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Permeability of Concrete

by Harry Gardner

June, 1911

Submitted to the Department of Civil Engineering of the University of Kansas in partial fulfillment of the requirements for the Degree of Master of Science

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PERMEABILITY OF CONCRETE

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Definition

Permeability is that property of concrete that permits it to conduct water through its body. The distinction should be made, however, that the water does not actually flow through the body of the material in the concrete but around and along the segregated ingredients therein. In this respect the hydraulic conductivity of concrete differs from the thermal and electrical; as is evident from the fact that water is matter and two material substances cannot occupy the same place at the same time. Since concrete with a high degree of permeability does not change its dimensions, or swell, appreciably while water is flowing through it beyond its dimensions under other conditions, it is evident that the percolating water must traverse void, or air, spaces. And hence we reason that permeability of concrete is due to the presence of void, or air, spaces therein.

Importance

The importance of the permeability factor depends upon the use to which the concrete is to be subjected. In the case of structures where the presence of water is not objectionable there is no advantage in incurring any additional expense to produce waterproof concrete. But in the case of basement foundations, tunnel linings, elevated tanks, reservoirs, etc., where percolating water would be undesirable or perhaps even dangerous, it is evident that the permeability factor presents an imposing aspect. Reinforced concrete containers for large volumes of water are ideal, the presence of the water in contact with the concrete being a condition tending to produce, and usually assuring, a concrete of maximun strength. Such containers also provide to the enclosed water a surface of contact almost identical with that with which the most wholesome water is in contact in Nature and insures the absence of undesirable chemical changes in the water in consequence of intimate contact between the water and metallic surfaces, a consideration by no means unimportant. Moreover masonry are the most enduring of all buildings erected, well constructed examples even outliving the civilization responsible for their erection, and that, too, at scarcely any expense for maintenance. Such, however, cannot be said concerning steel structures. Besides being expensive in first cost it requires constant vigilance and attention to maintain them only moderately safe and their lease of serviceable life is considerably more brief than that of the men who build them.

But steel is positively impermeable to water, a property not always belonging to concrete even under moderate pressures, much to the discomfiture and disappointment of the engineering fraternity, and for that reason relatively temporary steel containers are frequently commended where concrete structures, if impermeable, would present every other advantage.

Units and Methods of Measurement

So far there has not been proposed a standard method or set of units for the purpose of expressing different degrees of permeability. A system of units similar to that employed in electrical measurements might be proposed but perhaps the situation does not demand such intense scientific treatment. It would unify results, however, if standard units and methods were adopted. At present each investigator is his own guide in methods both of investigation and of expressing results, and consequently these items vary somewhat. However much details may have varied the attempt has generally been made, nevertheless, to submit concrete and mortar blocks of given dimensions to the action of water under pressure and to measure the amount of water flowing through the specimen in a given time. And while there are many reports of tests which are in ways in-complete it may be observed that they contain valuable information.

Two different methods have been employed heretofore in an effort to determine the degree of permeability of concrete one of which may be defined as the indirect method and the other as the direct.

Indirect Method. It has been assumed by some experimenters that, since concrete, to be permeable to water, must be porous, the degree of permeability is afforded by measuring the amount of water that a sample will absorb and, perhaps, the rate of absorption.

Such an assumption, however, is true only in certain instances but is erroneous in others, depending upon the nature and richness of the mixture. In the case of neat or rich cement mortars the percentage of voids is usually larger than in the case of well proportioned mixtures and the amount of absorption is large; and yet such mortars are absolutely impermeable. Further, concrete, which is correctly proportioned absorbs some water but such mixtures, too, are impervious. It is, then, only in the instance of improperly proportioned mixtures containing an excess of voids that the amount of absorption may be said to indicate the degree of permeability. Hence the assumption that absorption measures permeability is only rarely correct.

Direct Method. The majority of experiments, however, have been prosecuted under the direct method, i. e., by subjecting one side of thin specimens directly to water under pressure and measuring the amount of percolating water and, usually, the rate of percolation at given pressures.

As to the desirability of methods it may be said that circumstances alter cases. Where absolute impermeability is not required and where the more elaborate apparatus is not at hand something concerning the likelihood of extreme permeability may be learned, perhaps, by determining the amount and rate of absorption of a sample of concrete. But the criterion is by no means exact, and, in some cases, is not even approximate, depending upon the texture of the concrete.

"Porosity and Permeability. In this connection the difference between porosity and permeability should not be overlooked. Porosity is measured by the percent. of voids in the material, while permeability is measured by the amount of water that will pass through the material in a given time under specified conditions of thickness, area, and pressure. Porosity depends upon the amount of voids, while permeability depends upon the size of the voids and their intercommunication. The densest neat portland cement mortar has from 40 to 43 percent. of voids, but is absolutely impervious; while a I:2:4 concrete made of well assorted ingredients has only about I2 or I4 percent. of voids, and may be slightly permeable. In the first case, the voids are so small and so uniformly distributed that it is impossible after the concrete has set to displace the air in them by forcing in water; while in the second case, owing to the impossibility of getting a perfect mixture, the voids are larger and are interconnected so as to permit the percolation of water." (I).

Besides being misleading on account of the texture of the concrete, results secured by the indirect method are frequently misstated and that, too, unintentionally. Such results are usually obtained by weighing a specimen which has been thoroughly dried, then by saturating with water and weighing again; and by dividing the difference in weight by the weight of the dry specimen. The ratio thus obtained is then styled the percentage of absorption.

Insofar as the conception of weight only is maintained there may be no objection to that interpre-

(I) Baker's Masonry Construction, p. I82.

tation of the term; but as soon as the idea of volume becomes involved then the expression becomes erroneous. Evidently to determine the percentage absorption, from a volumetric standpoint, requires that the difference between the dry and wet weights of the specimen be multiplied by the specific gravity of the material in the specimen and that product, in turn, divided by the weight of the dried specimen. It is important to note, in this connection, that under the immediately preceeding interpretation, the porosity, percentage of voids and percentage absorption become numerically the same. It would avoid some confusion if this latter interpretation were maintained for percentage absorption and if the term "ratio of absorption" might be understood to mean the ratio obtained by dividing the difference between wet and dry weights by dry weight. It will be seen at once that the two conceptions above mentioned are not identical and in certain cases are only roughly proportional.

That the results secured by direct measurement of the amount of water that will flow through any sample of concrete under stated conditions are more trustworthy than those secured by measuring the absorption is undisputed; and such results are more valuable since operative conditions encountered in general practice can be duplicated in the experiments from which the results are desired to be obtained. Futhermore, the results obtained from direct measurement do not depend for their reliability upon the nature of the material tested, and practice shows (I) that results secured from laboratory tests where the direct method has been employed accord minutely with results secured in the field.

Controlling Factors

While it is possible to duplicate results in the laboratory and in the field it is nevertheless true that such coordination is not always secured. Laboratory experiments may produce one kind of results and practice another kind. But the apparent incongruity is usually attributable to a failure on the part of the investigator or artisan to duplicate either the material or the surrounding conditions under which the observations are made, or both. Certainly both factors bear an important relation to permeability.

The relative quantities of the ingredients usually exert the greatest effect upon the qualities of the concrete produced but the chemical and physi-

(I) Eng. Rec., Vol. 55, pp. 32 and 395.

cal properties of the ingredients also deserve consideration in that respect. The strength and impermeability of concrete which contains insufficient mortar to fill the voids in the included coarse aggregate will be reduced below what they would be if more mortar were used: but a sample of concrete scientifically proportioned and gauged with water containing an excess of undesirable chemical compounds has been known to disintegrate (I) within a few months after being constructed.

Material: Water. The effect that gauging water will produce in concrete is more often dependent upon the quantity used than upon the quality. If not enough water to produce a semi-fluid mass is used in gauging there will result a system of interconnected and rather large void spaces favoring percolation. And the same result may obtain when too much water is used, thus washing out the impalpable cement dust unless the forms are reasonably substantial and well fitted. When the correct amount of water is used ,however, although the percentage of voids may, because of evaporation, become rather large, the permeability of the concrete will be minimized.

Specifications for concrete ordinarily stipulate that the mixing water shall be pure and free from organic

(I) Geo. F. Morse, Trans. Am. S.C.E., Vol. 67,p.60I.

sediment, or make some other equally indefinite requirement, but very few, if any, specifications make any provision for analyzing the water to determine its chemical composition. A sample of water may appear perfectly pure and wholesome and yet contain compounds which would be deleterious to any concrete in which it might be incorporated. In general, decidedly acid or alkaline waters will, by producing chemical, and subsequently physical, changes in concrete tend to increase permeability if the water is kept in contact with the concrete.

Cement. The quantity, but not usually the quality, of the cement in concrete has a decided influence upon the permeability factor. Since the permeability of concrete is due entirely to the presence of intercommunicated porous spaces therein it is at once evident that a volume of cement paste at least equal to the volume of the voids in the fine aggregate is demanded. Tests (I) show, however, that, in order to obtain impermeability, a quantity of cement paste in excess of the volume of the voids in the fine aggregate is required, the excess requirement being caused, in all probability, by the impossibility of

(I) McIntyre and True, Eng. News, Vol. 47, p. 5I7.

securing an ideal arrangement of the granulometric particles and by the increase in the dimensions of the voids in the aggregate resulting from an increase in the effective dimensions of the particles themselves in the aggregate due to the surrounding envelope of cement and water. See Plate II.

Sand. Both the physical and chemical properties of sand have an important effect upon permeability. In fact these properties are so important that if either is unfavorable that circumstance will regulate the degree of the property.

Chemical Properties. The most undesirable constituents of material which is designed to be p placed in intimate contact with cement are the alkalies and other soluble sulphates and many failures (I) of well built concrete structures are traceable to them. "The alkali which seems most harmful generally contains sodium and magnesium sulphates, chlorides, and some gypsum or calcium sulphate. Chlorides alone do not seem to be harmful." (2) Magnesium sulphate shows special antagonism toward portland cement concrete.

(I) Trans. Am. S. C. E., Vol. 67, pp. 572-620.

(2) T. H. Means, Trans. Am. S. C. E., Vol. 67, p. 606.

It should be remembered, however, that the action of alkali in tending to render concrete permeable is slow and for that reason the more deceptive. A perfectly impermeable concrete structure may be constructed from materials containing an abundance of magnesium sulphate, but the slow chemical action between the magnesium and aluminum compounds in the cement will ordinarily cause the concrete to disintegrate and become pervious. However, the nature of the chemical composition of the sand assumes a serious aspect only, ordinarily, in the arid regions and even there proper precautions in preparing and draining the concrete can overcome the undesirable effects of chemically impure sand.

Phy sical Properties. Those physical properties of sand which most readily brand it as faverable or antagonistic to permeability in concrete are (a), the range in magnitude between the extreme large and small diameters, (b), the percentage distribution of the other sizes between the largest and the smallest, and (c), the shape of the individual grains. Sand composed of sharp or irregular grains or a preponderance of grains of any particular size will contain a larger percentage of voids than sand composed of rounded grains, particularly if the grains constituting the latter are so proportioned in size and numbers that each particular size will just fit in the void spaces formed by the next larger size. Unless the void spaces existing between sand grains of any particular size can be filled by smaller grains, either of cement or sand, percolation will be stimulated. Since only the impalpable dust in or, perhaps, one third of, the cement will be acted on chemically by water and the remaining two thirds has no office other than to act as void filling material it is important to notice that sand need not contain a superabundance of dust, but a small excess of dust serves to decrease percolation in concrete. The finest sand grains should be smaller than the largest grains of cement at all events.

Too large an excess of dust may decrease permeability and does, even, decrease the density, which is an undesirable circumstance. Where sand is used with crushed rock in concrete the most nearly impermeable material is produced if the dimensions of the sand grains of maximum size are about I/IOth the size of the largest particals of the stone.

Mortar. Mortar, as such, of ordinary proportions is impermeable to a measurable degree, at least, as indicated by table I which shows that I:3 mortar discs I" thick were impervious at a preąssure of 80 lbs. per square inch. But when incorporated with coarse aggregate unless the whole is proportioned by the granulometric method or unless a large excess of mortar over the volume of voids in the coarse aggregate is used, then a I:3 and often a I:2 mortar, depending upon the nature of the coarse aggregate, is sufficient to produce imperviousness. It has been shown (I) that a I:I mortar contains practically no air voids, but that in leaner mixtures the percentage of air voids increases directly as the proportion of sand to cement, as indicated in Plate I. Tests (2) on gravel concrete containing a quantity of I:I mortar varying in amounts between 30 and 45% of the amount of selected gravel showed such mixtures to be entirely impermeable although the amount of mortar was, in some instances, less than the volume of voids in the gravel, which latter was 33%. See Plate II. The same series of tests showed that some specimens of concrete in which the amount of I:2 mortar varied between 40 and 45% of the amount of gravel were impervious but all specimens of concrete

(I) L. K. Sherman, Eng. News, Vol. 47, p. 3I.

(2) McIntyre and True, Eng. News, Vol. 47, p. 5I7.

containing mortar leaner than I:2 were permeable. Similar results have been secured in tests by other investigators.

Stone. Whatever restrictions or limitations are placed on the use of sand in order to produce impermeable concrete may be repeated concerning stone and gravel intended for the same purpose. Just where the line of demarkation between sand and stone or gravel shall be placed is a relative position arbitrarily chosen in most instances(I). But experiments (2) have shown that the diameter of the maximum size of grains in a sample of sand intended to be fabricated with stone or gravel should be made a function of the diameter of the largest particles of the coarse aggregate if the most nearly impervious and strongest concrete is desired. This consideration is important when the aggregate is proportioned by weight or volume but is of no particular consequence when it is proportioned by the granulometric method.

Chemical Composition. The chemical composition of stone is perhaps of more importance than that of sand since a larger proportion of the former than of the latter is ordinarily used, and, for the same proportion of deleterious chemical compounds in both materials the stone

(I) Baker's Masonry Construction, p. 90.

(2) Fuller and Thompson, Trans. Am. S.C.E.,Vol.59, pp.I05-IIO.

will, therefore, introduce more of the compound into the concrete. However, the fact that the aggregate contains undesirable ch emical compounds is not, in itself, always serious. The chemical constituents in the gauging water in connection with those in the aggregate frequently define the value of concrete as an impermeable material. A prescribed sample of water has produced satisfactory results with one kind of stone but has proven disastrous with another (I).

Physical Properties. Almost any sample of stone will produce impermeable concrete if sufficient cement or rich mortar is incorporated with it. But it is reasonable to suppose, and experiments (2) show, that the physical peoperties of any coarse aggregate determine its ecenomic value as a material intended to be employed in the production of such concrete. In general it has been proven (3) that the degree of permeability of concrete, other conditions remaining the same, is a function of the shape and size of the fragments of the incorporated aggregate. The greater the dimensions of the largest particles of the coarse aggregate and the more

(I) Geo. F. Morse, Trans. Am. S. C. E., Vol. 67, p. 60I.
(2) Fuller and Thompson, " " " " " 59, " 72.
(3) " " " " " " " " " " I36.

nearly spherical such fragments are the less permeable the concrete. And the degree of imperviousness also increases with the hardness and solidity of the included materials. However, other factors may apparently invert these rules. See Plate III.

Quantity. Just what the economic proportion of stone to produce impervious concrete may be depends on conditions controlled by the character of the stone itself and the methods adopted in producing the concrete. If the material is proportioned by sieve analysis this feature need not be considered. But when the proportions are selected otherwise or when waterproofing ingredients are not employed it is an important consideration. Usually the proportions I:2:4, with gravel or broken stone, will be impermeable and sometimes slightly leaner mixtures, but the latter cannot be depended upon (I). See Plate II.

Conditions. The conditions under which concrete is fabricated and used naturally exert some influence on its general properties. Whether or not the surrounding conditions will be inimical depends somewhat upon the use to which the concrete is to be subjected and their import is not always discernable.

