubic foot mold was used for this purpose. The dry aggregate was put in the mold in two layers. Each layer was compacted by lifting the container two inches off the floor and dropping it six times. Six drops were sufficient to bring the aggregate to constant volume. This method was used instead of the standard "rodding" of the aggregate because it was felt that dropping the container filled with aggregate would more closely simulate the vibration technique that is used to compact concrete in the field. This non-standard method of compacting would make this procedure applicable to fragile aggregates also.

The combined coarse aggregate weighed 54.7 pounds per cubic foot and the fines weighed 67.7 pounds per cubic foot.

5. Maximum Density and Volumetric Corrections

The object of running the maximum density test was to determine the combination of aggregates which would result in the least volume of voids and therefore require the minimum amount of cement paste. The minimum void volume can be determined for conventional sand and gravel concretes by simply adding sand to the coarse aggregate until the compacted density (weight per cubic foot) of the mixture is maximum. Because the density of both conventional sand and gravel is about 100 pounds per cubic foot, the per cent sand required to give the mixture the maximum weight will also be the per cent sand which will result in a minimum void volume. This is true only when the weight per cubic foot of the sand and gravel are the same. This was not the case for Idealite fines and combined coarse aggregate.

To plot a minimum density curve which accurately conveyed the point at which the per cent fines to total aggregate resulted in a minimum volume of voids, a volumetric correction was made on the dry weight of the fines.

The combined [illegible] per [illegible] weighs [illegible] pounds per cubic foot and the [illegible] weighs [illegible] pounds per cubic foot.

5. Maximum Density and [illegible]

The object of [illegible] the [illegible] was to determine the [illegible] of aggregates which would result in the least [illegible] and would require the minimum amount of cement paste. The minimum void volume can be determined for conventional gravel concretes by simply adding sand to the coarse aggregate until the maximum density (weight per cubic foot) of the mixture is reached. [illegible] both conventional sand and crushed limestone [illegible] pounds per cubic foot, the [illegible] to give the mixture the maximum weight [illegible] which will result in a maximum [illegible] volume. This is true only when the weight per cubic foot of the sand and gravel are the same. This was not the [illegible] and combined coarse aggregate [illegible].

To plot a minimum density curve [illegible] conducted the point [illegible] aggregate resulted in a [illegible] 10 tests. [illegible] metric correction was [illegible].

In other words, $\frac{67.7}{54.7}$ = 1.24 pounds of fines occupied the same volume as one pound of combined coarse aggregate.

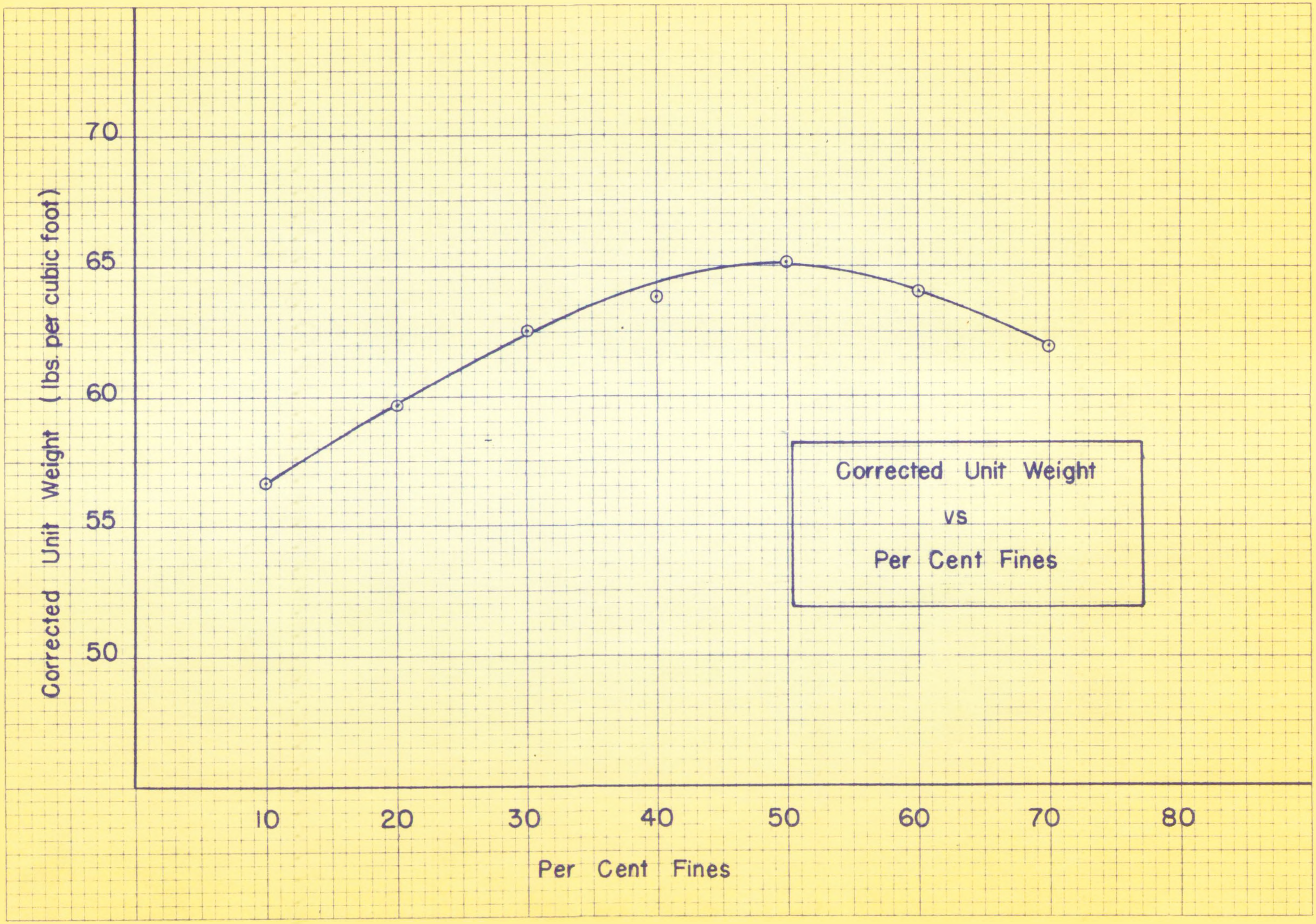
To obtain the data for the maximum density (minimum voids) curve, the one-fourth of a cubic foot mold was first filled with compacted oven-dry combined coarse aggregate. The compaction procedure was the same as that used for the unit weight determinations. The aggregate was dumped out on a clean floor, enough oven-dry fines were thoroughly mixed into equal ten per cent by volume of the total aggregate, enough of the mixture was compacted into the mold to fill it, and the mold was weighed. This procedure was repeated until the volume of the fines constituted eighty per cent of the total composite mixture.

The weight of the fines present after each incremental increase was then corrected to make its weight volumetrically equal to that of the combined coarse aggregate. In each case this volumetrically corrected weight of fines was then added to the actual weight of the combined coarse aggregate to give a relative unit weight of the total aggregate which consequently reflected the volume of voids present. (See appendix for derivation of correction formula and sample calculations.)

In other words, [illegible] of fines [illegible] the same volume as the pound of original coarse aggregate.

To obtain the data for the maximum density (minimum voids) curve, the procedure [illegible] was first filled with compacted [illegible] aggregate. The compaction procedure [illegible] used for the unit weight determinations. The aggregate was dumped out on a clean floor, [illegible] were thoroughly mixed into it. Ten [illegible] of the total aggregate, enough of the mixture was compacted into the mold to fill it, and the remainder weighed. This procedure was repeated until the volume of the fines constituted [illegible] per cent of the total aggregate mixture.

