PHYSICAL TESTS OF IOWA LIMES

BY

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CONTENTS.

CHAPTER II

GENERAL CONSIDERATIONS.

The lime of commerce is produced by the calcination of limestone and varies in composition and purity as do the limestones themselves. The latter range from practically pure calcium carbonate ($CaCO_3$) to the sandy and clayey limestones in which the impurities compose a large percentage of the rock. Again, the calcium may be in part replaced by magnesium which gives the magnesian limestones. If this replacement has taken place to the extent that magnesia (MgO) comprises 18 to 20 per cent of the stone, the term dolomitic limestone is more commonly applied.

A limestone composed essentially of $CaCO_3$ will furnish a high grade of quicklime, one containing little else than CaO; one composed of $CaCO_3$ with a greater or less percentage of $MgCO_3$ will afford a magnesian or dolomitic lime; while the argillaceous limestones will give a product of a degree of purity depending on the amount of clay in the original stone. The properties of the resulting limes will vary according to their composition.

Limestones are widely distributed in nature, both geographically and geologically. They are found interbedded with and overlapping other common sedimentary strata, and they have been produced in much the same way as other sediments. Good reasons are readily conceived why they should be apt to partake of the nature of, and to grade into or be contaminated with, other sedimentary materials. It is, nevertheless, not at all uncommon to find limestones that run over 90 per cent lime carbonate, and occasionally as high as 98 or 99 per cent. The analyses of nine samples of non-dolomitic Iowa limestones show a range of from 82.5 to 97.02 per cent carbonate of lime, three of the nine samples showing over 90 per cent.

As indicated, limestones depart in composition most commonly in the content of magnesia and in the clay and sand impurities. The effect of these substances on the resulting lime is of so much importance that they may be given separate consideration.

WHITE VERSUS BROWN LIMES.

A pure limestone when burned changes to calcium oxide (CaO) by the loss of carbon dioxide (CO_2) gas. The resulting lime is the white lime of commerce. It slakes readily and rapidly, with the evolution of much heat and becomes a perfectly white paste. The chemical reaction in slaking is:

$$\underset{\text{Quicklime}}{CaO} + \underset{\text{Water}}{H_2O} = \underset{\text{Slaked lime}}{Ca(OH)_2} + \text{heat}$$

This reaction with CaO furnishes with maximum intensity all of the evidences of the chemical change which is taking place. Any impurities in the quicklime, which may have been present in the limestone, tend to retard and to make less vigorous the slaking process, but the quantity of the impurity must be considerable before any pronounced interference will be noticeable.

Dolomitic limestones are very common and produce limes that slake slowly, evolve less heat and are of a gray or brown color. Over ten per cent of MgO must be present to appreciably alter the properties of a lime. Limes containing less than 10 per cent MgO are accordingly spoken of as magnesian limes, while those with over 10 per cent are properly called dolomitic or brown limes. Dolomitic limes produced from Iowa limestones range in magnesia content from 15.23 to 35.73 per cent in the marketed product.

With reference to the amount of magnesia contained, therefore, limes may be classified; (a) hot, white or high-calcium limes when MgO is below 10 per cent; and (b) cool, brown, or dolomitic limes when MgO is over 10 per cent. The value, properties and adaptability of the two classes will be briefly treated later.

WHITE VERSUS ARGILLACEOUS AND SILICEOUS LIMES.

Limestones which contain clayey matter produce limes that are gray in color and less vigorous in their action than the pure white limes. Sand or other siliceous impurities in the lime do not ordinarily exert any influence on its physical properties, acting simply as a diluent in the same way that sand does in a mortar. Should the latter be excessively fine, however, it may become susceptible to chemical combination with the lime if high temperatures are employed in the burning. As the amount of sand and clay increases, limestones are called sandy or arenaceous and argillaceous, and when these materials become the predominant constituents, the rock passes into calcareous or limy sandstones and shales.