(I) McIntyre and True, Eng. News, Vol. 47, p. 5I8.

There are certain conditions, however, that are of no advantage, if they are not entirely dangerous, and every precaution should be exercised to avoid or to change them.

Weather. Unless extreme precautions are observed it is undesirable to deposit concrete in freezing weather if permeability is desired. Nearly all concrete containers for liquids develop leaks at seams or joints in the walls at places at which the concrete laid in the morning joins that laid last on the previous day. Such phenomena are certainly not mitigated if the work is done at a temperature below freezing. Fresh concrete deposited on that which is frozen or deposited where it will freeze before setting cannot be sufficiently compacted to close the larger pores and, therefore, when such material thaws optimum conditions for the passage of water are provided. Moreover the alternate freezing and thawing of the water which has collected in the larger pockets or cavities exerts a tremendous rupturing influence.

The enormity of the rupturing tendency of freezing water confined in void spaces or cavities can be fairly well comprehended when one remembers that a unit volume of water at 0° C. produces I.09I volumes of ice at the same temperature, exerting, because of such expansion, a pressure of I50 tons per square foot, an amount equivalent to the weight of a column of ice one square foot in sectional area and one mile high (I). Hence it is discernable that voids of large dimensions are objectionable not only because of the tendency which they themselves, as voids, produce but also because of their tendency to enlarge consequent to their having become filled with water and then the contained water having been alternately frozen and thawed.

Temperature, however, is about the only atmospheric feature that needs consideration when fabricating exposed concrete intended to be impermeable. Humidity would become an important factor only when the precipitation might become extreme on newly placed material to the extent of flooding it and separating or actually washing away from the aggregate the included fine particles of cement and sand, thereby producing interconnected channels which may produce seepage.

Aside from the atmospheric conditions under which concrete is manufactured, the most important other conditions having any influence on permeability

(I) Bul. No. 4, Wis. Geol. Survey, p.20.

are (a), the care excerised in fabricating and placing the concrete, (b), whether or not the concrete is deposited uninterruptedly, (c), whether or not the concrete, after h aving been placed but before it has set, will be subjected to continuous shock or jarring, (d), the thickness of the concrete itself, (e), the magnitude of the water pressure encountered, and (f), the special methods employed and intended to produce permeability.

Care Exercised. It has been proven (I) in practice that impermeable concrete can be produced from ordinary materials without admixture or application of waterproofing ingredients or washes if the materials are carefully selected and graded. But besides exercising care to select and grade the material, the concrete should be deposited with vigilance. Where impermeability has been thus secured the recently deposited concrete has been moistened and mixed until it assumed a semi-fluid consistency and has been puddled or churned thoroughly into place. Sufficient tamping has been secured, however, by allowing the concrete to fall a few feet into place (2). Recently

(I) Fuller and Thompson, Trans. Am. S. C. E., Vol. 59, p. 67.

(2) Trans. Am. S. C. E., Vol. 50, p. 408et seq. Wm. B. Fuller.

mixed concrete containing an insufficient amount of moisture will contain an excess of voids and if too much moisture is present and the forms are not tightly arranged the excess moisture will escape and carry with it the most valuable part of the cementing material - two conditions decidedly antagonostic to impermeability.

Continuity of Work. Whether or not a concrete container will be impermeable depends, in some instances, upon whether or not the concrete is deposited continuously. If recently fabricated concrete is deposited on concrete that has set, leaks generally develop. They may, however,be only temporary.

Shocks. Just what may be the effect of repeated concussions or shocks on recently deposited concrete is not definitely known but it is generally considered that such a situation is damaging. Of course the extent of the damage that may be done will depend ordinarily upon the magnitude of the shock and the duration of the period of repetitions but since the exact effect of shocks is not known it is not safe to subject newly fabricated material to such influences. The effect of shocks is to loosen the texture of the material if not entirely to disintegrate it (I).

(I) Eng. Rec., Vol. 63, p. 358.

It is generally agreed that permeability is directly dependent upon the thickness and age of the concrete body and the pressure to which it is subjected.

Effect of Permeability

On Concrete. The effect on concrete of the degree of its permeability depends on numerous conditions, principal among which is the chemical composition of the penetrating liquid. If the liquid should contain acid the porosity would tend to increase, due to the gradual dissolving action of the acid; but if alkali, the porosity might decrease because of the expansive action of new chemical substances formed, provided the quantity of new compounds formed is insufficient to disintegrate the concrete. Ordinarily, however, alkali water is the most dangerous natural enemy of concrete that is encountered and many failures are attributable to it (I). The only effective method so far devised of preventing such failures is to drain the ground in the vicinity of the concrete.

If, however, the water does not contain a sufficient percentage of chemical agents to injure the concrete it will prove beneficial thereto both by

(I) Trans. Am. S.C.E., Vol. 67, pp. 572-620.

furnishing sufficient water to insure perfect hydration of the cement and by reducing the porosity. The latter phenomenon is effected by the action of the water in dissolving calcium from that portion of the concrete in contact with the impinging water and carrying it towards the side of the concrete wall exposed to the atmosphere. There it unites with the carbonic acid of the atmosphere to form an efflorescence which eventually extends well into the concrete wall, filling the small void spaces and eventually preventing the passage of water.

On Reinforcing. The effect of percolating water on embedded steel can not be beneficial but will be otherwise. Besides affording an abundance of oxygen for the destruction of the steel, the percolating water will carry away an easily soluable iron silicate formed under certain conditions when steel is embedded in concrete (I), and will thereby cause a failure both of the concrete and its embedded reinforcing material. To obviate, as far as may be, the possibility of destruction of exposed reinforced members the Concrete Institute of Great Britian recommends (2) that the concrete con-

(I) J. W. Schaub, Trans. Am.S.C.E.,Vol. 5I, p. I24.

(2) Eng. Rec., Vol. 63, p. 364.

tain a minimum percentage of voids, that the materials in the concrete be properly graded, and that the presence of undesirable chemical compounds be avoided.

Methods of Insuring Permeability

In this connection the distinction between rendering concrete waterproof and rendering it impermeable should be emphasized. There are two general methods by which concrete structures may be made proof against the percolation of water, viz., by protecting the structure from the presence of water and by making the concrete in the structure impermeable. The latter method will be considered here.

In order to fabricate economically a sample of concrete that, when indurated, will effectually resist the percolation of water under pressure two methods have been developed. One consists of so proportioning the grains of cement and aggregate that there will result a concrete of maximum solidity and the other consists of securing increased solidity by the addition of some foreign substance to the concrete. In both methods the idea is to reduce the percentage of voids as far as possible. Whichever method is adopted for any particular instance will depend upon donditions.

Grading Materials. In an attempt to produce impermeable concrete by means of properly grading the materials therein two methods of operation have been followed. It seems to have been recognized for some time that permeability is largely determined by the percentage of voids present and consequently the object in view has been to reduce the amount of void space to the minimum. In order to accomplish that end the first method employed consisted in proportioning the cement, sand and coarse aggregate so that there might be employed enough cement to fill the voids in the sand and enough cement and sand combined to fill the voids in the coarse aggregate irrespective of the proportion of different sizes of the grains in the aggregate; and the other consisted in proportioning the constituents according to the granulometric composition of each material used but irrespective of the relative proportion of each material.

To employ the former method it is necessary only to measure the percentage of voids in the coarse and fine aggregate and to proportion them accordingly. But in employing the latter method the idea of volumetric proportions is disregarded and it becomes necessary to combine the ingredients in such a manner that the fragments of any particular size will just fit into the voids between the fragments of the next larger size, thus reducing the percentage of voids to a minimum. Since the former method will permit the use of sand and stone each screened to a particular size it is apparent that an unusually large percentage of voids will exist in a sample of concrete fabricated thereby, unless an unusually large amount of cement is used (I). Since, also, cement is the most expensive constituent in concrete the extravagant aspect of the method is boldly apparent. While it is possible to produce impermeable concrete by the former method it is not economical to do so.

Since all experiments show that the ability of concrete, in contradistinction to mortar, to resist permeability depends directly upon the solidity it is apparent that, by properly grading the material from the finest cement to the coarsest stone, a perfectly impermeable sample of concrete can be produced. It is also significant to note that such scientific grading is easily accomplished and that it reduces considerably the proportion of required cement, thereby producing

(I) McIntyre and True, Eng. News, Vol.47,p. I57.

the best grade of cement at a minimum cost (I).

Incorporating Materials. Occasionally where the necessity for impervious concrete is emphatic engineers adopt the expedient of incorporating in the ingredients in the concrete certain materials, which, by their mechanical or chemical action, assist in producing impermeability. That a considerable number of different materials have given satisfactory results within recent years is an important fact which has removed many limitations and restrictions on the variety of uses to which concrete may be subjected. While it is true that the reason why certain materials do decrease permeability has not been definitely explained, tests prove that they do serve that purpose and that, too, at no expense to the other properties of the stone. At the same time the market has been flooded with proprietary waterproofing materials concocted more especially to sell than to serve, some of which are of doubtful value. Those, however, that are of any value are constituted principally of mixtures of compounds mentioned herein later.

Among the materials which are known to expedite impermeability reground cement, pozzolan, lime,

(I) Fuller and Thompson, Trans. Am. S. C. E., Vol. 59, pp. I44-9.

soap, alum, or soap and alum, and clay have produced the most satisfactory results. There are other materials, usually colloids and electrolytes, that have been used occasionally but not to a degree sufficient to establish their practicability.

It will be observed that the materials named possess one of two widely different properties, viz., the property of attracting water or being bibulous, and the property of repelling water. Whichever of the above properties any material may possess will exert a decided influence on the amount of that material necessary to produce impermeability. Ordinarily, to produce effective results in practice, there will be required an amount of bibulous material from 5 to 10 times as large as the amount of water repellent material necessarily employed. However, other than quantitative considerations may decide the merits of the two kinds of materials.

Bibulous Materials. Of the materials of a bibulous nature used for the purpose of producing impermeability in concrete reground, pozzolan, and natural cements, clay and lime have been most generally employed.

Reground Cement. The value of reground cement as a waterproofing compound has not been appreciated to any great extent although it is, chemically and physically, an ideal material intended to be incorporated in concrete. Its increased effectiveness over stock cement is due to the large amount of impalpable dust it contains which is acted on by the gauging water and more effectually seals the capillary intercommunications in the concrete. The chief objection to using it is its cost and the consequent fact that it cannot, ordinarily, be secured. Tests (I) show that it is more desirable and effective as a waterproofing ingredient than any other material so far used.

Pozzolan. Pozolan may be incorporated in concrete for the purpose of making i t waterproof only if the concrete is to be in contact with sea water. Specimens of concrete containing pozzolan and exposed to the atmosphere are liable to disintegrate and become permeable. Moreover pozzolan is as expensive as portland cement in most locations. Hence it is seen that there is no advantage to safety or cost if this material is used in concrete for the purpose of

(I) W. A. Burton, Ia. State Col., Bul. No.3,p.29.

decreasing the permeability.

Clay. Because of its wide distribution in Nature and its consequent cheapness clay would be the ideal waterproofing material if its other properties were all favorable. It can be employed very readily in experimentation on a small scale and will produce good results so long as it can be kept very finely pulverized. But the fact it partially solidifies when kept stored in packages or bins makes its use impracticable on a working scale since it is then difficult to fabricate it evenly with the other materials in the concrete. If, however, the aggregate employed contains a perceptible amount of clay dust uniformly incorporated it will produce impermeable concrete if the clay dust displaces from 5 to 20% of the sand.

Effect on Concrete. Clay probably exerts both a mechanical and chemical action in reducing permeability. Besides acting as a pulverized, inert, void-filling material it is conjectured that it unites chemically with the other ingredients. However, the nature of the chemical action is not known nor is it positively known that such action actually takes place (I). That it does act mechanically is undis-

(I) R. H. Gaines, Trans. Am. S.C.E., Vol. 59, p. 168.

putable and is, in fact, sufficient explanation of its effect. The mechanical effect is possible, however, only when the clay is so finely pulverulent that it may occupy what might be the minutely fine void spaces existing between the sand grains, it being recalled that a waterproofing material of any description is of value only when there is an insufficient amount of cement to fill such voids. Pulverized clay is a distinct colloid or hydrogel whose finely pulverized particles have the property, in the presence of water, of forming gelatinous or coagulated solutions thereby tending to fill more completely the existing void spaces and, if it be assumed that chemical action does take place, to subject themselves more readily to a chemical union with the other materials in the concrete during the indurating process or until chemical equilibrium is established.

The effect of pulverized clay on the properties of comcrete is usually of a desirable nature. Tests (I, 2, 3, 4) show that the strength of cement-

(I) R. H. Gaines, Trans. Am. S. C. E., Vol. 59, p.I66.
(2) W. C. Hoad, Bul. Ka's. Acad. of Sci., Vol. I9,p.8I
(3) E. C. Clark, Trans. Am. S. C. E., " I4, " I64.
(4) G. J. Griesenauer, Eng. News, Vol. 5I, p. 4I3.

sand mortars is invariably increased when pulverized clay displaces as much as I5 % of the sand in I:3 or leaner mixtures; that the solidity is increased and the porosity decreased; that the permeability is decreased; but that the time of setting is delayed. However, lengthening the period of induretion is not of much consequence unless the concrete is proposed to be subjected to working stresses soon after being deposited, or to be submerged, in which case danger of disintegration will be imminent. Experiments (I) indicate, also, thay concrete containing allowable percentages of clay is not seriously affected by weather conditions, and structures (2) that have been built from such materials show no undesirable effects induced by the clay content. See Plates VI and VII.

Loam. Since loam is a material of rather indefinite composition its effect on the properties of concrete as a constituent thereof cannot be very definitely foretold. Its chemical and granulometric composition will usually determine its fitness and and these features should be investigated before any sample of it is used as a waterproofing ingredient.

(I) Bul. No. 2, Ohio Geol. Survey, I904, p. 34.

(2) J. C. Hain, Eng. News, Vol. 53, p. I28.

If clay or stable mineral compounds predominate it may be advantageously usdd; but if its composition is principally vegetable refuse then its presence will be undesirable. Just what proportion of organic matter in it will condemn or recommend it has not been determined. Several tests (I,2,3,4,5) of its effect on the strength of portland cement mortar have been made but they differ widely among themselves and only general conclusions can be drawn. In some cases an admixture of loam was positively advantageous and in others as positively deleterious. Such results, however, are not surprising since the loam was selected at widely separated places and the organic content of the different samples was not uniform. The tests demonstrate that the greater the organic content of the loam the weaker the mortar. See Plate VIII.

Lime. Lime has given good satisfaction as an admixture to concrete to reduce permeability, the prin-

(I) G. J. Griesenauer, Eng. News, Vol. 5I, p. 4I3.

(2) J. C. Hain, " " " 53, " I28.

(3) (no name) " " " 49, pp.446-447.

(4) C. E. Sherman, " " " 50, p. 454.

(5) W. C. Hoad, Trans.Kas.Acad.ofSci.,Vol.I9,p.8I.

cipal reasons why it has been used so extensively being its chemical composition and low cost. Since it is the compound forming the major part of the concrete the addition of a reasonable amount of it does not predicate undesirable results and, if it replaces part of the cement, the cost of the concrete will be reduced somewhat. Both the lump and hydrated varieties have been used but the latter is more in demand.

Lump Lime. Before lump lime can be incorporated in mortar it must be hydrated or slaked. Such an operation as generally effected adds somewhat to its cost and besides produces a mass containing a considerable amount of free water. Moreover the slaked material will contain numerous unslaked lumps which will hydrate slowly and which are not easily confined because of their expansive tendency. For these reasons lump lime is not an ideal ingredient as a waterproofing compound. While it does increase the imperviousness (I,2) and strength of lean cement mortars it is not as effective in that respect as the hydrated lime of commerce and its use

(I) Bul. No. 2, Ohio Geol. Sur.,I904,Pp.43-45.