The weight of the fines present after each incremental increase was then corrected to make it a weight volumetrically equal to that of the original coarse aggregate. In each case this volumetrically correct weight of fines was then [illegible] the combined coarse aggregate and [illegible] weight of the total aggregate which consequently reflects the volume of voids present. (See Appendix for derivation of correction formula and sample calculations.)


70
65
60
55
50
Corrected Unit Weight (lbs. per cubic foot)
10
20
30
40
50
60
70
80
Per Cent Fines
Corrected Unit Weight
vs
Per Cent Fines

V. MIX DESIGN PROCEDURE

1. Moisture Content of Aggregate

The previously mentioned absorption tests proved that getting the aggregate in a saturated-surface dry condition was virtually impossible. Also, the maximum corrected density or minimum voids test was run on oven-dry aggregate. It was apparent that the combining of the aggregates used in the actual concrete mixes also had to be on an oven-dry basis to correlate results with the maximum density tests. The possibility of using nothing but oven-dry aggregate in the mixes was ruled out as being impractical in both the field and the laboratory. It was obvious that the water content of the aggregate at the time of mixing had to be determined to obtain a water-cement ratio for the mixes.

This was done by laying the aggregate out on airtight plastic sheets and carefully covering it with more airtight plastic sheets on the day before the mixing took place. Samples taken from each aggregate fraction were then weighed in their air moist condition, dried in an oven overnight at 230°F., and reweighed in their oven-dry condition. In this manner the per cent by dry weight of

V. MIX DESIGN AND [illegible]

1. Moisture Content of Aggregates

The previously mentioned [illegible] tests showed that getting the aggregate in a saturated-surface-dry condition was virtually impossible. [illegible], the maximum corrected density or minimum voids test was done on oven-dry aggregate. It was apparent that the condition of the aggregate used in the actual concrete mixes should also be on an oven-dry basis to correlate results with the maximum density tests. The question of using anything but oven-dry aggregate in the mixes was ruled out as being impractical [illegible]. It was obvious that the water content of the aggregate at the time of mixing had to be determined [illegible] water-cement ratio for the mixes.

This was done by placing the aggregate out on air-tight plastic sheets and carefully covering it with more airtight plastic sheets on the day before the mixing took place. Samples taken from each aggregate [illegible] were then weighed in their natural condition, dried in an oven overnight at 230 °F., and reweighed in their oven-dry condition. In this manner the per cent of dry weight of each aggregate that was actually water was determined.

2. Dry Weight Proportions

Since the aggregate combined to comprise each mix had to be weighed out on a dry weight basis, each portion of aggregate had to be measured, taking the additional weight of the moisture into account. This was accomplished by making use of the previously determined per cent moisture in each aggregate fraction. For example, if the required dry weight of aggregate in a mix was 21 pounds and the moisture content on a dry weight basis was 2 per cent, 21 x 1.02 = 21.42 pounds of moist aggregate was weighed out. (See appendix for more sample calculations.) In this manner, the proportions of fine and combined coarse aggregate were rigidly controlled, and the per cent fines to total aggregate on a dry volume basis was maintained at desired values.

3. Mixer

To simulate field conditions, an electrically powered one cubic foot capacity concrete mixer was used. The use of the mixer did present one minor difficulty. Because all yield values had to be determined by actual measurement of the volume of the combined ingredients, all of the contents of the mixer had to be carefully scraped out into the volumetrically calibrated measuring device after the constituents were mixed. This was not an easy task, and as a result, the volumetric yield

measurements of each mix may have been too low by one or two per cent.

4. Actual Mixing

The actual mixing process was relatively simple. First, enough aggregate for about eight-tenths of a cubic foot of concrete was put into the mixer with about two-thirds of the total estimated water requirement. Both of these quantities were weighed out carefully. Eight-tenths of a cubic foot was chosen because it is just enough concrete to fill up four standard six inch diameter twelve inch high cylinder molds. So that the aggregate would absorb only water and not any cement particles into its inner vesicules, the water and aggregate were allowed to mix for ten minutes (the time determined from the absorption tests) before any cement was added.

Because cement was one of the chosen mix parameters, it was desired to add just enough to equal a previously chosen number of sacks per cubic yard of concrete. Since the final volume of the mix was not known either, determining the proper amount of cement to add was an estimating process. It was done by first making an "educated guess" of the final volume and adding enough cement to satisfy the estimated final volume's require-

ment. Then if the final volume turned out to be grossly in excess of the estimated amount, more cement was added to the mix. If the final volume was less than the estimated amount, more aggregate was added to the mix. For variations of five per cent or less, the mix was not altered.

After the cement was thoroughly mixed with the aggregate and the premixed water, enough water was added so that the slump of the mixture fell within the specified one to two inch range. The weight of all of the water added to the mix was recorded for later water-cement ratio calculations.

5. Volumetric Measurement

The determination of the final volume of the mixes was accomplished by using a calibrated volumetric assembly. (See p. 33) It consisted of a large one cubic foot capacity steel mixing bowl and a flat bar having a calibrated movable pointer. The pointer had been previously calibrated by filling the bowl with known volumes of water.

The volume of a concrete mix was obtained by first carefully scraping all of the contents of the mixer into the volumetric measuring bowl. To simulate field compacting processes, the bowl was then placed on the vib-

measurements of each mix may have been [illegible]
two per cent.

4. Actual Mixing

The actual mixing process was [illegible]. First, enough aggregate for about [illegible] of a cubic foot of concrete was put into the mixer with [illegible] thirds of the total estimated water requirement. [illegible] of these quantities were weighed out carefully. [illegible] tenths of a cubic foot was chosen because it is just enough concrete to fill up four standard [illegible] twelve inch high cylinder molds. [illegible] would absorb only water and not any cement [illegible] its inner vesicules, the water and aggregate were allowed to mix for ten minutes (the time [illegible] absorption tests) before any cement was added.

Because cement was one of the principal parameters, it was desired to add just enough to attain the previously chosen number of sacks per cubic yard of concrete. Since the final volume of the mix was not known, either, determining the proper amount of cement to add was an estimating process. It was done by first making an "educated guess" of the final volume and adding enough cement to satisfy the [illegible]

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Calibrated Volumetric Scale Assembly, Volumetric Measure, and Vibratory Compactor.

ratory compactor (See p. 33) and vibrated at 1,000 r.p.m. until water began to rise to the surface, but not long enough for aggregate segregation to start. (About seven seconds.) The surface of the compacted concrete was smoothed off with a trowel, and the volume of the mix was measured and recorded. To prepare for the making of test cylinders, the contents of the bowl were then emptied into a large flat pan and mixed slightly.

6. Filling of Cylinder Molds

Four standard six inch diameter twelve inch in height test cylinders were made from each mix. Each waxed cardboard cylinder mold was filled in two compacted layers. The layers were compacted by placing the cylinder mold on the vibratory compactor for about two seconds at 1,000 r.p.m. This was the time necessary for water to just start appearing at the top of the cylinder but was not long enough for segregation of the aggregate to start. Vibratory compaction is probably superior to the standard "rodding" method of compaction because it correlates laboratory work closely with field conditions.

7. Curing of Concrete

After the filled cylinder molds were allowed to ratory compactor (Fig. 43) and vibrated at 1,000 r.p.m. until water began to rise to the surface, but not long enough for aggregate segregation to take place (about seven seconds). The surface of the compacted concrete was struck off with a trowel, and the volume of concrete was measured and recorded. To prepare for the making of test cylinders, the concrete in the container was emptied into a large flat pan and mixed slightly.