The presence of a small proportion of the above named impurities causes limes to become hydraulic, that is, to possess the property of hardening under water, by the gradual taking of water into chemical combination. When the quantity of clayey impurities in the limestone reaches 6 per cent, they begin to produce hydraulicity. Below 6 per cent the only noticeable effect is in the retardation of slaking. Limestones carrying 6 to 12 per cent furnish limes that are cool and slow slaking, gray in color and make the best of mortar if burned at ordinary lime kiln temperatures. There is, however, much greater danger of overburning than in the case of white limes as the clay has a tendency to combine with the lime, which decreases its value unless finely ground. Fifteen to twenty-five per cent of clay renders a lime strongly hydraulic if properly burned, but care is required to avoid overburning and consequent clinkering. If clinkering is permitted to take place, the product is found to possess, after fine grinding, a hydraulicity greater than that of the hydraulic limes and similar to cement, which property becomes more prominent the greater the clay content and the higher the temperature of burning. The limit at present is Portland cement in which the raw materials are artificially blended and thoroughly clinkered at very high temperatures.

It is clear, therefore, that limes are but one end of a series of products of which Portland cement is the other. The dividing lines separating the various members of the series that are put upon the market are to some extent arbitrary. The following four divisions are commonly referred to:

1. Common or fat limes.
2. Hydraulic limes.

3. Hydraulic or Roman cements.
4. Portland cement.

The points of distinction between 1 and 2 have been noted. In composition, 2 and 3 are not separable. By an increased temperature in burning some hydraulic limes will become hydraulic cements. Twenty-four per cent of clay is about the permissible upper limit for the hydraulic limes, while Roman cements are in use which contain but little over 20 per cent of clayey impurities. The chief distinguishing feature of these two groups lies in the ability of the limes to slake to a paste with water without previous pulverization. Fine grinding is necessary before water will affect appreciably Roman cements and before they will harden as a mortar.

The feeble hydraulicity of the limes and the relatively strong of the cements appears to be due to the varying degree to which chemical combination has been brought about in burning. In lime burning, little if any chemical action occurs between the lime and the clay. What does take place tends to produce an unstable or "unlocked" condition of the clay and other siliceous materials such that, in the presence of water, the lime hydrate slowly attacks these and combines with them to form silicates that are harder and more durable than ordinary lime mortar. Clinkering in burning, is an indication of chemical action, further progress in rendering available and susceptible to the attack of the lime and water the clay and other siliceous substances in the stone. Burned to this condition, the product is properly termed a cement and in use attains a stony hardness and relatively great permanency.

Hydraulic or Roman cements are spoken of also as natural or rock cements, since they are made from limestones in which the ingredients occur naturally in the proper proportions. Such limestones are found in different parts of the United States, but have been utilized principally in the Appalachian states of the East and along the Ohio river. The actual composition ranges between wide limits as shown in the table below in which are compiled the analyses of five reputable brands of natural cements:

Analyses of Natural Cements.

NAME	Silica	Alumina	Iron oxide	Lime	Magnesia	Alkalis	Loss on ignition
"Fern leaf" brand, Louisville, Ky.	26.4	6.28	1.00	45.22	9.00	4.24	7.86
N. L. & C. Co., Rosendale, N. Y..	30.5	6.84	2.42	34.38	18.00	3.98	3.78
"Hoffman," Rosendale, N. Y.....	27.3	7.14	1.80	35.98	18.00	6.80	2.98
Utica brand, Utica, Ill............	27.6	10.60	0.80	33.04	7.26	7.42	2.00
Mankato, Minn....................	28.43	6.71	1.94	36.31	23.89	1.80	0.92

Numbers 3 and 4 in the outline on page 98, bear to some extent a similar relation to that briefly given for 2 and 3. A more complete vitrification of the ingredients in the cement mixture until they issue from the kiln as thoroughly vitrified clinker produces the maximum amount of hydraulic silicate. The chemical changes which occur in burning are complicated and become more so the higher the temperature over that employed in the manufacture of natural cement. Just what these changes are is not accurately known, but experimentation has determined within fairly narrow limits what proportions of the various constituents entering into a mixture of clay, silica and limestone will produce the greatest amount of unstable, hydraulic silicate, and what temperatures are required to accomplish this result. These proportions and temperatures are employed in the manufacture of Portland cement and are considered in Chapter I.

The foregoing remarks will serve to show the relation of limes as a mortar material to other substances used for similar purposes. This paper has to do with limes alone and the several physical properties of the latter that are of chief importance will be briefly discussed.

SLAKING.