(2) Proc. Am.S.T.M., Vol. IO, pp. 328-340.

is being abandoned for the latter.

Hydrated Lime. The fact that the lump lime must be hydrated before it can be incorporated in concrete and that the pulverized material can be purchased readily and cheaply are sufficient reasons for using only the latter. But in addition to these advantages tests (I) show that the hydrated variety of commerce exerts a much more desirable effect on concrete than equal amounts of the other variety. The reason why the hydrated lime produces a more derirable result than the lump variety is because the former is the more completely hydrated and pulverulent and can be incorporated more uniformly in the body of the concrete.

The advantages commending hydrated lime as a material for the purpose of reducing permeability are its cheapness, its specific gravity, its granular state, its chemical composition, and the ease with which it can be incorporated in concrete. The property which would seem to unfit it for that purpose is its solubility in water. Experiments (2) show that if IO to 20% of the cement in sand

(I) Proc. Am. Soc. T. M., Vol. IO, pp. 328-340.

(2) Bul. No. 2, Ohio Geol. Sur., 1904, p. 45.

mortar is displaced by lime paste the cost of the cementing material is reduced about 5%. See Plate XI. The fact, also, that cement is heavier than lime, volume for volume, shows that when a definite percentage of cement, by weight, is displaced by hydrated lime the volume of the intermixed cement and lime will be considerably larger than that occupied by the cement alone and hence the tendency of the mixture will be to reduce greatly the percentage of voids in any aggregate under what would exist if the cement were used alone.

The ease, however, with which lime dissolves in water has made its use as a waterproofing ingredient questionable to some extent. If water continues to flow through a specimen of concrete it is reasoned that the porosity will increase because the lime will be dissolved out; and observations on some specimens which were tested for permeability in connection with this thesis showed that such reasoning is occasionally correct. One particular specimen, after having been subjected to water at a pressure of 60lbs. per. sq. in. for two days had become somewhat porous on the side in contact with the water. However, certain parts of the specimen leaked badly from the beginning of the test and the leakage did not decrease during the test. It was observed, further, that the side of the speciman exposed to the air was not more porous after than before the test and that the increased porosity extended only about I/3 the depth of the speciman which was one inch thick and was composed of .8 parst portland cement, .2 parts commercial hydrated lime and three parts standard Ottawa sand, by weight.

Since, under ordinary conditions of practice, the thickness of concrete subjected to high pressures is many inches, rarely less than three, it would seem that any apprehensions of the porosity increasing because of percolating water is unfounded.

Observations (I, 2) all show that, unless the concrete barrier is cracked or is extremely porous, percolation decreases with time until it ceases altogether. See Plate IV. Such decrease in percolation is attributed, however, to the fact that the lime in the concrete is easily soluble and on being dissolved and carried through the spec-

(I) Eng. Rec., Vol. 55, p. 32.

(2) " " " " " 582.

imen is precipitated as $CaCo_3$ in the capillary pores connecting with the outside air, the precipitation eventually extending entirely through the body of the concrete. Hence it is seen that the fact that lime is easily soluble is one of its chief requisites as a waterproofing compound.

Lime affects the properties of concrete in much the same way in which clay affects them but, owing to its chemical composition and the ease with which it can be handled, it is a more desirable material to use than clay. Indeed the very fact that it does not induce undesirable effects makes it more valuable as an admixture to concrete than most other materials. A great many tests of its effects on cement mortar and concrete have been reported but none show that it has proven injurious. On the other hand, its value as a waterproofing material has been thereby established for ordinary pressures at least.

The effects which it has invariably produced on the properties of concrete are as follows: (a) less than 18% increases the solidity by decreasing the porosity and thereby the amount of absorption; (b) it decreases the cost; (c) it increases the strength; (d) it does not affect seriously the

the period of induration; and (e) it does effectively reduce the permeability.

For curves illustrating the effect of lime on the properties of mortar and concrete see Plates IX to XIII.

Water Repellent Material. Since the intercommunicating channels between the larger void spaces in concrete are extremely small it is evident that if a water repelling compound can be placed therein the permeability will be minimized. In an effort to realize the above condition of affairs many materials have been employed with more or less success. Among the materials thus employed wax, resin, paraffine, oils, salts of organic acids, alum, soap and the Sylvester compound have been most widely used. The fact that such materials as wax, resin, and oils affect seriously the indurating process of the cement has limited their usefulness in this connection and they will not be given further consideration here. The Sylvester compound and the lime and soap mixture, however, deserve consideration since they have been in use for nearly a century and are being used at present more extensively perhaps than any other waterproofing compound. Besides they have the unqualified endorsement of some of the leading civil engineers at the present time.

Sylvester Compound. The Sylvester Compound is a mixture of soap and alum solutions, preferably combined according to their chemical formulas so that there may be no excess of either. The fact, however, that there exists in the concrete certain indefinite proportions of aluminum and calcium compounds which will unite chemically with all of the organic acid in the soap makes an exact artificial mixture unnecessary so long as too great an excess of soap or alum is not employed. Instead of using alum which has the chemical formula K_2SO_4, $Al_2(SO_4)_3$, $24H_2O$, aluminum sulphate, $Al_2(SO_4)_3$, $18\ H_2O$, may be substituted with a considerable degree of economy and with the same results. If alum is used the proportions recommended in practice are I part alum to 2.2 parts hard soap by weight, but if aluminum sulphate is substituted the proportions become I of that material to 2.8 of soap. If soft soap is used the amount of water in it should be ascertained and correction for it should be made accordingly. To apply the Sylvester compound to concrete the materials are dissolved separately in portions of the mixing water, or the pulverized material may be added to the cement or sand. If the latter procedure is adopted precautions must be observed to thoroughly incorporate the materials together. When applied as solutions they can be more uniformly incorporated.

The effectiveness of the Sylvester compound in preventing permeability is attributed to the fact that the constituents therein unite chemically to form insoluable aluminum salts (4I) of the organic acids in the soap having the property, like oil or wax, of warding off water. It is assumed that when traces of this material exist in the capillary ducts in concrete water will not pass through the ducts. Some such physical action is evidently called into play for, unlike lime or other bibulous material, the salts will effectually diminish permeability when a quantity of it equal in volume to only a very small percentage of the voids is used.

While the precautions necessarily involved in using the Sylvester compound make it expensive in some instances it is nevertheless a valuable water-

(I) C. G. Derick, The Technograph, Univ. of Ill., Vol. 23, p.57.

proofing material.

Effect on Concrete. The effect (I,2,3,4) of the Sylvester compound on theproperties of concrete are as follows: (a) it slightly increases the solidity and thereby reduces the porosity and absorption; (b) it diminishes the permeability; (c), where less than 2% of the cement is replaced by the material the strength is not materially decreased; (d), from 2 to 5% decreases the strength; and (e), as much as 5% destroys the concrete. See Plate V.

Lime and Soap. "Lime and soap combines to form calcium soap, a finely divided, water repelling compound; and hence another method of rendering mortar or concrete waterproof is to incorporate lime and soap in it. The proper proportion is unslaked lime I part and hard soap I2 parts; and, since it is impossible to dissolve more than about 3 percent of hard soap in cold water, the amounts to be used in practice are unslaked lime 0.25% and hard soap 3% o f the weight of the water, and these amounts

(I) Edward Cunningham,Trans.Am.S.C.E.,Vol.5I,p.I27.

(2) Eng. Record, Vol. 60, p. 4I3.

(3) W.A.Burton,Ia.State Col.,Bul.No.3,pp.I6and28.

(4) I.O.Baker,The Technograph,Univ.of Ill.,Vol.23,p.89

will give 2.7% of void-filling compound. These quantities will make any reasonably good condrete absolutely water-tight. Before the water containing the soap and lime is used, it shoul d be stirred to mix the ingredients and to keep the precipitate in suspension. Calcium soap is a product in the manufacture of candles; and hence if a considerable amount of concrete is to be waterproofed, as in the construction of a long aqueduct, it might be wise to buy the calcium soap and add it directly to the cement.

"Calcium soap is formed, if an excess of soap is added in the alum and soap compound, provided the cement contains any free lime - as it usually does. Apparently calcium soap is the essential element of several proprietary waterproofing compounds." (I)

Calcium soap is stable at ordinary temperatures and even in the vicinity of hot water and steam pipes, but it cannot be used with safety in concrete coming in contact with fires.

Other Compounds. Permeability is affected by a great many compounds not heretofore mentioned

(I) Baker's Masonry Construction, p.

when they are mixed intimately with the natural ingredients in the concrete. Some of the materials used are inexpensive and therefore practicable, others are not economical and some exert a deleterious influence on the concrete. Electrolytes, in weak solution, have given satisfaction in some instances (I). In one instance (2) a solution of $CaCl_2$ effectually reduced permeability, but briquettes stored in a 5% solution in the cement laboratory at the University of Kansas disintegrated. See Plate V.

Conclusions

The results from all experiments show that permeability is a property of improperly proportioned concrete. True it is that all specimens of concrete need not be proportioned for imperviousness, some other property of the material, such as its strength, being the controlling factor, and almost any ordinary proportions will develop strength enough for ordinary purposes. But in that class of structures in which permeability is an important consideration the existence of perco-

(I) R. H. Gaines, Trans. AM.S.C.E., Vol.59, pp.I59-I69

(2) Eng. News, Vol. 58, p. 39I.

lating water is inexcusable since it can be obviated.

During the last decade many experiments have been performed for the purpose of gaining a better understanding of mortars and of concrete and of controlling that property in these materials. While no single set of experiments has been entirely complete nor has covered the entire field embraced in the subject and while different investigators may express slightly different views on the subject as observed from their own experiments, nevertheless the results of the combined experiments are conclusive and make deductions incontrovertible.

Some conclusions from tests of impermeability by men of good repute follow:

Mr. Feret (I).

"In all mortars of granulometric composition, the most permeable are those which contain the least quantity of cement."

J. B. McIntyre and A. L. True (2).

"Of the various mixtures we may safely choose (for impermeability) either I;2;4 or I:2½:4,

(I) Annals des Ponts et Chaussees, July, I892.

(2) Eng. News, Vol. 47, p. 5I7.

on account of their simplicity and the ease with which they may be proportioned, either for hand or machine mixing. In exterme cases, however, it might be advisable to use one of the richer mixtures."
W. A. Burton (I).

"One fact that stands out prominently in all of the tests is that broken stone is much better for permeability than gravel........

"As to the value of the different methods of waterproofing clay was rather a disappointment.

"The tests on the briquettes corresponding to the soap and alum pipes showed that the tensile strength is not materially affected by the addition of soap and alum.

"The conclusions to be drawn from the tests are unmistakable and indicate that cement of the fineness (reground, 94% passing a No. 200 sieve) of that used in these experiments would be the safest thing to try for impermeability under high pressure..".
E. W. Lazell, Ph. D. (2).

"From a study of these results, obtained by various investigators, it would seem that hy-

(I) Bul. No. 3, Iowa State Col.,1908.

(2) Monograph.

drated lime is the best material at present procurable, economically both for use in concrete to render the mass more water-tight, and in cement mortars to render them more plastic, without in either case materially decreasing the strength."
F. B. McCullough (I).

"Unless extreme care is taken in proportioning, it is necessary that some form of waterproofing be used for a I:3:5 concrete for pressures from 20 to 40 lbs. per. sq. inch.

"For nearly all specimens the rate of flow decreased rapidly with time."
W. B. Fuller and S. E. Thompson (2).

"The permeability or flow of water through concrete is less as the percentage of cement is increased, and in a very much larger inverse ratio.

"The permeability is less as the maximum size of the stone is greater.......

"Concrete of cement, sand and gravel is less permeable than concrete of cement screenings and broken stones; that is, for equal permeability, a slightly smaller quantity of cement is required

(I) Bul. No. 336, Univ. of Wis.

(2) Trans. Am. S. C. E., Vol. 59, p. 72.

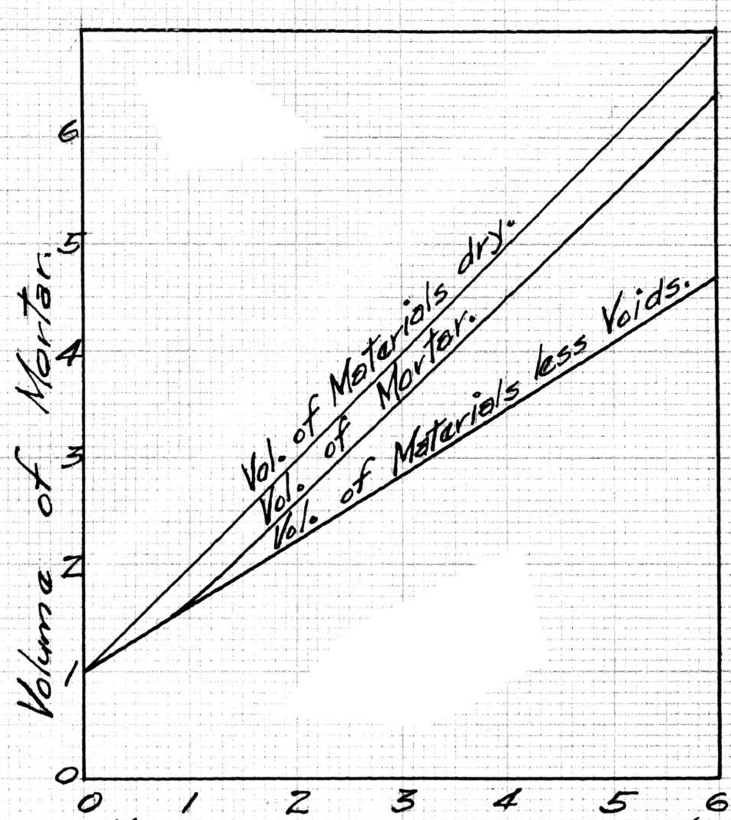
with rounded aggregates like gravel than with sharp aggregates like broken stone.

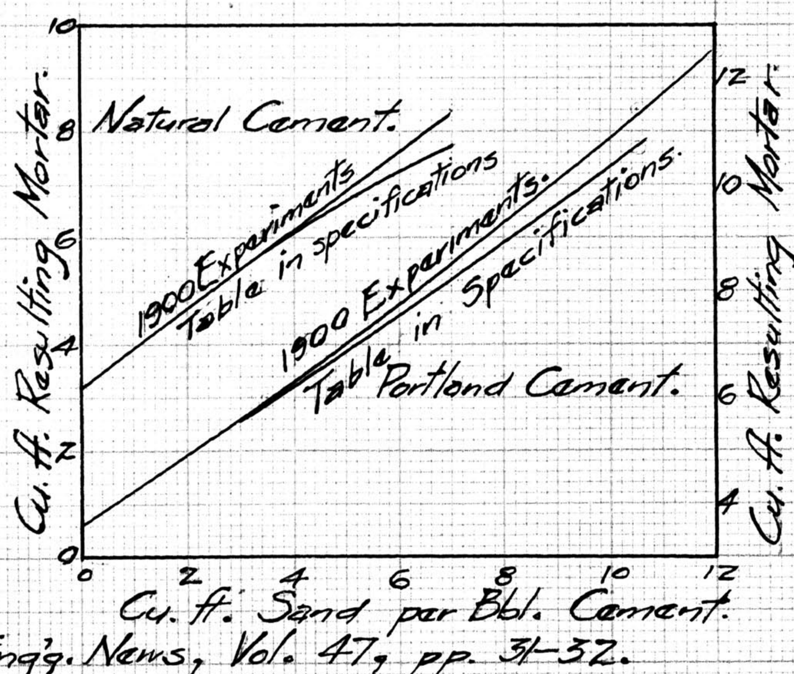
"Concrete of mixed broken stone, sand and cement is more permeable than concrete of gravel, sand and cement, and less permeable than similar concrete of broken stone, screenings and cement; that is, for water-tightness, less cement is required with rounded sand and gravel than with broken stone and screenings.