6. Filling of Cylinder Molds

Four standard 3 inch diameter by 6 inch in height test cylinders were made from each batch. Each standard cardboard cylinder mold was filled in two equal layers. The layers were compacted by placing the cylinder mold on the vibratory compactor for about two seconds at 1,000 r.p.m. This was the time necessary for water to just start appearing at the top of the cylinder and was not long enough for segregation of the aggregate to occur. Vibratory compaction is probably superior to the standard "rodding" method of compaction because it correlates laboratory work closely with field conditions.

7. Curing of Concrete

After the filled cylinder molds were allowed to be stand between 20 and 40 hours in the laboratory, the cardboard molds were removed, and the cylinders were placed in the moist room to cure. In the moist room the relative humidity was maintained at 100 per cent and the temperature was constant between 65°F. and 75°F. The cylinders were not removed from the moist room until they were tested.

8. Compressive Tests

All of the six inch diameter twelve inch in height cylinders were tested for their ultimate compressive strength. One cylinder from each mix was tested seven days after it was molded, and three cylinders from each mix were tested twenty-eight days after molding.

Before being tested, each cylinder was capped with a commercial sulfur compound, called Cyl-Cap, which is composed of fire clay and sulfur. This was to insure that each face of each cylinder was smooth and level.

After the cylinders were capped, they were placed in a Tinius Olsen Hydraulic Testing Machine at the University of New Mexico. The load was applied to each specimen at a rate of 12 p.s.i. per second until the cylinder's ultimate compressive strength was reached. The load at which the cylinder failed was divided by the cross-sectional area of the cylinder and expressed to the nearest 10 p.s.i. to obtain the cylinder's ultimate compressive stress.

The seven day specimen was tested merely to observe the trends in compressive strengths as the curing period progressed. To conform to A.S.T.M. specifications, the compressive strength values obtained at twenty-eight days were found by averaging the ultimate compressive strengths of three cylinders from each different mix.[17]

Because the object of this research was to determine the concrete making properties of Idealite, each failure of each cylinder was observed to note whether the failure was in the aggregate or in the bonding between the aggregate particles. In no case could the cylinder failure be attributed to a failure of the aggregate.

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[17] 1958 Book of ASTM Standards, Part 4, op. cit., pp. 655-656.

VI. RESULTS

TABLE 3

TABLE OF MIX PROPORTIONS ACTUALLY USED

Mix No.	% Fines	Wt. of Fines (lbs.)	Wt. of Med. (lbs.)	Wt. of Coarse (lbs.)	Wt. Cement (lbs.)	Gross Wt. Water (lbs.)	Vol. (ft.^{3})
1a	35	27.00	11.91	26.50	11.14	13.91	.814
1b	35	28.43	11.14	25.93	14.28	15.51	.860
1c	35	24.83	11.14	25.93	18.80	15.51	.900
1d	35	24.50	10.97	25.59	22.00	16.38	.931
1e	35	24.50	10.97	25.59	26.74	17.46	.970
2a	40	28.50	10.37	23.93	11.83	15.75	.862
2b	40	28.06	10.21	23.56	14.45	15.69	.850
2c	40	26.06	9.48	21.88	18.17	14.42	.870
2d	40	24.05	8.75	20.20	20.23	14.66	.830
2e	40	24.05	8.75	20.20	22.28	15.08	.820
3a	45	30.07	8.98	20.55	11.28	15.75	.833
3b	45	30.07	8.98	20.55	14.80	15.38	.830
3c	45	30.07	8.98	20.55	17.76	15.70	.862
3d	45	30.07	8.98	20.55	21.45	16.28	.888
3e	45	28.99	8.58	19.99	23.67	15.62	.855
4a	50	31.99	7.75	18.05	11.55	14.23	.790
4b	50	31.99	7.75	18.05	14.28	15.10	.825
4c	50	31.99	7.75	18.05	17.76	15.12	.855
4d	50	31.99	7.75	18.05	21.20	15.12	.859
4e	50	31.99	7.75	18.05	24.23	16.05	.885
5a	55	34.99	6.94	16.14	11.14	14.29	.800
5b	55	34.99	6.94	16.14	14.28	14.99	.820
5c	55	34.99	6.94	16.14	17.76	15.07	.848
5d	55	34.99	6.94	16.14	21.20	15.63	.861
5e	55	34.99	6.94	16.14	24.51	16.09	.900
6a	60	39.20	6.33	14.75	11.00	15.40	.795
6b	60	39.20	6.33	14.75	14.10	15.63	.820
6c	60	39.20	6.33	14.75	17.55	16.13	.871
6d	60	39.20	6.33	14.75	21.69	16.69	.896
6e	60	39.20	6.33	14.75	25.62	16.90	.924

TABLE 4

TABLE OF MIX PROPERTIES

Mix No.	% Fines	Slump	Fresh Unit Wt. (#/ft.^{3})	Dry Unit Wt. (#/ft.^{3})	7 Day Comp. Strength (p.s.i.)	28 Day Comp. Strength (p.s.i.)
1a	35	½	106.3		1730	2940
1b	35	1¼	106.6		2380	3650
1c	35	1½	106.9	93.0	3530	4890
1d	35	1¼	106.8		3920	4620
1e	35	1½	108.5		4750	5380
2a	40	1¼	104.8		1640	3050
2b	40	1½	108.2		2350	3170
2c	40	1½	104.5	92.2	2950	4440
2d	40	1¼	105.9		4400	4880
2e	40	1½	110.2		4670	4980
3a	45	1½	104.0		1680	2470
3b	45	1¼	108.2		2280	3500
3c	45	1¼	108.0	91.3	2740	4260
3d	45	1½	109.6		4180	5330
3e	45	1	113.3		4620	5720
4a	50	½	105.8		1860	2950
4b	50	1	105.7		2210	3620
4c	50	2	106.0	91.0	3060	4660
4d	50	1¼	109.6		3800	5420
4e	50	1¼	110.8		4600	6340
5a	55	½	104.4		1560	2840
5b	55	1	106.5		2100	3130
5c	55	1¼	107.2	90.2	2840	3990
5d	55	1¼	110.2		3710	5310
5e	55	1	109.6		4520	5780
6a	60	1	109.0		1230	2180
6b	60	1	109.8		1650	2650
6c	60	1	107.9	88.5	2220	3400
6d	60	1½	110.1		3350	4720
6e	60	1¼	111.3		3930	5250