"The permeability decreases materially with age; increases nearly uniformly with the increase in pressure; and increases as the thickness of the concrete decreases, but in a much larger inverse ratio."

VOIDS IN CEMENT MORTAR Plate I

Volume of Mortar Produced by Varying Proportions of Sand and Cement.

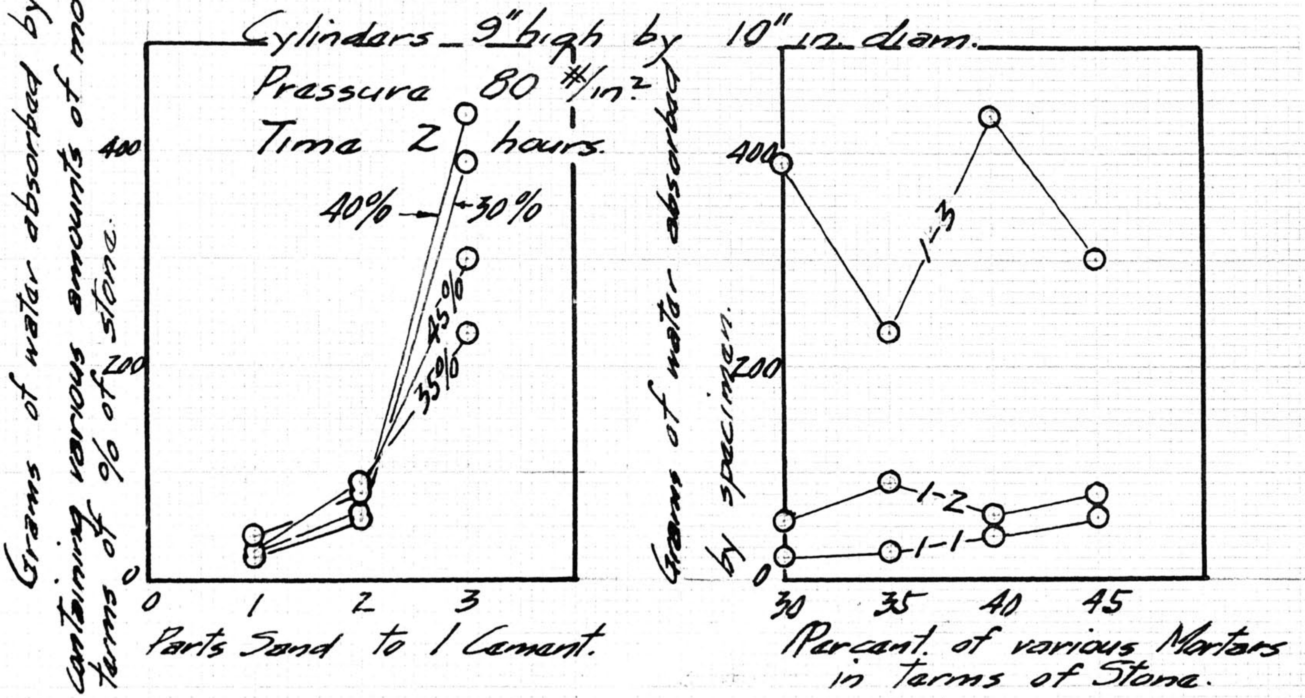


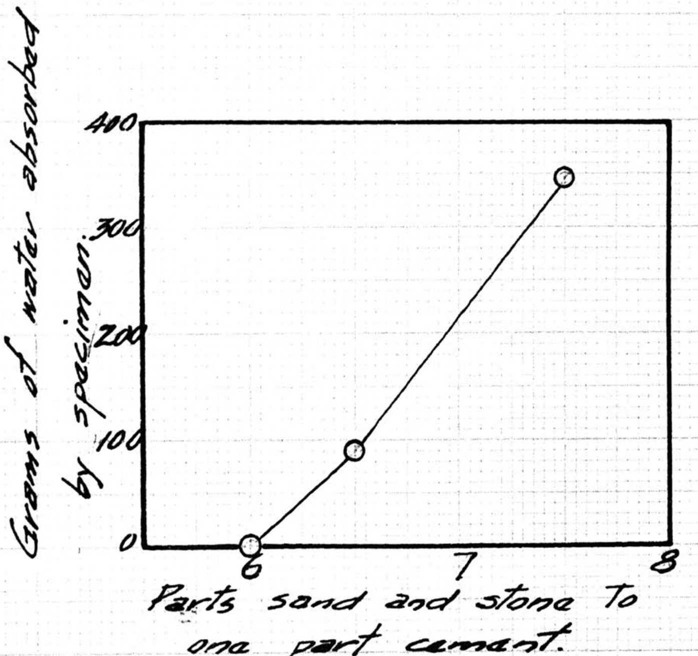


From Eng'g. News, Vol. 47, pp. 31-32.

EFFECT OF QUALITY AND QUALITITY OF MORTAR ON ABSORPTION OF CONCRETE

Plate II

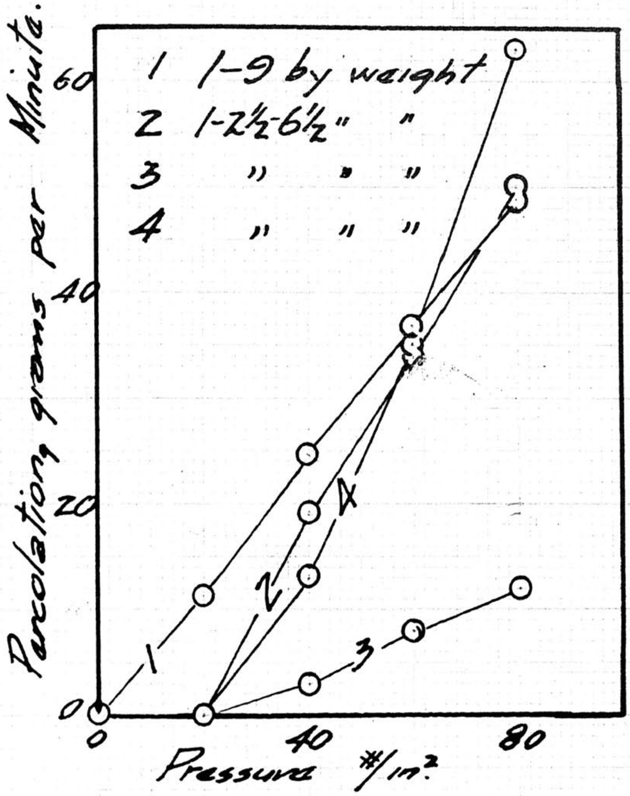




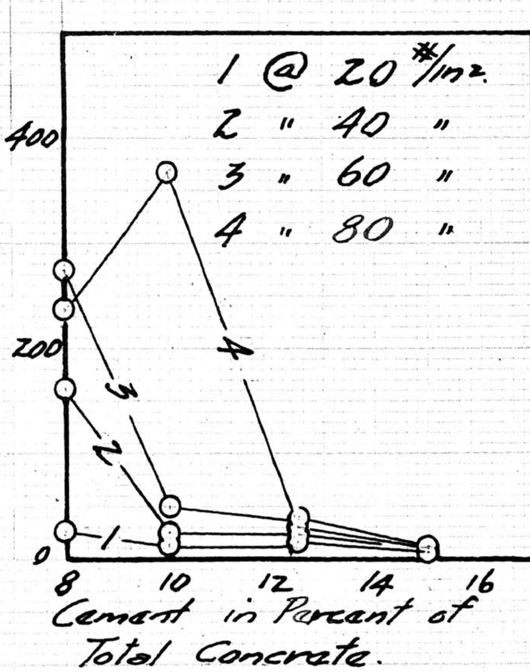
McIntyre & True, Eng. News, Vol. 47, p. 517.

PERMEABILITY FACTORS. Plate III
(CONCRETE)

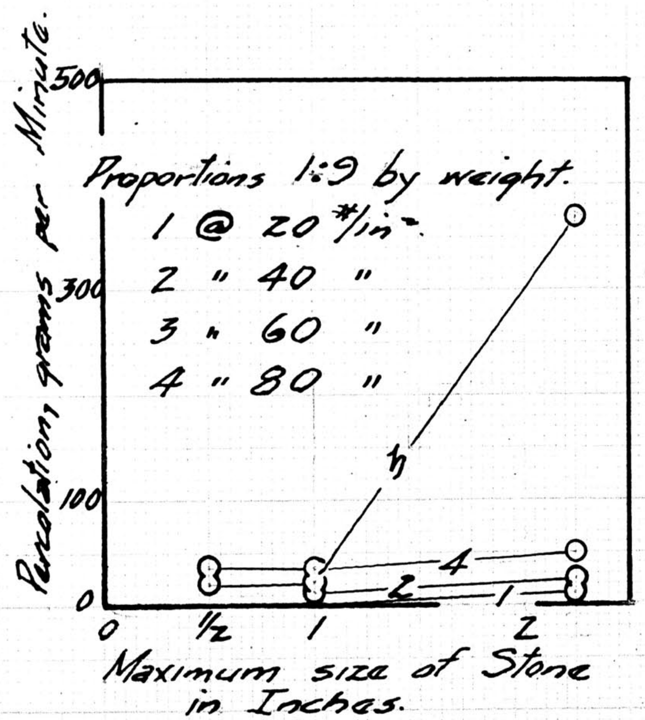
PRESSURE.

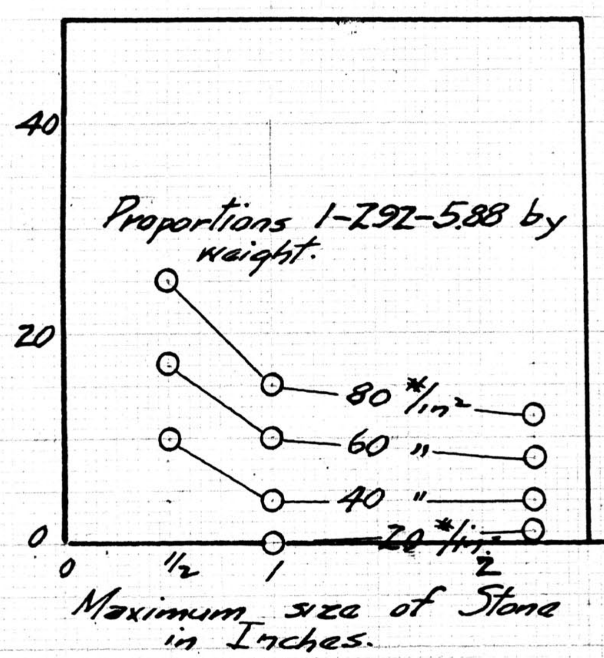


% OF CEMENT.



SIZE OF AGGREGATE.



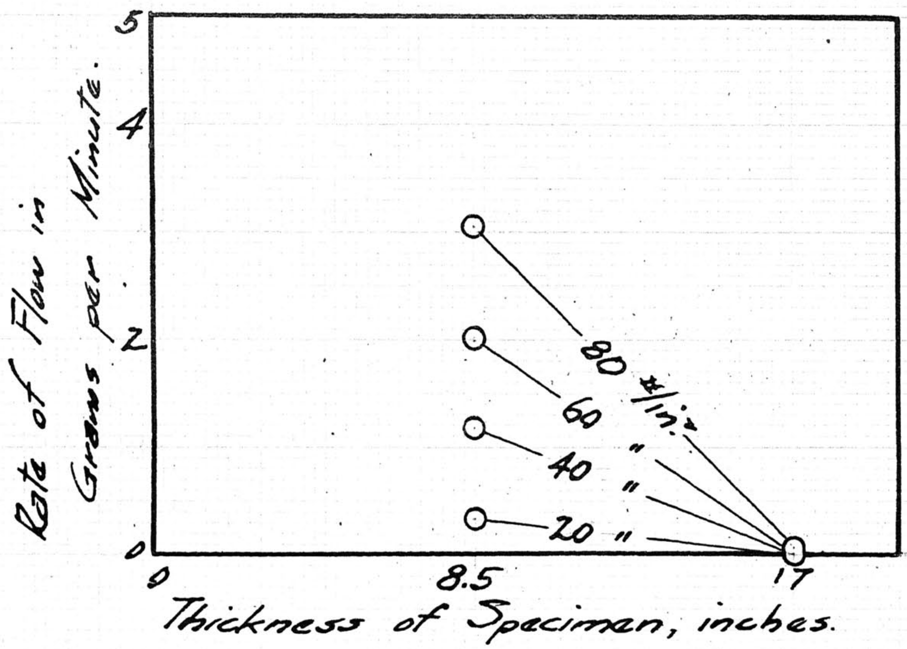


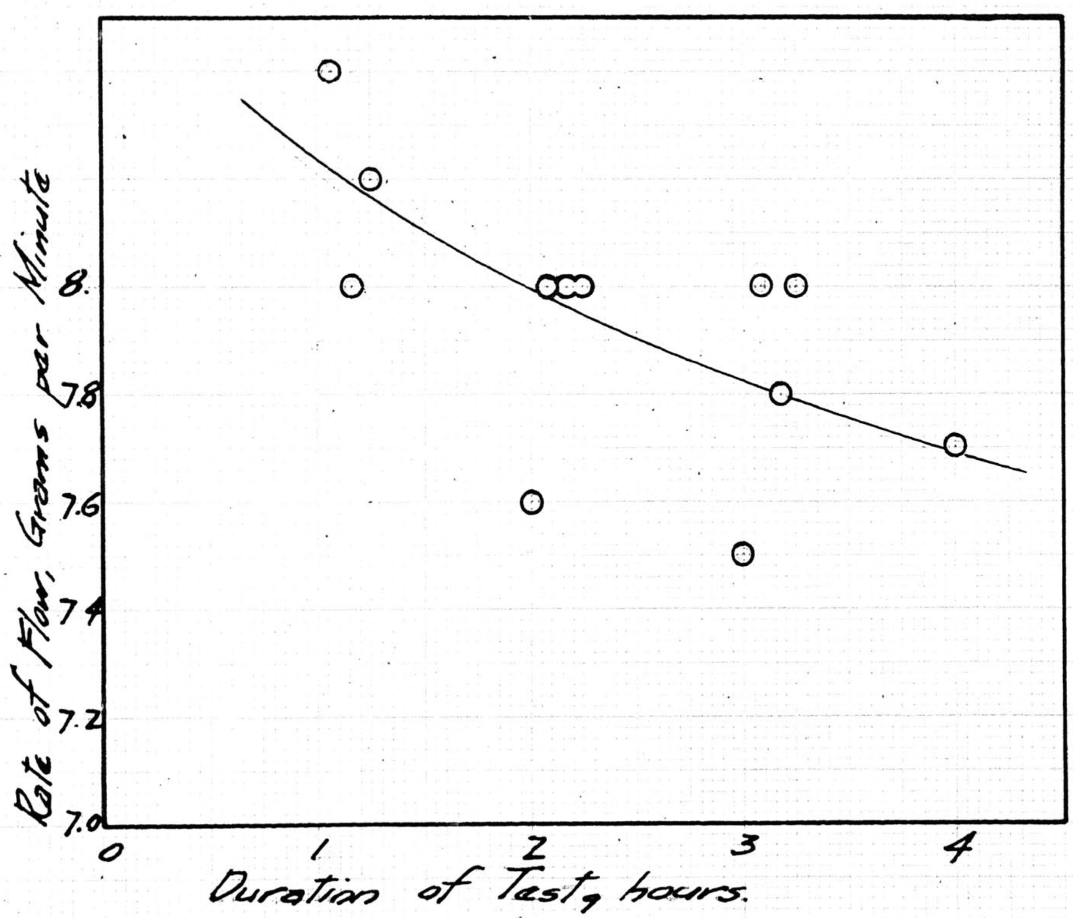
Fuller & Thompson, Trans. Am. S.C.E., Vol. 59, p. 136.