TABLE 5

TABLE OF QUANTITIES FOR ONE CUBIC YARD YIELD

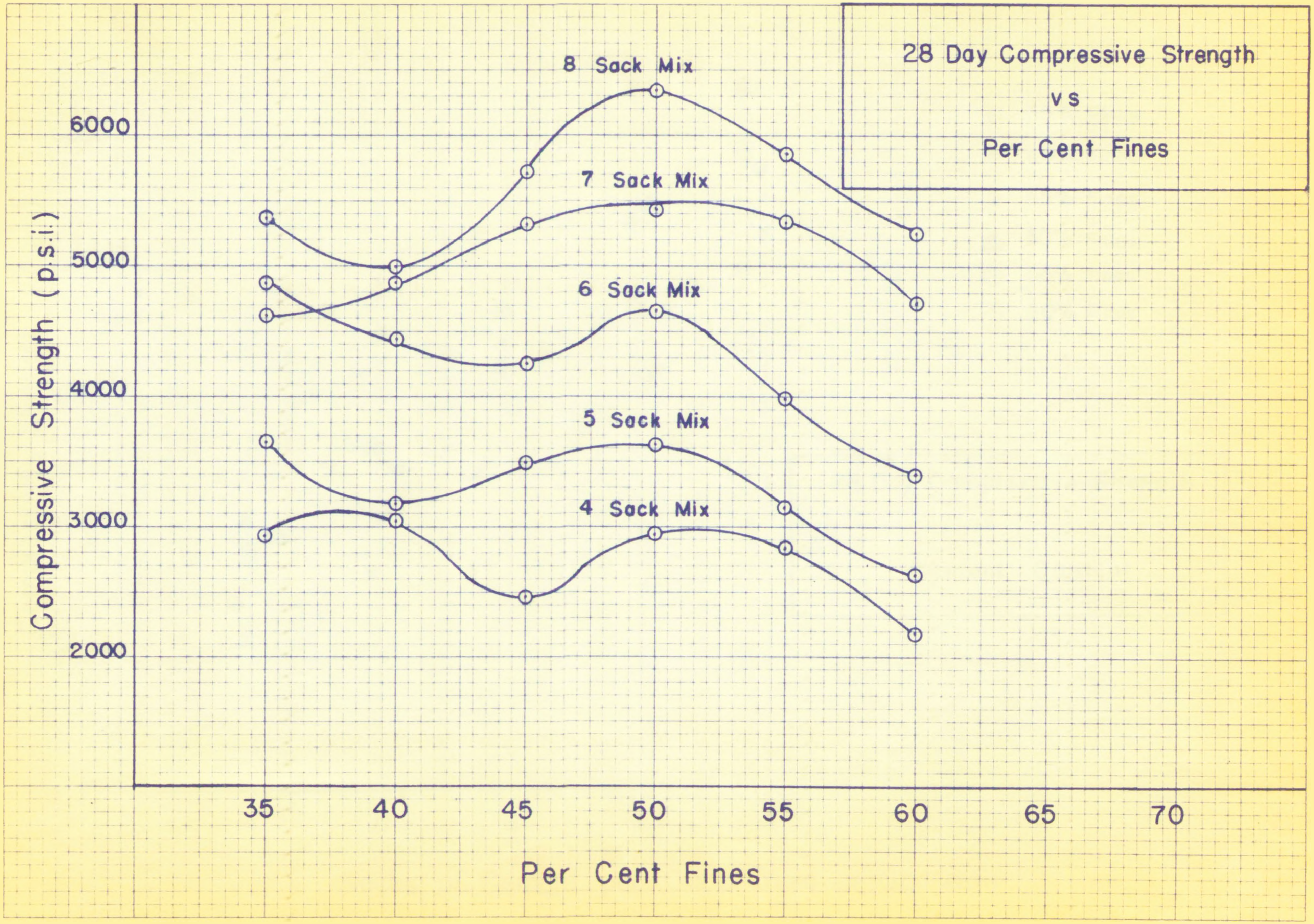
Mix No.	Wt. Fines (#Dry)	Wt. Med. (#Dry)	Wt. Coarse (#Dry)	Gross Wt. Water (#)	Sacks of Cement
1a	895.6	395.0	878.0	448.2	4
1b	779.6	349.7	814.1	486.8	5
1c	744.9	334.2	777.9	465.2	6
1d	710.5	318.1	742.1	474.9	7
1e	682.0	305.3	712.3	486.0	8
2a	892.7	324.8	749.5	493.2	4
2b	891.3	324.3	748.4	498.4	5
2c	808.8	294.2	679.0	447.4	6
2d	782.3	284.6	657.1	507.6	7
2e	791.9	288.1	665.1	496.5	8
3a	974.7	291.1	666.1	510.6	4
3b	978.2	292.1	668.5	500.3	5
3c	941.9	281.3	643.7	491.7	6
3d	914.3	273.0	624.8	494.9	7
3e	915.5	270.9	631.5	493.3	8
4a	1093.3	264.9	616.9	486.3	4
4b	1046.9	253.6	590.7	494.1	5
4c	1010.2	244.7	570.0	477.4	6
4d	1005.5	243.6	567.3	475.2	7
4e	976.0	236.4	550.7	489.8	8
5a	1180.9	234.2	544.7	482.2	4
5b	1152.1	228.5	531.4	493.6	5
5c	1114.0	221.0	513.9	479.8	6
5d	1097.2	217.6	506.1	490.0	7
5e	1050.0	208.2	484.2	482.8	8
6a	1331.3	215.0	500.9	523.0	4
6b	1290.7	208.4	485.7	514.6	5
6c	1215.2	196.2	457.2	500.0	6
6d	1181.2	190.7	444.4	503.0	7
6e	1145.4	185.0	431.0	493.8	8

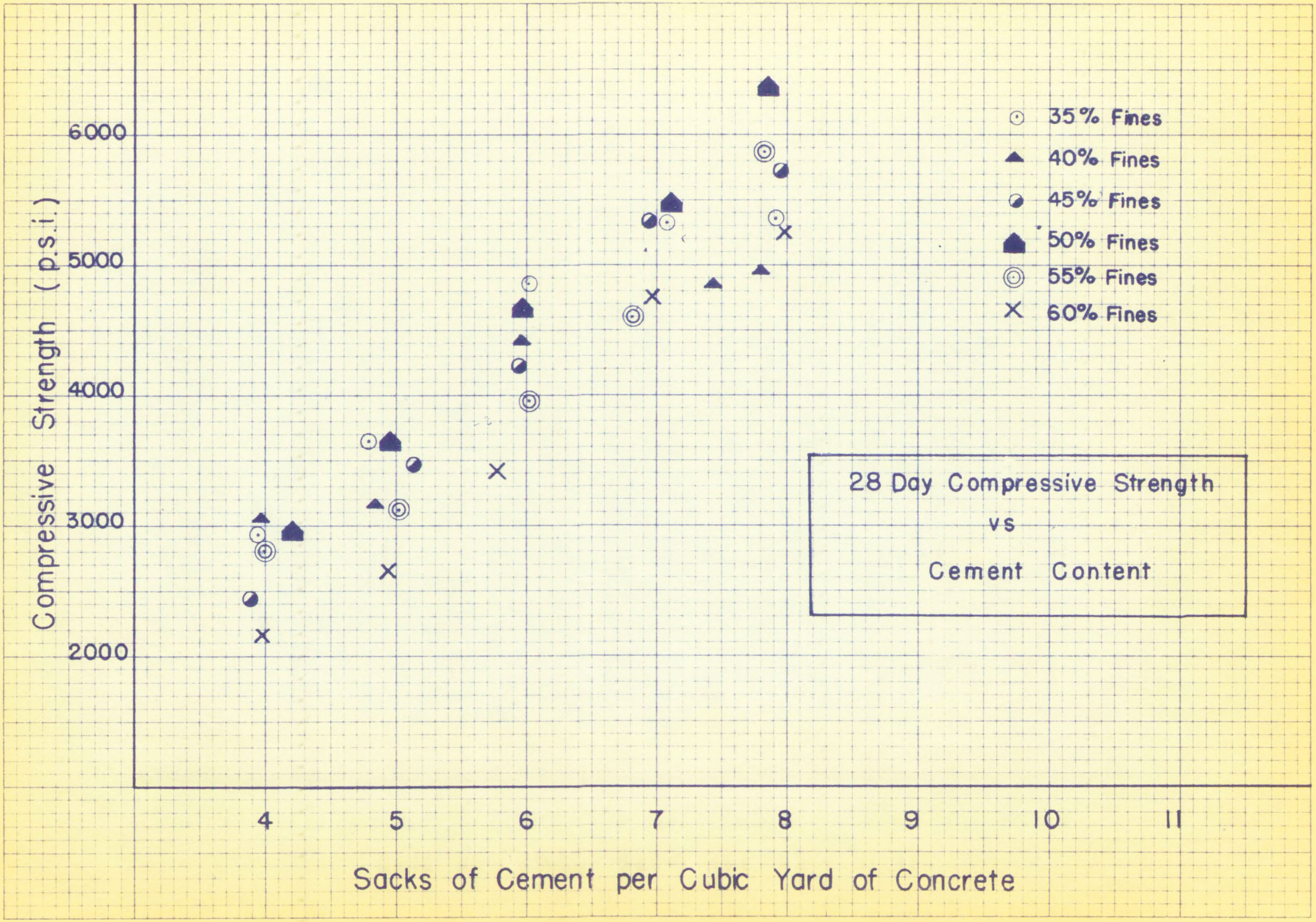
TABLE 6

COMPARISON OF 7 DAY AND 28 DAY COMPRESSIVE STRENGTHS

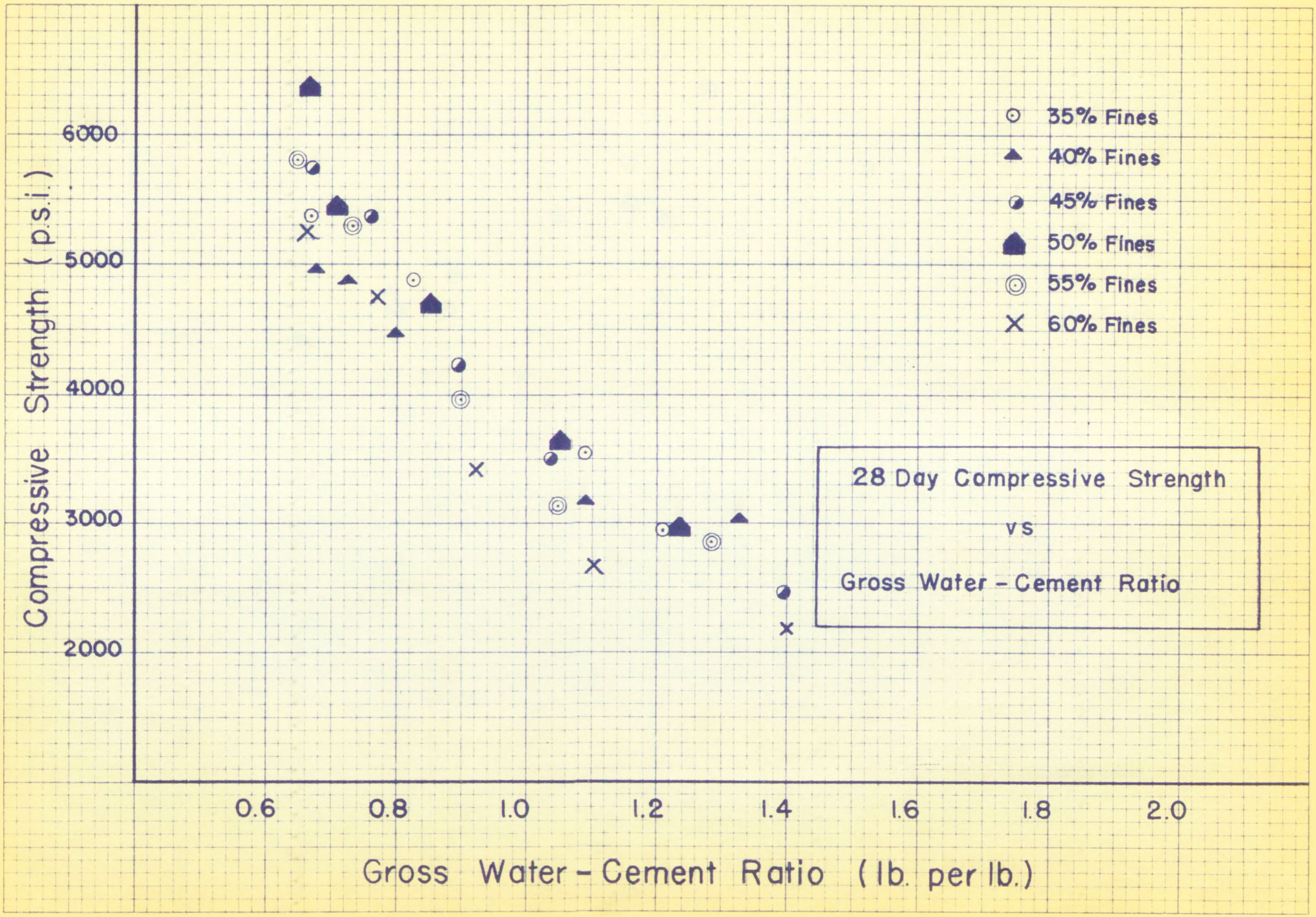
Mix No.	% Fines	Gross W/C (#/#)	7 Day Comp. Strength (p.s.i.)	28 Day Comp. Strength (p.s.i.)	Factor 28 Day divided by 7 Day
1a	35	1.213	1730	2940	1.70
1b	35	1.086	2380	3650	1.53
1c	35	0.825	3520	4890	1.39
1d	35	0.744	3920	4620	1.18
1e	35	0.664	4750	5380	1.03
2a	40	1.331	1640	3050	1.86
2b	40	1.086	2350	3170	1.35
2c	40	0.794	2950	4440	1.50
2d	40	0.725	4400	4880	1.11
2e	40	0.677	4670	4980	1.07
3a	45	1.396	1690	2470	1.47
3b	45	1.039	2280	3500	1.54
3c	45	0.884	2740	4260	1.55
3d	45	0.759	4180	5330	1.28
3e	45	0.660	4620	5720	1.24
4a	50	1.232	1860	2950	1.59
4b	50	1.057	2210	3620	1.64
4c	50	0.851	3060	4660	1.52
4d	50	0.713	3800	5420	1.43
4e	50	0.662	4600	6340	1.38
5a	55	1.283	1560	2840	1.82
5b	55	1.050	2100	3130	1.49
5c	55	0.849	2840	3990	1.40
5d	55	0.737	3710	5310	1.43
5e	55	0.656	4520	5780	1.28
6a	60	1.400	1230	2180	1.77
6b	60	1.108	1650	2650	1.61
6c	60	0.919	2220	3400	1.53
6d	60	0.769	3350	4720	1.41
6e	60	0.660	3930	5250	1.34