PERMEABILITY FACTORS.
(CONCRETE)

Plate IV

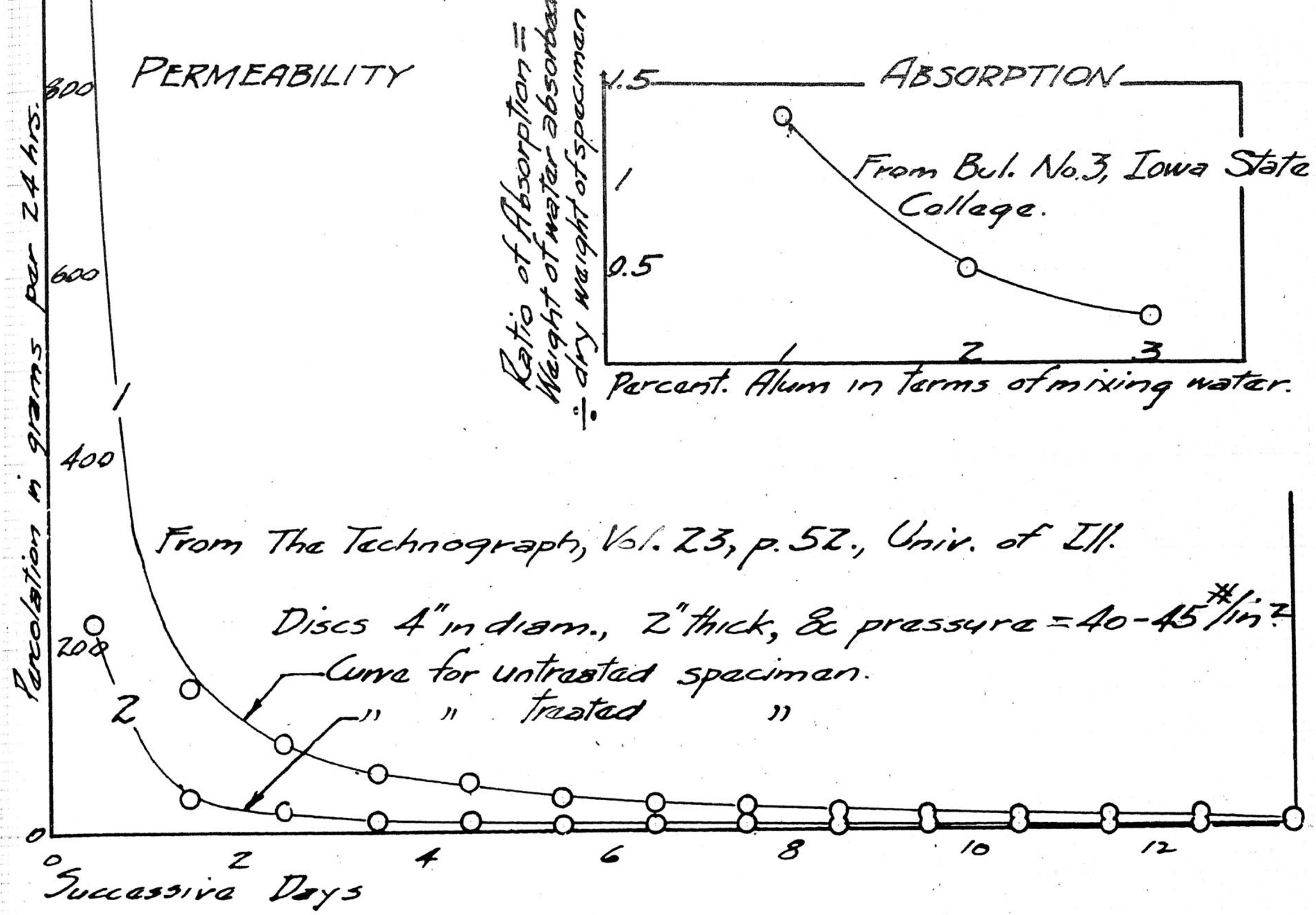
THICKNESS OF SPECIMEN



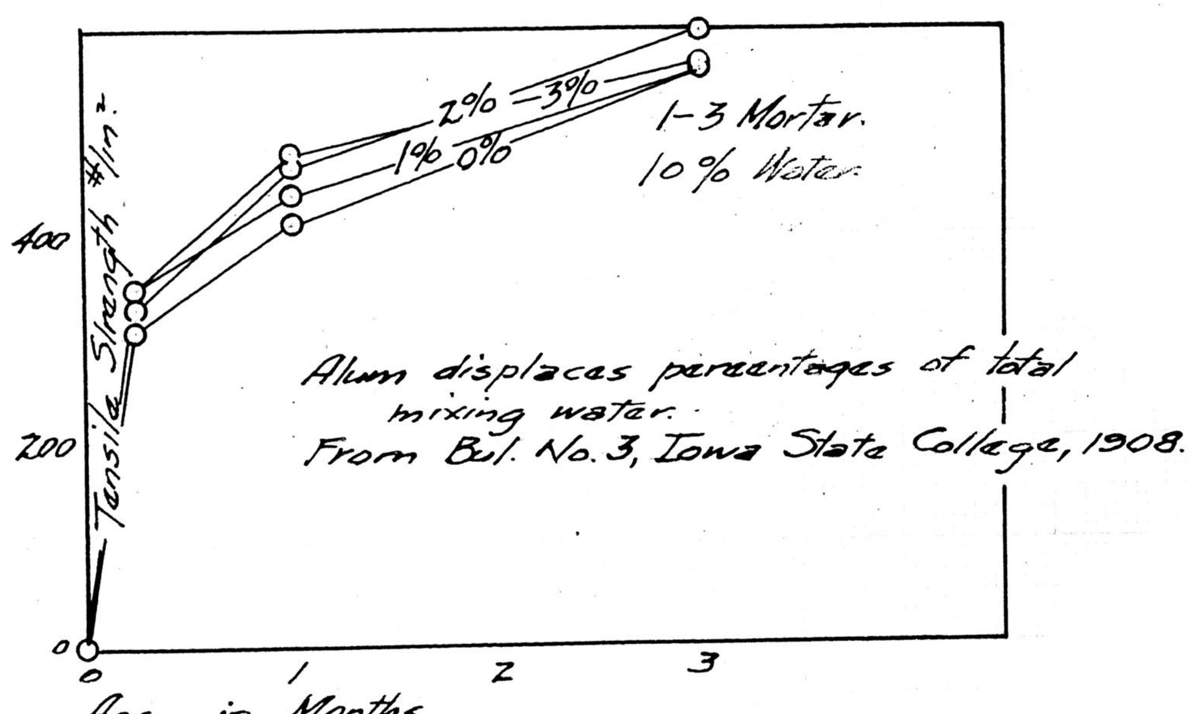


Fuller & Thompson, Trans. Am. S. C. E., Vol. 59, p. 136.

EFFECT OF SYLVESTER COMPOUND ON P.C. MORTAR.

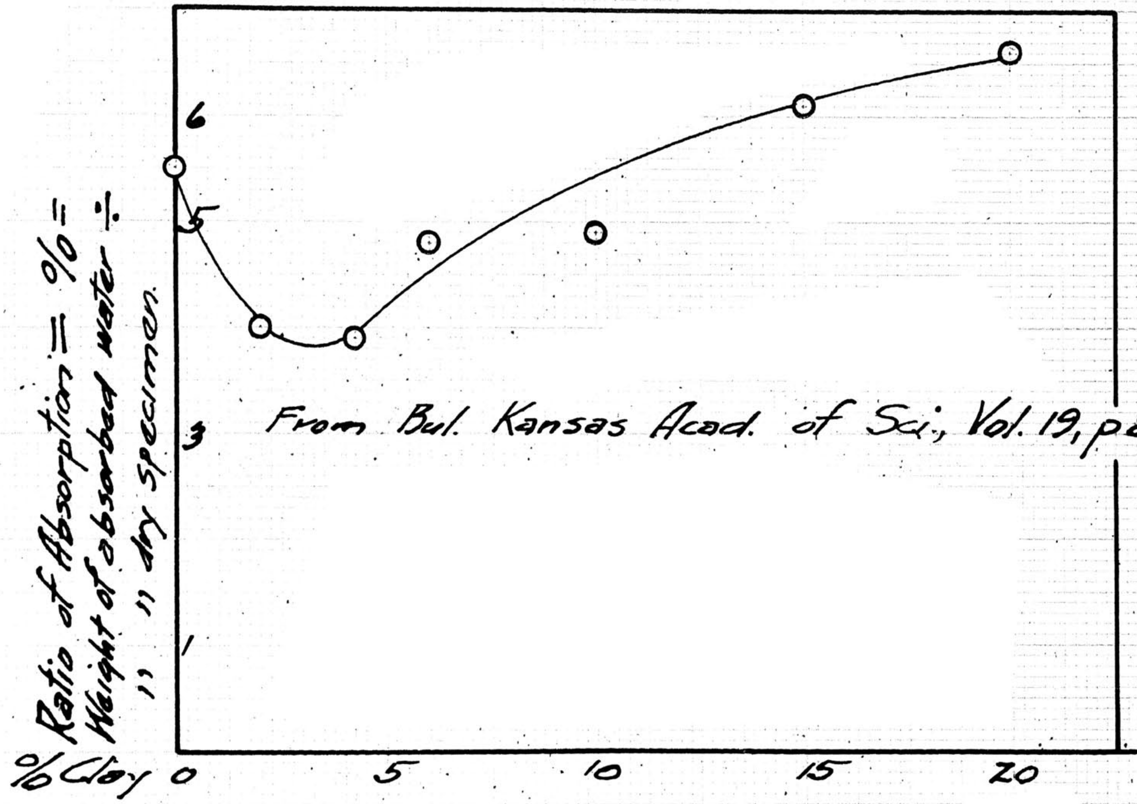


EFFECT OF ALUM ON STRENGTH OF MORTAR.

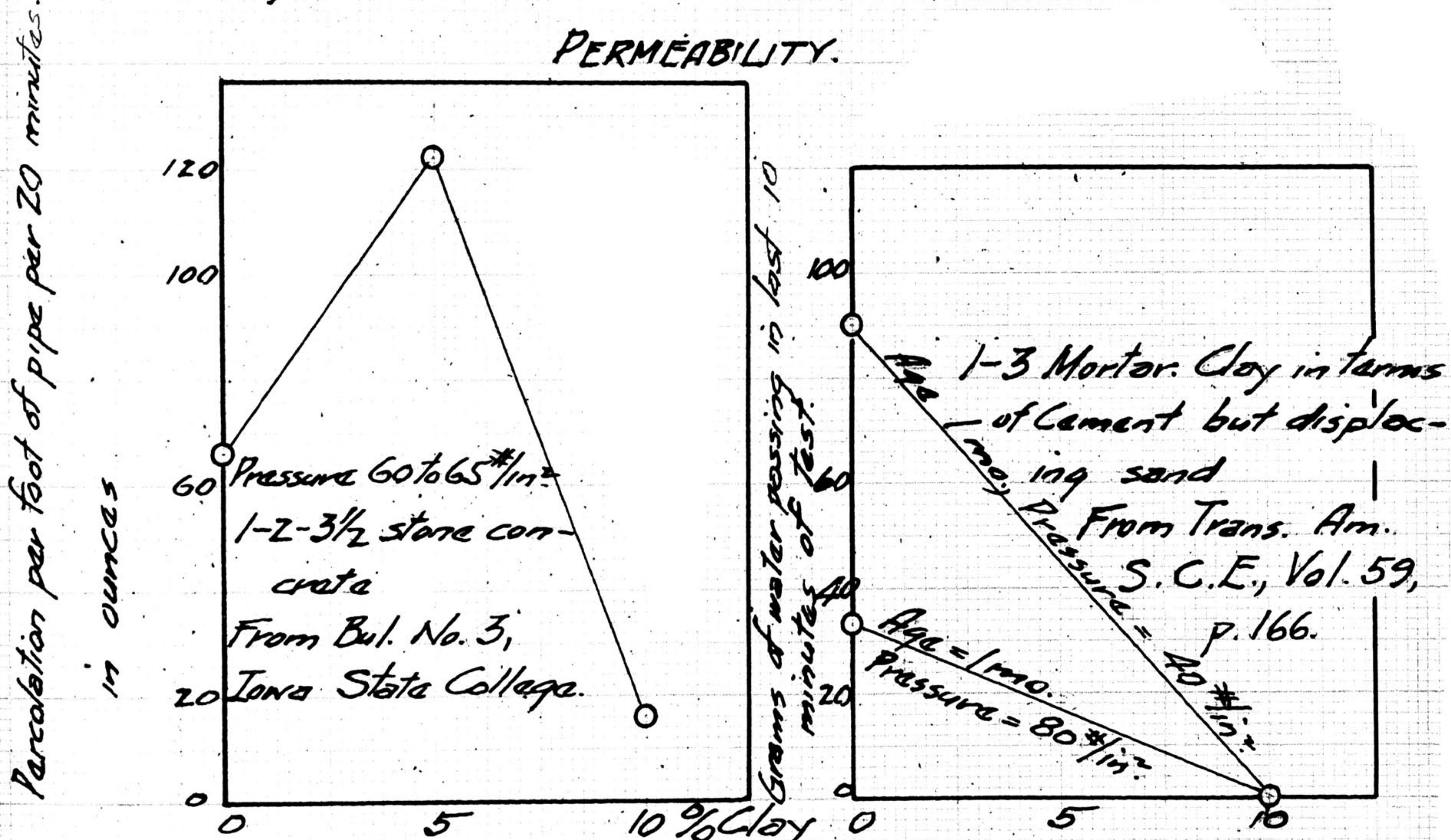


EFFECT OF CLAY ON P.C. MORTAR. Plate VI

ABSORPTION

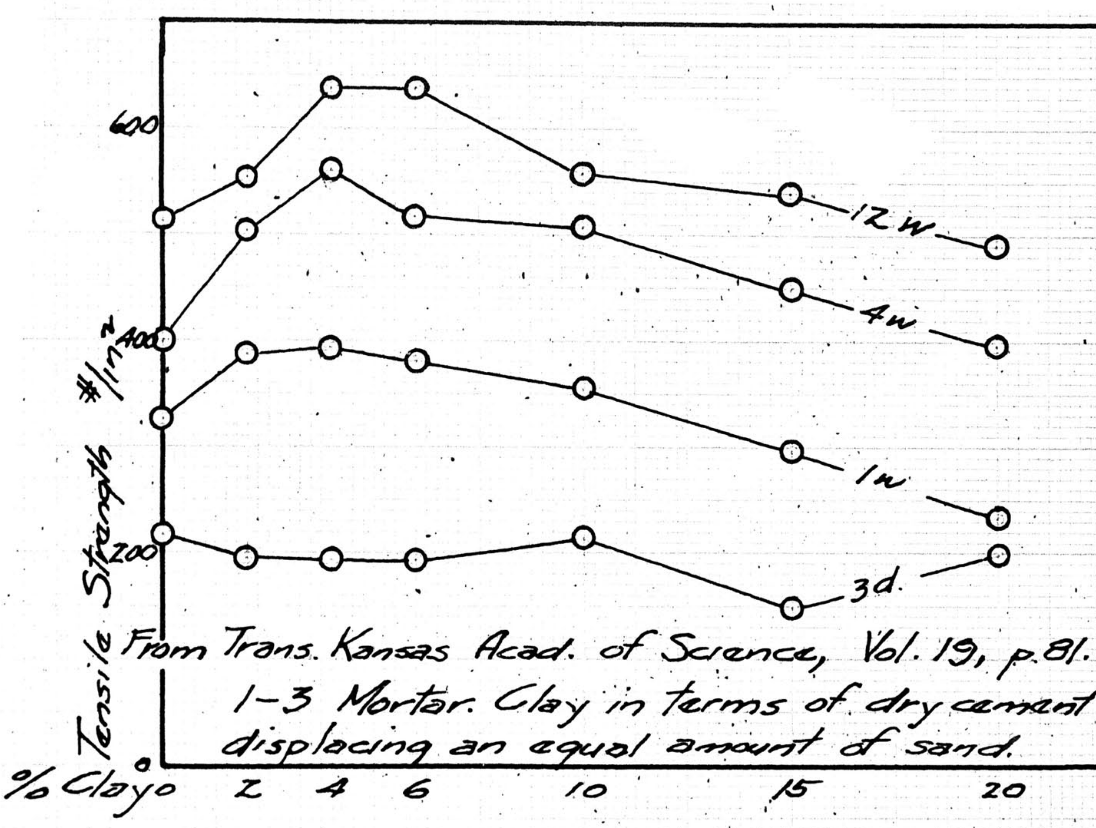


PERMEABILITY.