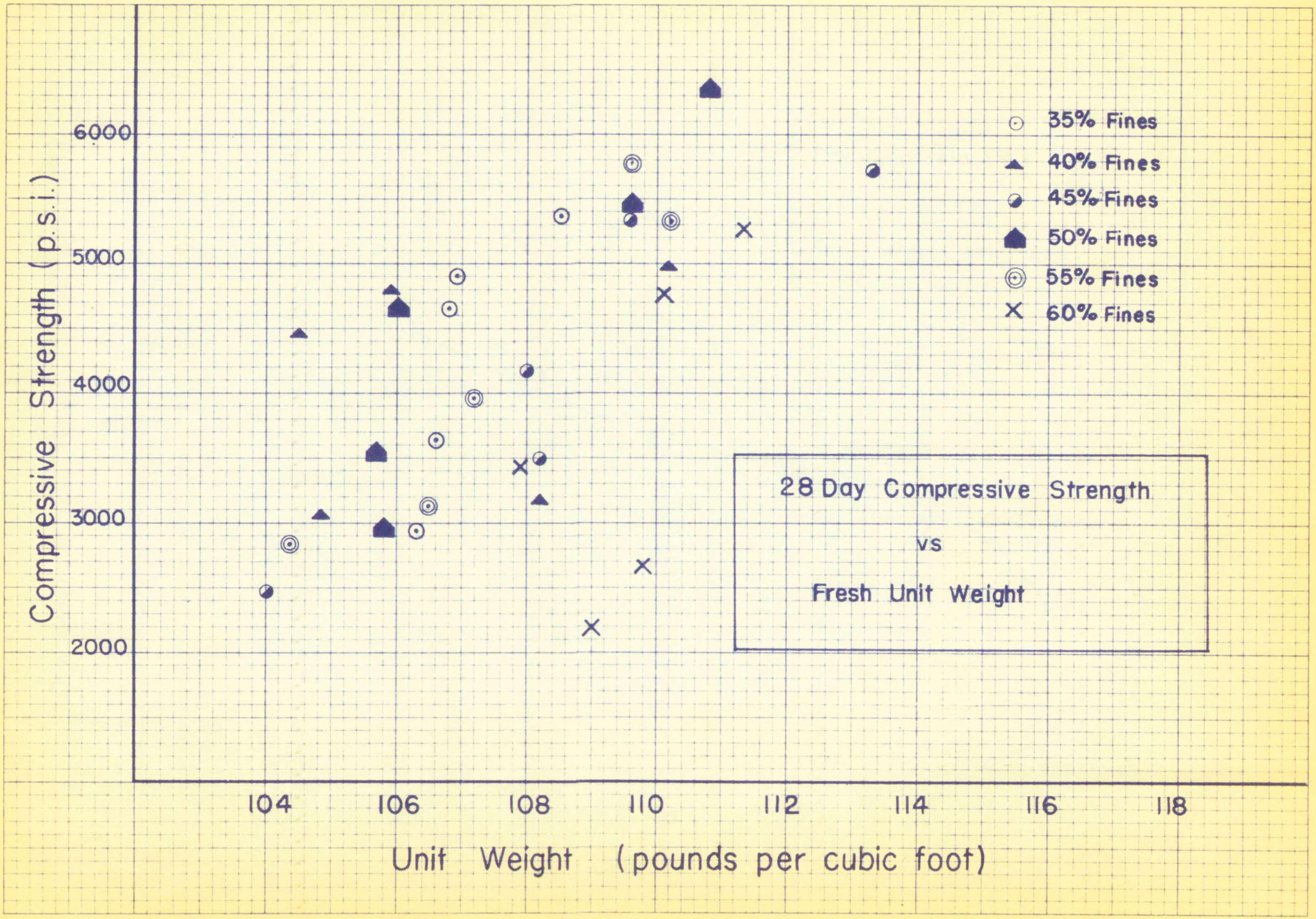
Ave. Factor = 1.48

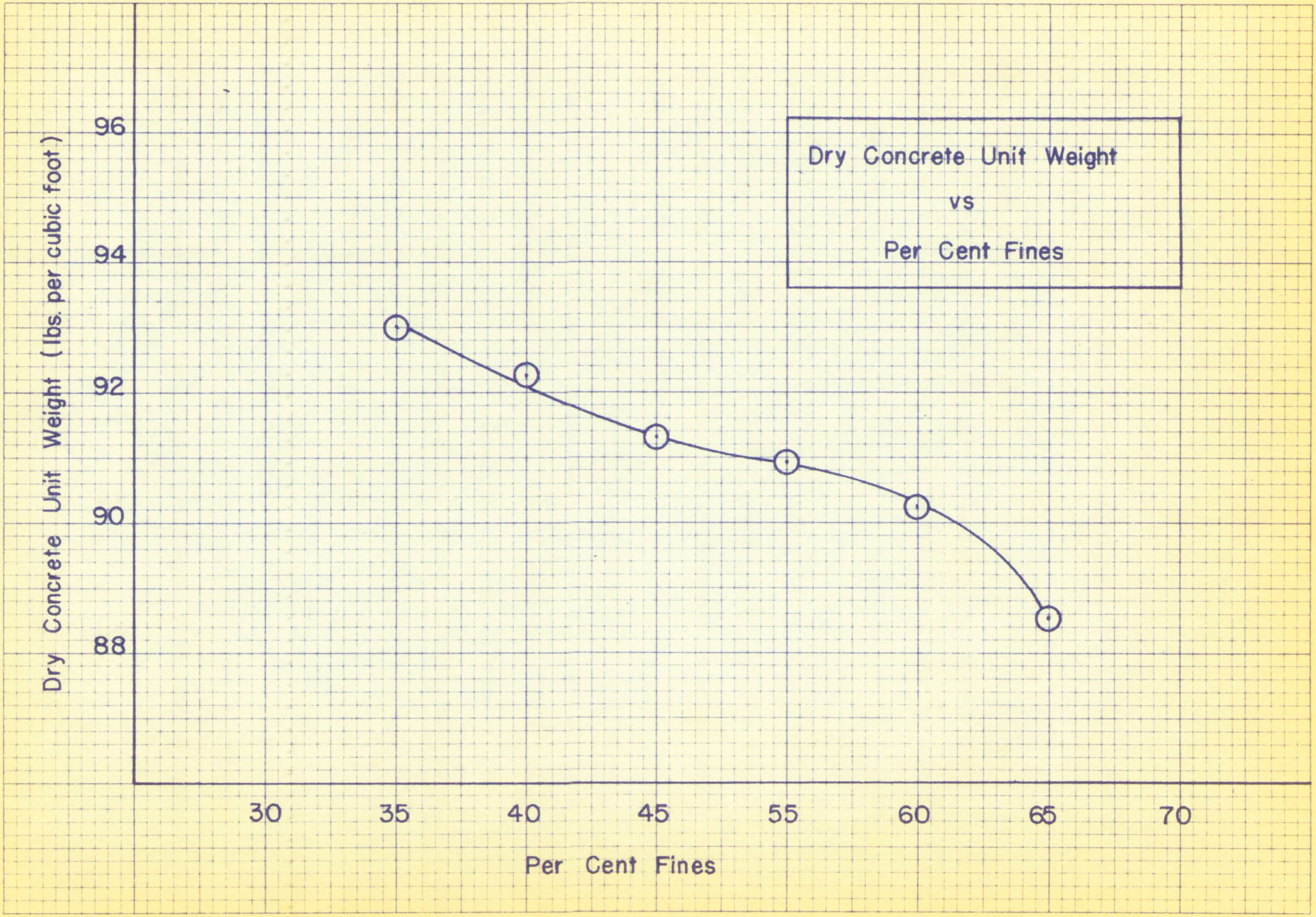

28 Day Compressive Strength
vs
Per Cent Fines
8 Sack Mix
7 Sack Mix
6 Sack Mix
5 Sack Mix
4 Sack Mix
Compressive Strength (p.s.i.)
6000
5000
4000
3000
2000
35
40
45
50
55
60
65
70
Per Cent Fines



28 Day Compressive Strength vs Cement Content


28 Day Compressive Strength
vs
Gross Water - Cement Ratio
⊙ 35% Fines
▲ 40% Fines
◐ 45% Fines
⬟ 50% Fines
◎ 55% Fines
× 60% Fines
Compressive Strength (p.s.i.)
6000
5000
4000
3000
2000
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Gross Water - Cement Ratio (lb. per lb.)


6000
5000
4000
3000
2000
Compressive Strength (p.s.i.)
104
106
108
110
112
114
116
118
Unit Weight (pounds per cubic foot)
⊙ 35% Fines
▲ 40% Fines
◐ 45% Fines
⬟ 50% Fines
◎ 55% Fines
× 60% Fines
28 Day Compressive Strength
vs
Fresh Unit Weight


Dry Concrete Unit Weight
vs
Per Cent Fines
Dry Concrete Unit Weight (lbs. per cubic foot)
96
94
92
90
88
30
35
40
45
55
60
65
70
Per Cent Fines

VII. DISCUSSION OF RESULTS

1. Minimum Aggregate Voids

As was established previously, the minimum void content of a mixture of the different fractions of Idealite occurs when the corrected unit weight value is maximum. From the plot of Corrected Unit Weight versus Per Cent Fines on page 27, it can be seen that the minimum void content occurred when the fines constituted 50 per cent of the dry aggregate volume. This is equal to 55.3 per cent on a dry weight basis.