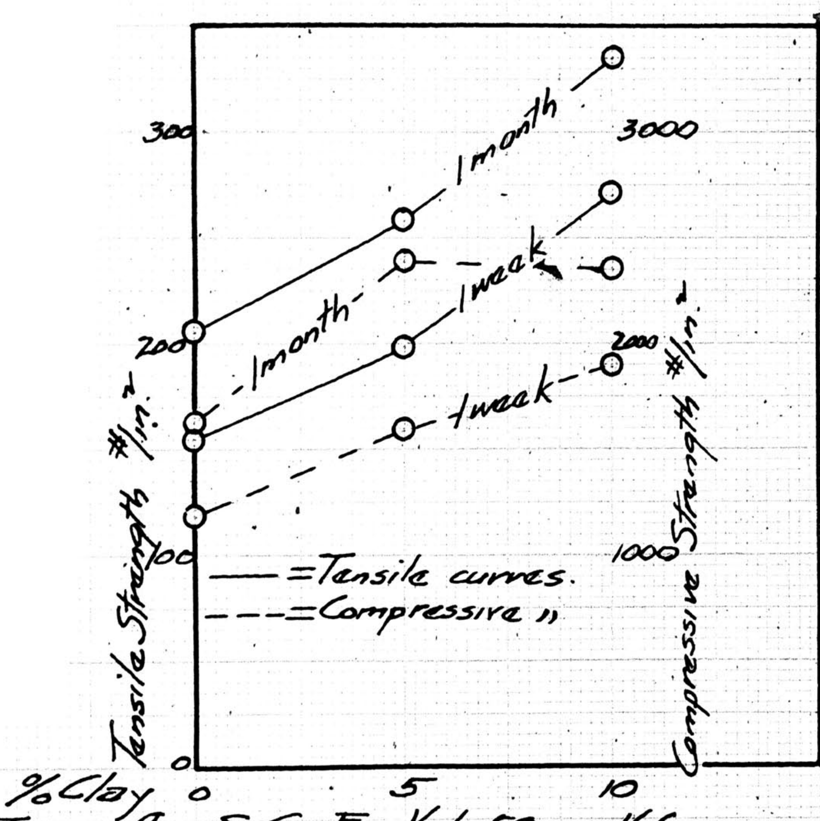


EFFECT OF CLAY ON P. C. MORTAR. Plate VII

STRENGTH.



From Trans. Kansas Acad. of Science, Vol. 19, p. 81.
1-3 Mortar. Clay in terms of dry cement and displacing an equal amount of sand.

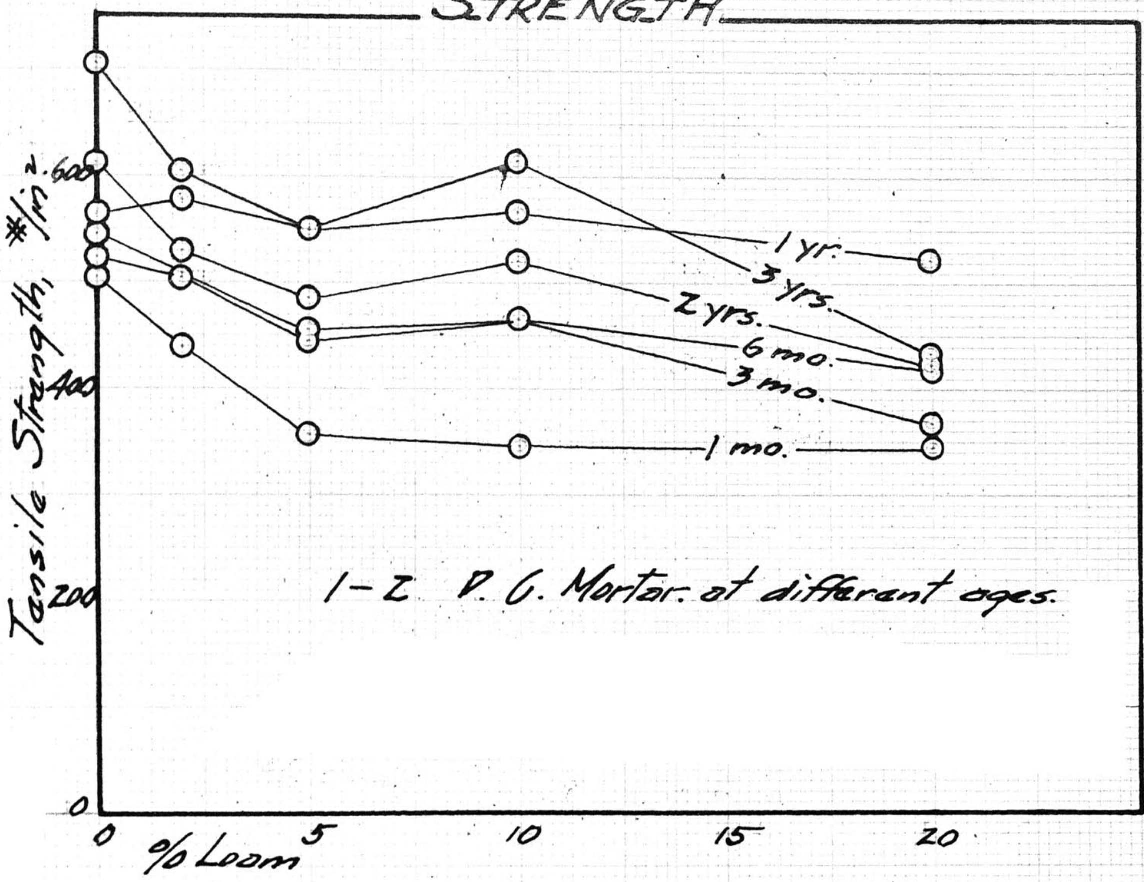


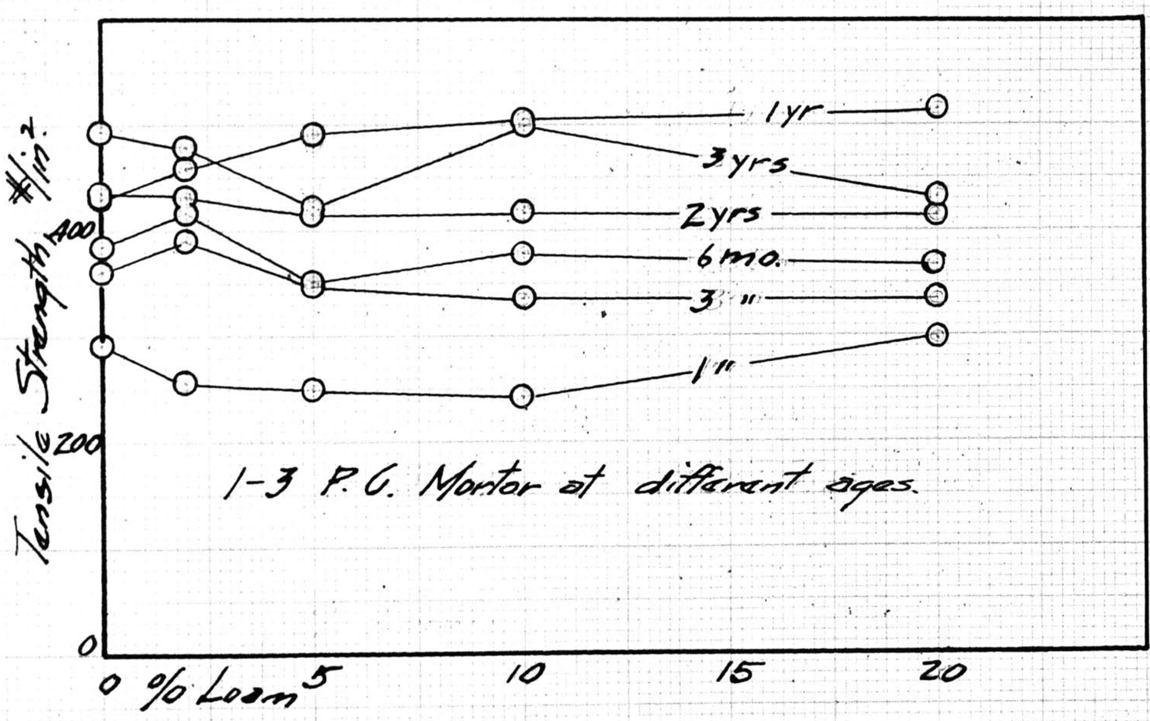
From Trans. Am. S.C.E, Vol. 59, p 166.
1-3 Mortar. Clay proportioned as in upper curves.

EFFECT OF LOAM ON P. C. MORTAR. Plate VIII

Tests by G. J. Griesenauer, Eng. News, Vol. 51, p. 413.
Loam displacing percentages of sand.

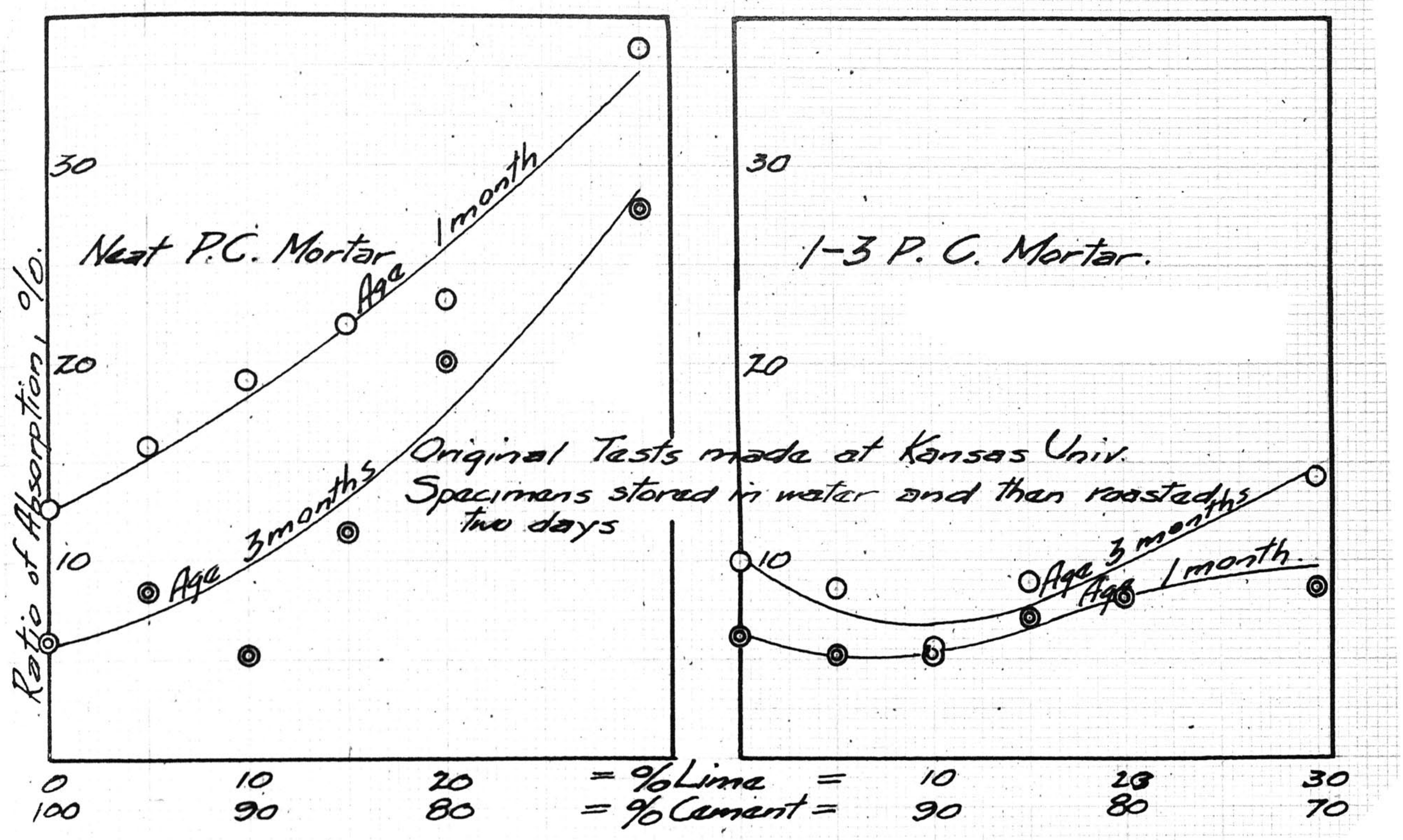
STRENGTH.