By consulting the plot of Compressive Strength versus Per Cent Fines on page 41, it can be noticed that the strengths of each constant cement concrete mix increased as the fines were added until the volume of the fines was equal to 50 per cent of the dry aggregate volume. Then as more fines were added, the strength of the constant cement mixes decreased.

It can therefore be concluded that a definite correlation exists between the point of minimum aggregate voids and the point of maximum compressive strength. This seems reasonable when one considers that the cement

used in a minimum void mix is largely used to bind the aggregate particles together while if a larger void volume exists, the cement must also serve as a space filler. A minimum void content means an economical mix.

2. Cement Content

Regardless of the aggregate proportions used in the laboratory work, the compressive strength of each mix increased as the cement content was increased. The rate of increase was linear as can be seen in the plot of Compressive Strength versus Cement Content on page 42. It seems probable that if more than eight sacks of cement per cubic yard of concrete were used, the strength of the concrete would increase proportionately; however, after a certain maximum point, the aggregate would fail, and it would be useless to add more cement in hopes of gaining strength. This plateau of maximum aggregate strength was not reached at any time during the course of the aforementioned laboratory work.

3. Per Cent Fines

Idealite aggregate used in concrete will give maximum strength values when the dry volume of the fines is one-half of the total dry aggregate volume. Any amount of fines under this value results in a mix which is too

harsh and somewhat unworkable. It was observed that the workability of the mixes generally increased as more fines were added. When less than 50 per cent fines were used, the cement paste had to occupy the space which should have been filled with fines.

4. Water Requirements

The water required to give the mixes the desired consistency was fairly constant and varied from 450 to 500 pounds of water per cubic yard of concrete. As the per cent fines increased, there appeared to be an increase in the water demand of the mixes. The fact that an increase in fines increased the amount of water needed to obtain a given consistency can probably be attributed to the greater surface area present in a given volume of fines than is present in the same volume of coarse aggregate. This greater surface area offers more area for more water to adhere to.

5. Gross Water-Cement Ratio

The comparison of gross water-cement ratios and compressive strengths on page 43 shows that they are closely related for Idealite aggregate concretes. In all cases the compressive strength increased as the water-cement ratio decreased. However, it should be noted

that the lower cement content mixes had a high water-cement ratio because they lacked fines and needed water to become workable. Theoretically, decreasing the water content of these mixes might increase their compressive strength, but in actuality this would not be the case. Decreasing the water content in the concrete would make it so unworkable that it might be impossible to place it correctly into forms. Also it would be extremely difficult to mix a four of five sack mix made too stiff by reducing its water content. In this case the cement would not be evenly distributed throughout the concrete.

6. Fresh and Dry Unit Weights

The fresh unit weight did not seem to be well related to the ultimate compressive strength of the various concrete mixes. This can be seen by observing page 44. The results seem to indicate that a high fresh unit weight will result in a high compressive strength, but many of the plotted points seemed to be scattered almost at random. It can therefore be said that the fresh unit weight of the mixes was not always indicative of their ultimate 28 day compressive strength.

The plot of Dry Concrete Unit Weight versus Per Cent Fines had a definite trend. The oven dry unit weight that the lower cement content mixes had a high water-cement ratio because they [illegible] more water to make them workable. Theoretically, decreasing the water content of these mixes might increase their compressive strength, but in actuality this would not be the case, because if the water content of the concrete would decrease [illegible] that it might be impossible to place it properly in the forms. Also it would be extremely difficult to get a slump of five each mix made workable by reducing the water content. In this case the cement would not be evenly distributed throughout the concrete.

6. Fresh and Dry Unit Weights

The fresh unit weights do not seem to be well related to the ultimate compressive strength of the various concrete mixes. This can be seen by observing Figure [illegible]. The results seem to indicate that a high fresh unit weight will result in a high compressive strength, but the range of the plotted points seemed to be rather an almost [illegible]. It can therefore be said that the fresh unit weight of the mixes was not always indicative of their ultimate 28 day compressive strength.

The plot of dry concrete unit weight versus per cent fines had a definite trend. The average unit weight of the concrete mixes decreased steadily as the per cent of fines was increased. Furthermore, the per cent moisture based on the dry weight of the concrete increased as the per cent fines in the mix increased. This can be noted in the following table:

TABLE 7

UNIT WEIGHTS AND MOISTURE CONTENTS OF MIXES

Mix No.	% Fines	Fresh Unit Weight (#/ft.^{3})	Dry Unit Weight (#/ft.^{3})	% Moisture (dry wt. basis)
1c	35	106.9	93.0	15.5
2c	40	104.5	92.2	16.0
3c	45	108.0	91.3	16.4
4c	50	106.0	91.0	17.1
5c	55	107.2	90.2	17.8
6c	60	107.9	88.5	19.4

It would appear that an increased amount of fines will result in a greater water demand, but the water can be driven off by heat. This seems to verify the preceding statement which relates the increased water demand of high per cent fines mixes to the increased surface area that the added finer particles present.

VIII. CONCLUSIONS

1. Structural Concrete is Possible

The use of Idealite as a lightweight structural concrete aggregate will be economical and advantageous in many instances. It can result in a concrete which makes both prestressed and precast members feasible.

2. Fifty Per Cent Fines is Optimum

On a dry volume basis, the use of 50 per cent fines to total aggregate volume gave the maximum compressive strength in all cases. Converted to a dry weight basis, 55.3 per cent fines is optimum. This would not necessarily be the case for Idealite aggregate whose gradation and other physical properties vary from the aggregate used in this study.

3. Cement Content

The best cement content for a particular mix will depend upon the maximum compressive strength requirements. It can be roughly estimated from the plot of Compressive Strength versus Cement Content on page 42. Here again the results will diverge if the aggregate has physical properties which do not conform to the physical properties of the aggregate used in this work.

4. Slump

A one to two inch slump in the laboratory mixes resulted in concrete of excellent workability and consistency. It appeared to be more than equivalent to a four inch slump in ordinary sand and gravel concrete.

5. Water Content

The total water required to obtain slump values in the one to two inch range was fairly constant for all mixes. The water required, including the aggregate water, was between 54 and 60 gallons per cubic yard of concrete.

6. Recommended Mix Design Procedure

The following mix design procedure is recommended for the design of Idealite concrete mixes. This method, if used with discretion, is applicable to all aggregates whose specific gravity varies from one size fraction to the next or whose absorption values are high.

The following steps are recommended:

a. Run a standard sieve analysis on the aggregate and compare the results with the A.S.T.M. requirements for lightweight structural aggregates.[18] This will offer a rough indication of how to com-

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[18] "1959 Supplement to Book of A.S.T.M. Standards, Including Tentatives," (Philadelphia: American Society for Testing Materials, 1959), p. 78.

bine the different aggregate sizes and will also indicate whether or not the aggregate is gap-graded and must be supplemented.

b. Determine the time it takes for an oven-dry sample to absorb most of the water that it will absorb during a twenty-four hour period. This will give the time required to premix the aggregate and a portion of the mixing water before the cement is added.

c. Run a dry compacted unit weight test on each aggregate fraction.

d. Run a minimum voids test (corrected maximum density) on the oven-dry aggregate. Start out with a known weight of combined coarse aggregate and add fine aggregate in ten per cent increments on a dry volume basis. Make the volumetric corrections needed on the basis of the compacted unit weight values obtained in step c. (See appendix for volumetric correction procedure.)

e. Take moisture content samples from each aggregate fraction unless it is known to be oven-dry, and protect the aggregate against drying or wetting conditions. (Enclose it in airtight containers.)

f. Make the trial mixes using at least three different cement contents. Use dry aggregate propor-

tions which conform to those giving the minimum void content in step d. If any moisture is contained in the aggregate, the amount of aggregate weighed out should be increased by an amount equal to the weight of the moisture in it.