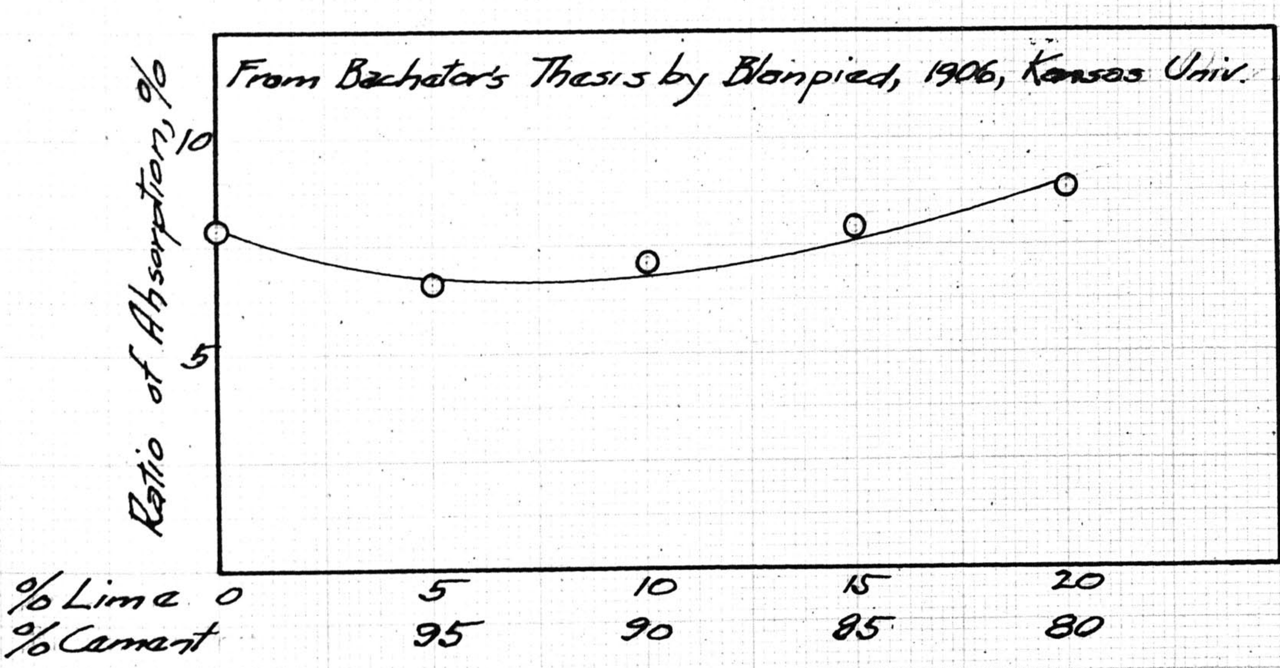




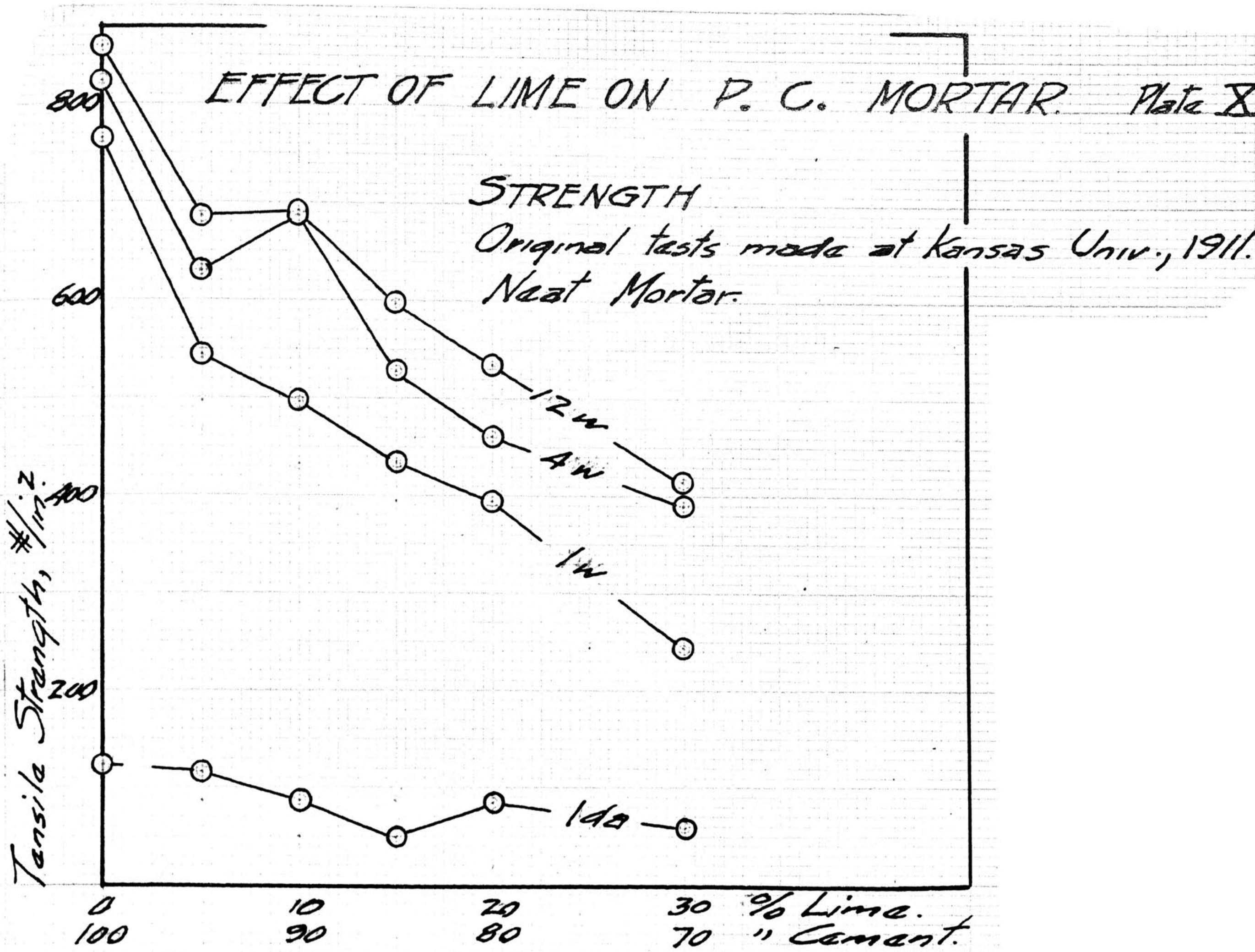
EFFECT OF LIME ON P.C. MORTAR. Plate IX

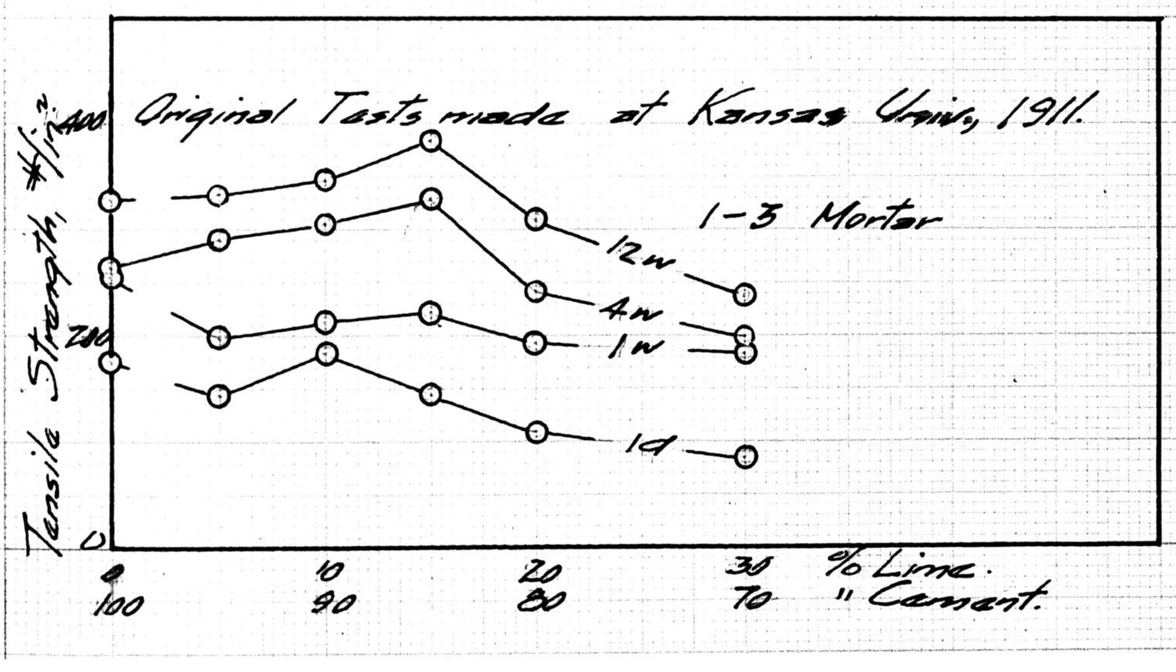
ABSORPTION.





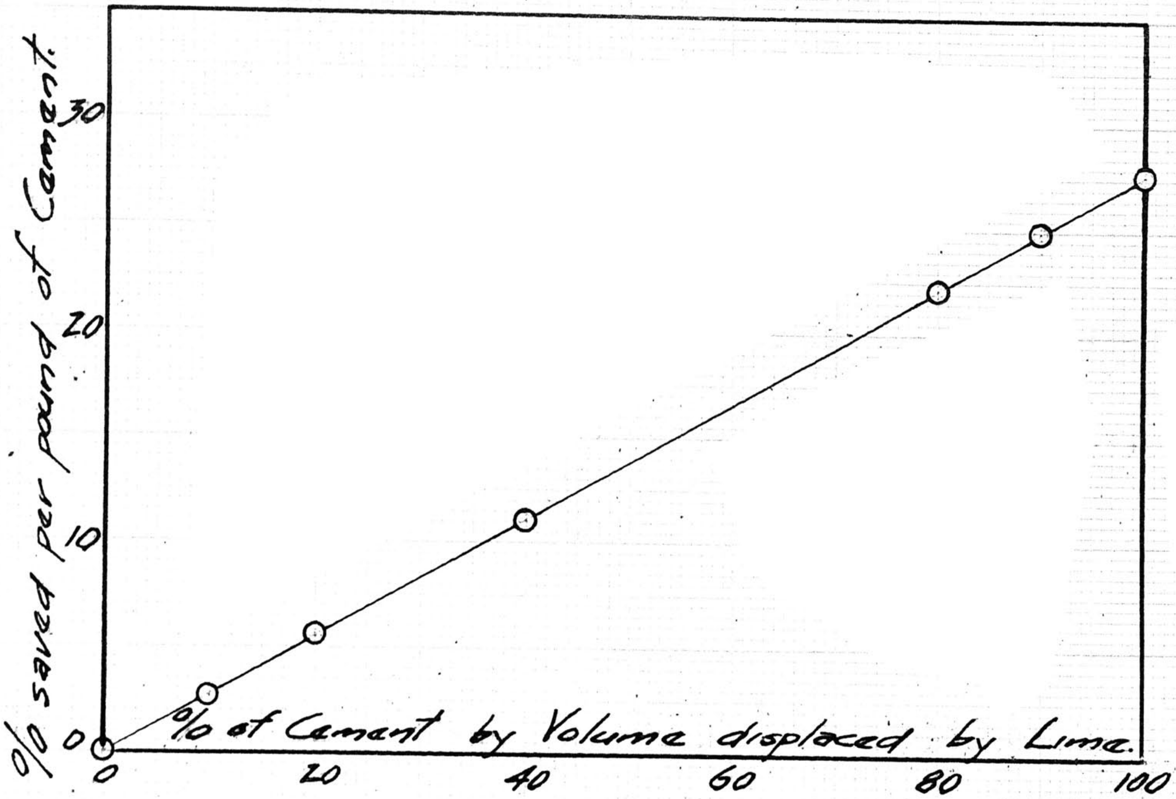
EFFECT OF LIME ON P. C. MORTAR. Plate X



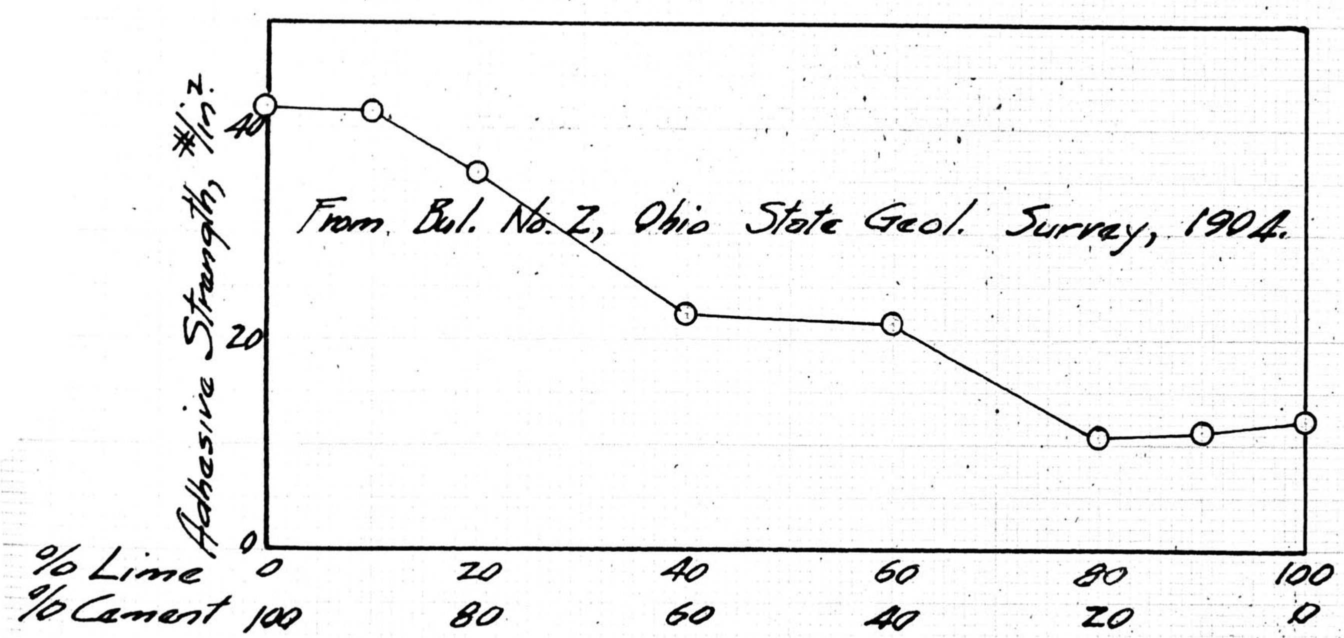


EFFECT OF LIME ON NATURAL CEMENT MORTAR.

COST.