g. Put the aggregate in the mixer and weigh out about two-thirds of the estimated water with it. Mix the water and aggregate for the time determined in step b.

h. Add the desired amount of cement to the aggregate and water. If the mix is too stiff, weigh out a little more water and add it; if the mix is too "soupy," add aggregate and cement in proportion to the original weights of each. The stiffness or consistency can be determined by the standard slump test.[19]

i. After the components of the concrete have been thoroughly mixed into a homogeneous mass of the desired consistency, carefully empty the contents of the mixer into a previously calibrated volumetric measuring bowl. The concrete should be compacted (vibration is suggested as a compacting procedure)

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[19] 1958 Book of ASTM Standards, Part 4, op. cit., pp. 718-719.

and the volume of the mix should be measured. This will enable the engineer to make yield computations for the mix.

j. The contents of the volumetric measuring bowl should then be emptied and mixed slightly. Test specimens can then be made from the concrete. Here again, vibration is suggested as a means of compaction, but the standard rodding technique can be used if the aggregate is not too fragile or brittle.

k. The test specimens should be moist cured for the desired length of time. Compressive or flexural specimens can then be tested and the results can be plotted. From the plotted or recorded results, one can expand the trial batch mix proportions to obtain desired volumes of concrete for placement in the field.

and the volume of the [illegible] [illegible]. This will enable [illegible] [illegible] [illegible] of [illegible] computations for the [illegible].

j. The consistency of the [illegible] [illegible] [illegible] should then be [illegible] [illegible] [illegible]. [illegible] specimens can [illegible] [illegible] [illegible] [illegible]. [illegible] again, vibrating is [illegible] as a means of [illegible]tion, but [illegible] [illegible] [illegible] [illegible] be used if the [illegible] [illegible] are [illegible] [illegible].

k. The test specimens should [illegible] [illegible] the desired length of [illegible] [illegible] for flexural specimens [illegible] [illegible] [illegible] can be plotted. From the plotted [illegible] results, one can [illegible] [illegible] [illegible] computations to obtain desired [illegible] of concrete for placement in the field.

IX. RECOMMENDATIONS FOR FURTHER RESEARCH

1. Air Entrainment

More research should be done to determine the desirability of adding air entraining ingredients to Idealite concrete mixes. Most of the current literature on the design of lightweight aggregate concretes recommends the use of entrained air as a means of reducing the unit weight and cement content of a concrete. About one ounce of air entraining admixture per sack of cement is recommended.[20]

The addition of air to the mixes would lower the unit weight of the concrete if air bubbles are substituted for some of the heavy fine particles in the mix. This might also lower the water requirement of the mix by making it more workable.

2. Absorption

Much more should be done to determine the total absorption rates and values for Idealite aggregate. Until accurate absorption values are known, it will be difficult to simplify the design of lightweight aggregate concretes.

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[20] Kluge, op. cit., pp. 385-386.

3. Correlation of Vibration and Tamping

Vibration is almost universally used to compact concrete in the field. To simulate field practices, it seems reasonable to either use vibratory compaction methods in the laboratory or to precisely correlate vibratory and laboratory tamping methods.

4. Creep

Before many structures made from Idealite concrete are designed, further studies should be made of the long range creep strain values for Idealite concrete.

5. Durability

Studies of the durability of Idealite concrete could be done, but it is assumed that the porous nature of the inner aggregate particles would make it more durable than ordinary sand and gravel concrete. The air pockets in the aggregate particles would act as cushions and absorb shocks caused by freezing and thawing cycles.

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APPENDIX

I. CALCULATION OF CORRECTED UNIT WEIGHTS

From the compacted dry aggregate unit weight test:

Density of Combined Coarse = $54.7\#/\text{ft.}^3$
Density of Fines = $67.7\#/\text{ft.}^3$

$\frac{67.7}{54.5}$ = 1.24 pounds of Fines has the same volume as 1.00 pounds of Coarse aggregate

Let: x = Starting weight of combined coarse aggregate (30% Medium and 70% Coarse on a dry wt. basis)
y = Weight of Fines
M = Fines Ratio = Ratio of the dry volume of Fines to the total dry aggregate volume

$$M = \frac{\text{Volume of Fines}}{\text{Total Volume}} = \frac{\frac{y}{1.24}}{x + \frac{y}{1.24}} = \frac{1}{\frac{1.24x}{y} + 1}$$

$$\text{or} \quad \frac{y}{1.24} = \frac{Mx}{1 - M}$$

In the laboratory $x = 14.28^{\#}$ of combined coarse dry aggregate was used as the starting weight. A one-fourth of a cubic foot container was filled with a portion of the aggregate in two compacted layers and weighed. Then the container was emptied, and enough fines were added and mixed into equal ten per cent by dry volume of the total aggregate. Again, the container was filled in two compacted layers with a portion of the mixture and weighed. This procedure was repeated until the fines constituted 70% of the total aggregate volume.

Let:

M = Fines Ratio
x = Weight of combined coarse = $14.28^{\#}$
y = Weight of fines
h = Fraction of total aggregate it took to fill the one-fourth of a cubic foot container
x_r = Weight of combined coarse actually used to fill the container
y_r = Weight of fines actually used to fill the container
$G/4$ = Volumetrically Corrected Weight of aggregate that it took to fill the one-fourth of a cubic foot container
G = Volumetrically Corrected Weight per cubic foot of the aggregate

M	x+y	R	x_r	y_r	$\frac{y_r}{1.24}$	$x_r + \frac{y_r}{1.24}$	G/4	G
.0	14.68	.957	13.67	0.00	0.00	13.67	13.67	54.7
.1	16.25	.892	12.74	1.76	1.42	14.16	14.16	56.6
.2	18.71	.835	11.92	3.70	2.98	14.90	14.90	59.6
.3	21.87	.767	10.05	5.82	4.69	15.64	15.64	62.6
.4	26.08	.671	9.58	7.92	6.39	15.97	15.97	63.9
.5	31.99	.570	8.14	10.09	8.14	16.28	16.28	65.1
.6	40.84	.448	6.40	11.90	9.60	16.00	16.00	64.0
.7	55.60	.326	4.65	13.47	10.86	15.51	15.51	62.0

II. SAMPLE MIX DESIGN SHEET

The following type of data sheet was used in the laboratory to simplify calculation and recording procedure: (See page 63)

Idealite Mix Design

Date Feb. 18, 1951

1. Design Data:

Design No. 1b   Fines Ratio(M) 0.35

Slump Req'd 1" to 2"   Slump Obtained 1¼"

Cement Content 5 $\frac{bags}{yd.^3}$ or 17.41 $\#/ft.^3$

2. Lab Data:

(a.)

Material	Pan Wt.	Wt. of Pan + Wet Agg.	Wt. of Pan + Dry Agg.	Moisture Ratio (w)
Fines (x)	1.072	2.164	2.076	0.0876
Medium (y)	1.420	2.560	2.486	0.0694
Coarse (z)	1.016	2.500	2.468	0.0220

(b.)

Material	w	Equivalent Wt. for $x = 1\#$ dry
x	0.0876	$1+w=$ = 1.09
y	0.0694	$(1+w)\left(\frac{1-M}{M}\right)(.242)=$ = 0.48
z	0.0220	$(1+w)\left(\frac{1-M}{M}\right)(.564)=$ = 1.07

(c.)

Material	Δ_1	Δ_2	Δ_3	Total Wet	Water Used	Total Dry	Agg. Water	Total Water	Total Cement	Final Volume	Cement Content
x	27.00			27.00		24.83	2.17				
y	11.91			11.91		11.14	0.77				
z	26.50			26.50		25.93	0.57				
Cement	14.28				12.00			15.51	14.28	.860	16.60