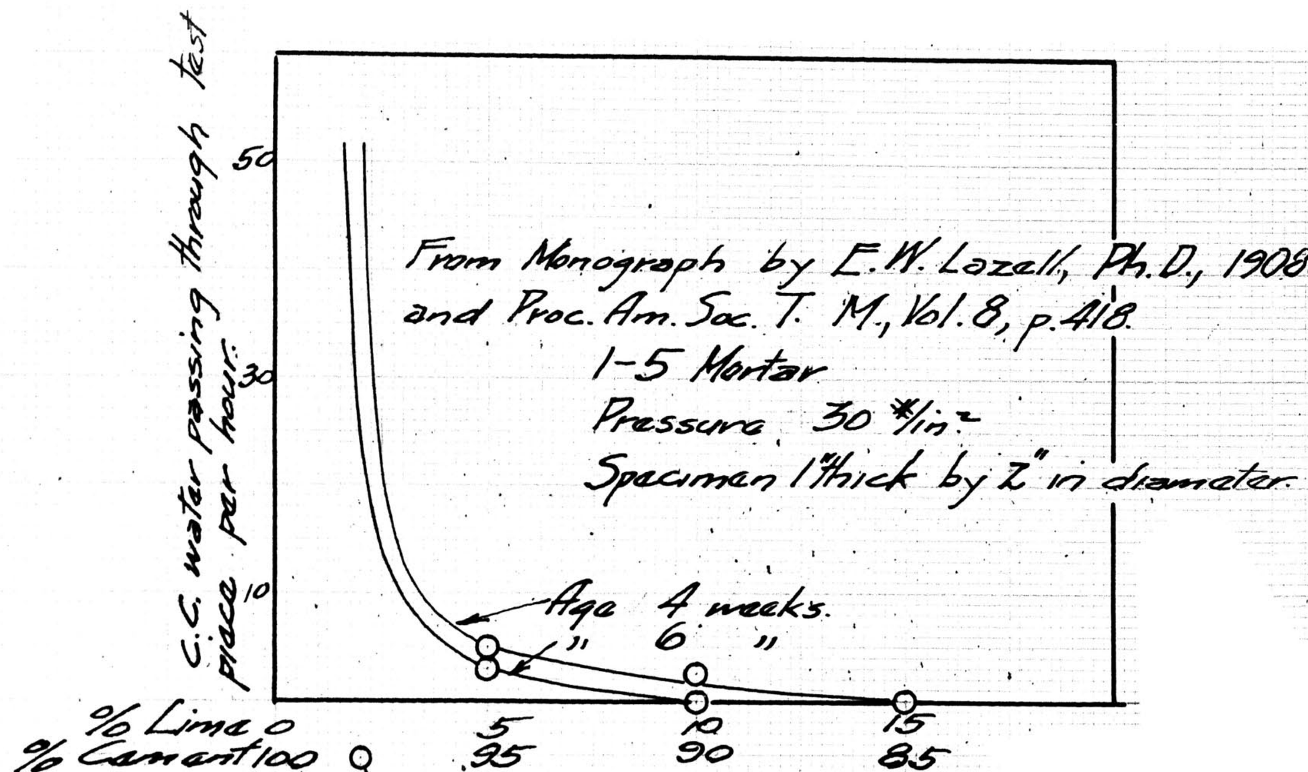


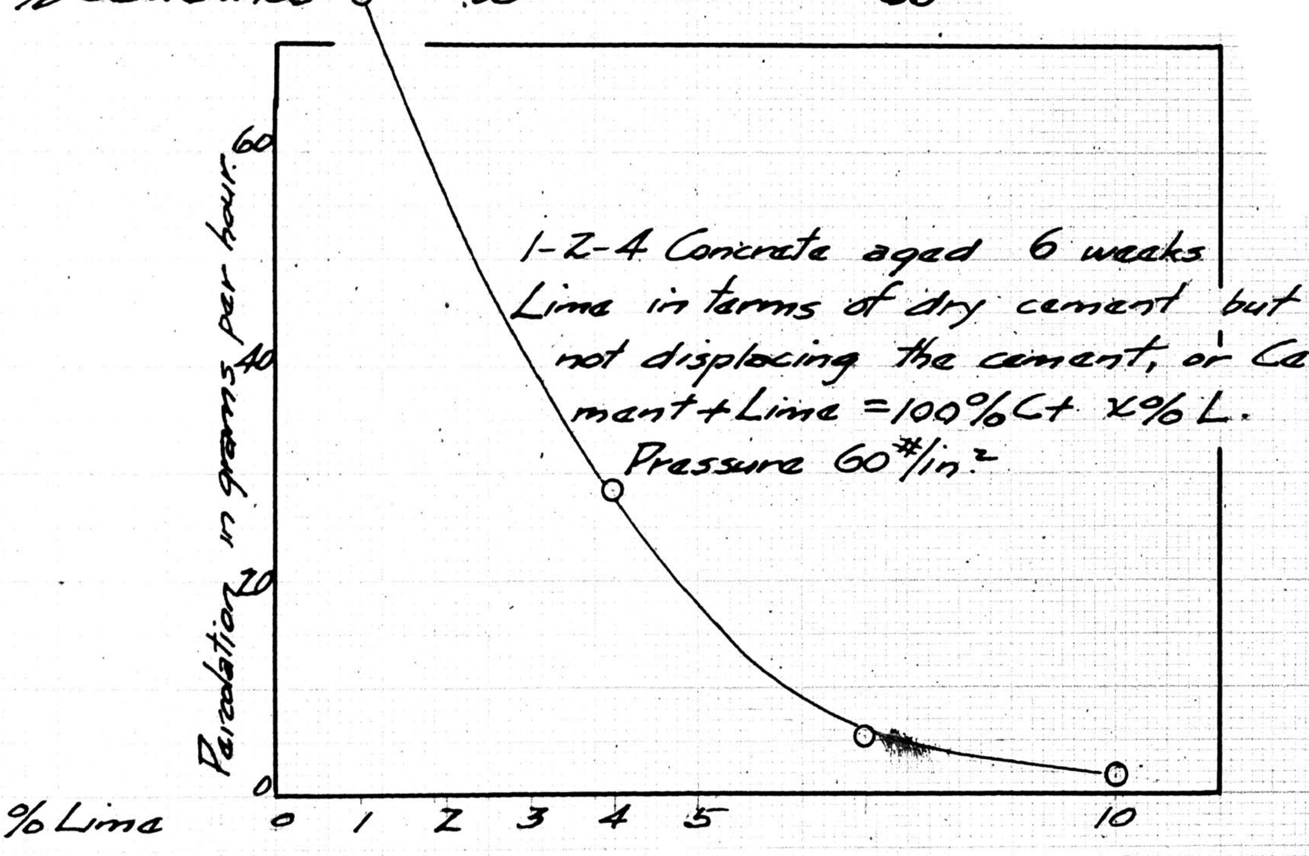
ADHESIVE STRENGTH.



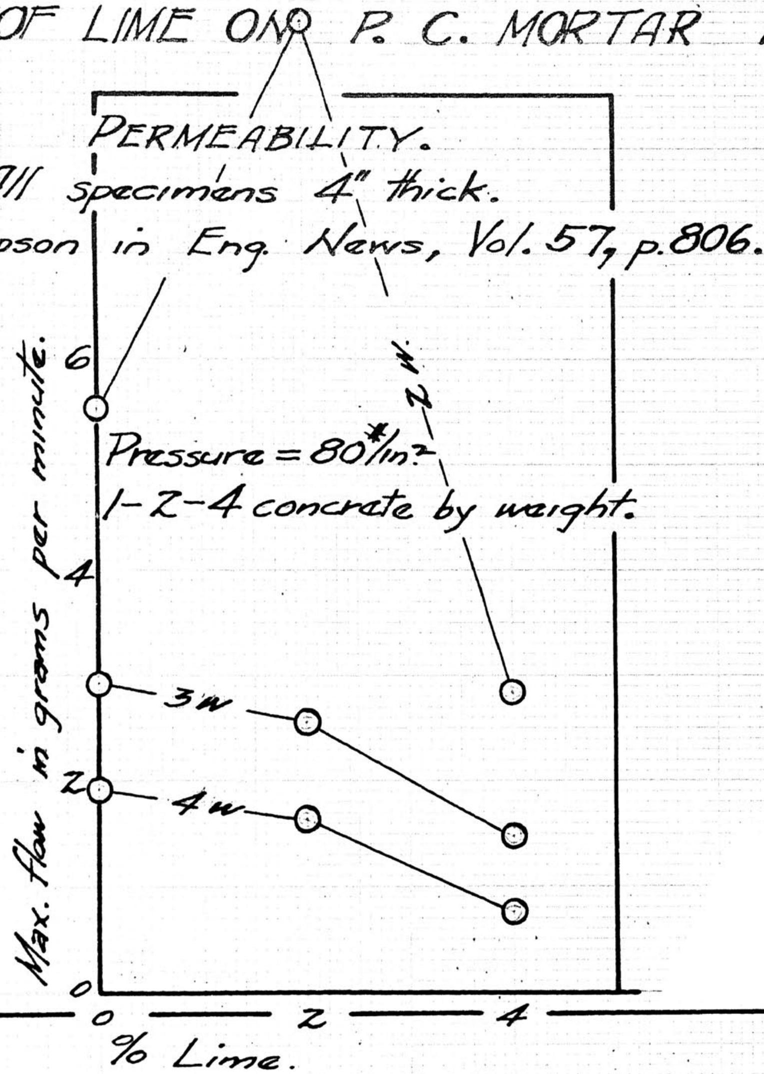
EFFECT OF LIME ON P. C. MORTAR. Plate XII

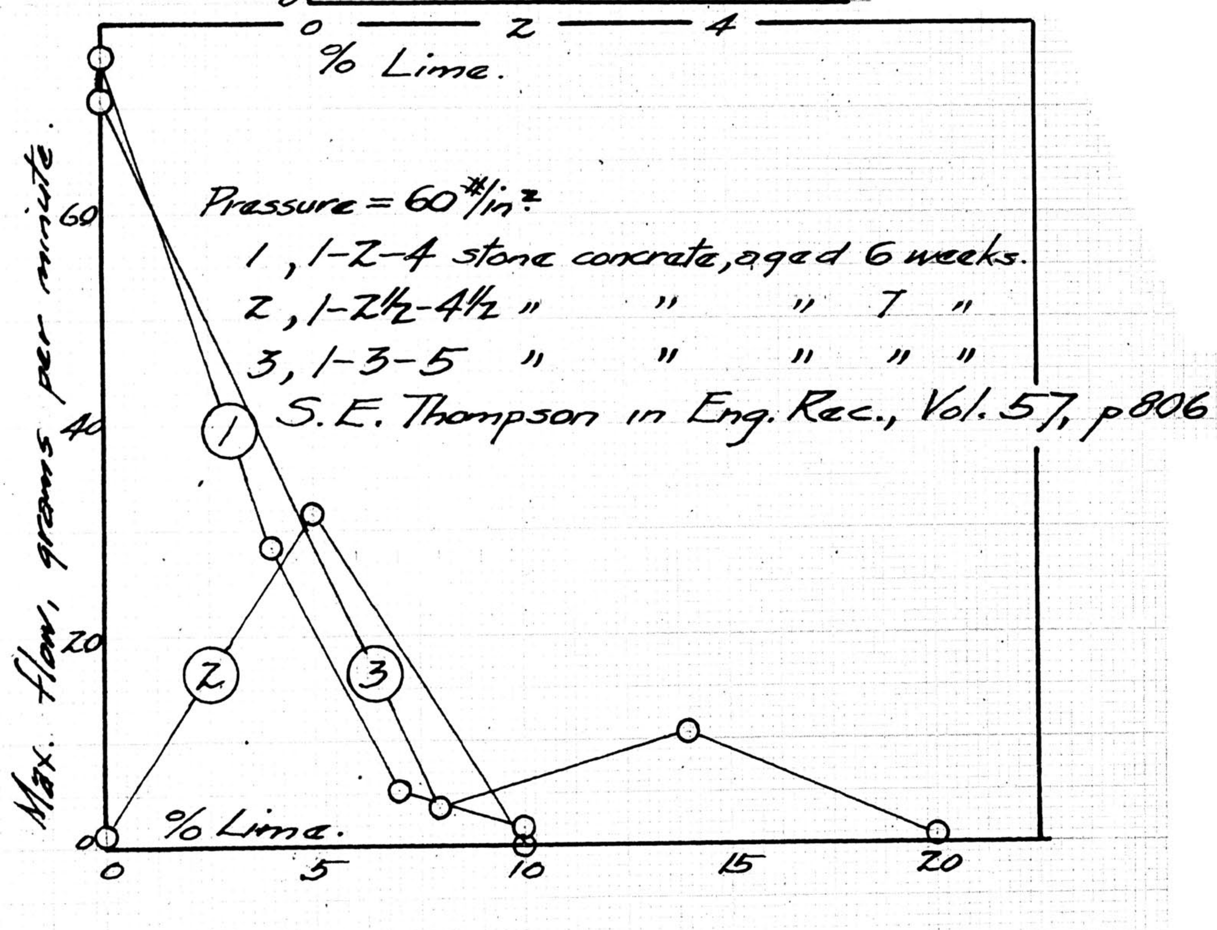
PERMEABILITY.



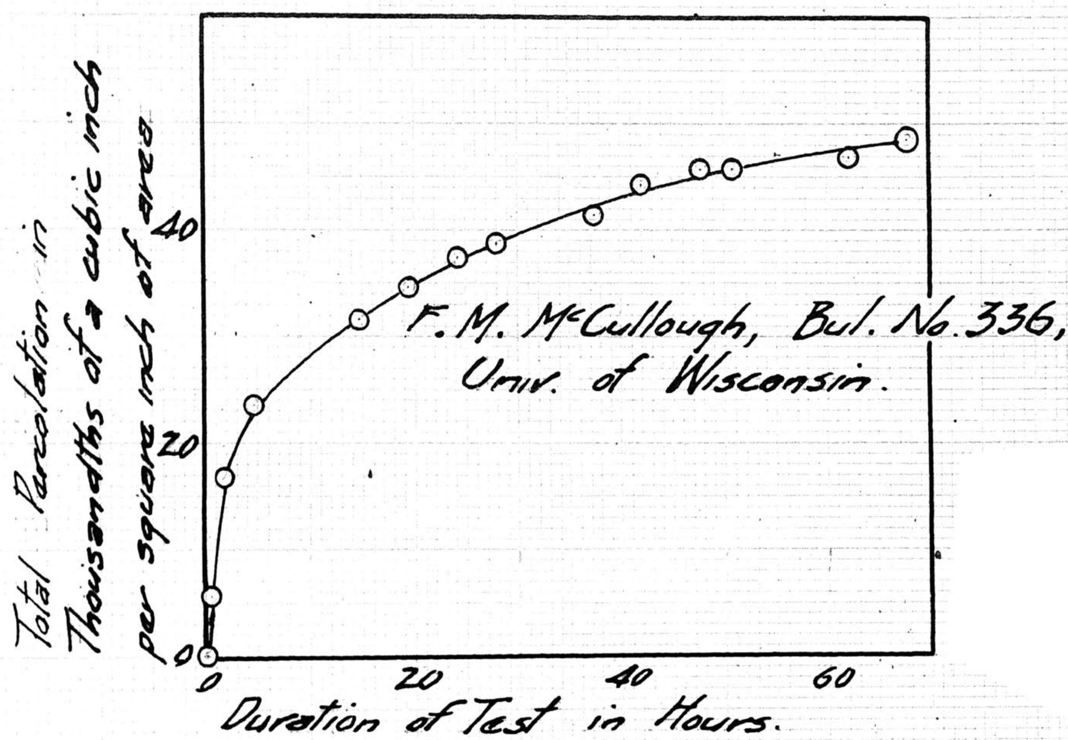


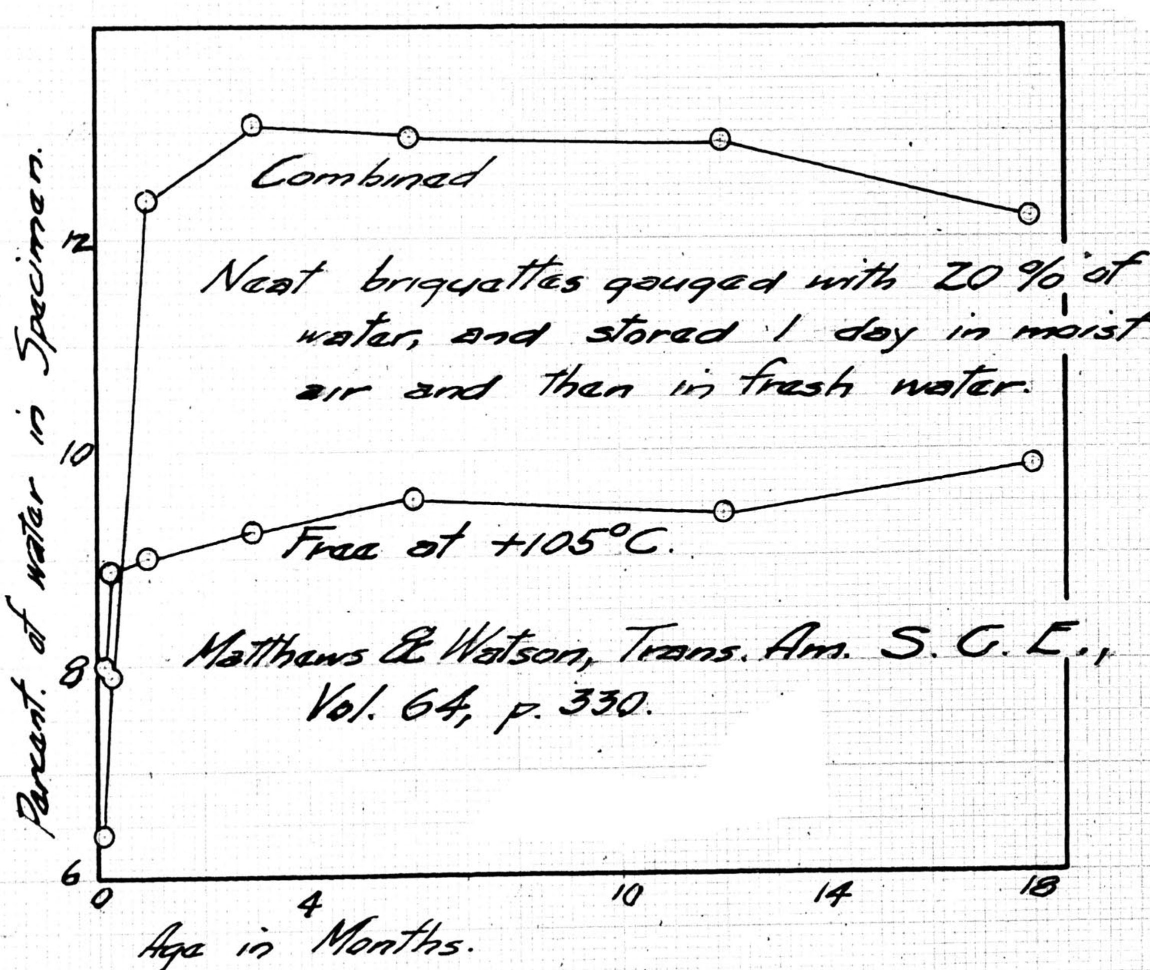
EFFECT OF LIME ON P. C. MORTAR Plate XIII





EFFECT OF TIME ON PERMEABILITY AND ABSORPTION Plate XIV





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