The property belonging to limes which makes them of industrial value is their ability to slake or crumble to a powder on the addition of water, and to harden when allowed to stand in contact with the atmosphere. The reaction which occurs in slaking has already been given. If a lime is properly burned, all lime carbonate in the original stone has lost its carbon dioxide, and becomes quicklime (CaO). It is the rapid change accompanied by the evolution of heat when water is added that causes lime to slake. Slaking is a physical evidence of the hydration of lime, but it is not to be understood that slaking is a necessary result of such chemical action. The two processes are really distinct. The exposure of caustic lime to a moist atmosphere occasions slow hydration, accompanied by crumbling to a powder. Along with this change occurs an increase in volume of about 1¾ times that of the original lime. Such lime is air-slaked and is largely changed to the hydroxide $Ca(OH)_2$. If this lime be exposed to water, it will further increase in volume, but the paste resulting will be sharp and sandy in texture, and of much less value for mortar purposes than freshly slaked lime. In this case a portion of the CaO has no doubt combined with the CO_2 of the air, so that air-slaked lime is actually a mixture of lime hydrate and carbonate. It is possible also to bring about the complete hydration of lime by steam at temperatures above boiling, without any change of volume or any sign of crumbling.

Slaking may therefore be defined as the hydration of calcium oxide, quick-lime, accompanied by an increase in temperature and volume. The increase in temperature is caused by the combination of the lime and water. It is an exothermic reaction, one in which heat is evolved. Whether or not this heat becomes evident depends on the vigor and rapidity of the reaction.

Slaking is commonly accomplished by the addition of sufficient water to cover the lime, and by further additions as needed. It is desirable from the practical standpoint that the greatest possible increase in volume be secured in slaking. This is accomplished by careful control of the amount of water throughout the process. The evolution of heat in such quantities as to generate steam within the mass is a necessity to the slaking process. At the same time, more water than simply that required for hydration is essential. It is the expansion of the steam between the molecules of hydrating lime which forces them apart and causes the mass to crumble. As the particles are separated, the surrounding excess of water acts to remove them, as in the case if any fine sediment, and, as they settle away in partial suspension, new surfaces of the lime are constantly exposed. A large excess of water prevents proper slaking by keeping the temperature so low that the necessary steam does not form. The mass then expands poorly, slakes slowly, and the product is lumpy. The lime is said to be "drowned".

The result of too little water is a "burnt" lime. In this case, the water forms a gelatinous film of hydroxide over the surface of the lumps which dries down, enclosing caustic quick-lime in the center, and so clogs the pores that further progress is much retarded or prevented. When too little water is used, the initial action is apt also to be so violent in the case of "fat" limes, that much or all of the moisture passes off as a vapor, because of the excessive temperature developed. This frequently leaves the lime but partially hydrated, dry, and imperfectly slaked.

Dolomitic limes slake more slowly and at a much lower temperature than high-calcium limes. The heat generated is due to the hydration of the calcium oxide, the magnesia remaining as the oxide during slaking. Although magnesium carbonate loses CO_2 at a lower temperature in burning than does the carbonate of lime, it hydrates only with difficulty and probably passes directly from oxide to carbonate in the hardening process. It is thus necessary to add the water required very gradually in slaking dolomitic limes in order to avoid "drowning" and to secure the best results.

The proper amount of water to use varies, and can be ascertained for each individual lime only by actual trial. It is usually found more satisfactory to add the water in several different portions as slaking progresses, especially with the lean, slow slaking and dolomitic limes. In this way, by a little attention, the temperature of the slake can be controlled so that the best product is obtained from the lime in use.

The expansion of volume in slaking may be as high as 3½ times with pure white limes. It is found to range from 2½ to the figure named. Lean, so called hydraulic limes, and dolomitic limes expand less. Increase in volume is ordinarily estimated by a comparison of the bulk of the dry quick-lime and of the paste after slaking. Careful experiments with samples of both high-calcium and dolomitic limes made by the Ohio Geological Survey* show an increase in apparent volume for the white limes of from 136 per cent, using 20 per cent less water than theoret-

*S. V. Peppel, Bulletin 4, Ohio Geol. Survey (4th series), p. 337.

ically necessary for hydration, up to 264 per cent with 40 per cent excess of water. With 300 per cent excess, the increase was but 45 per cent. The comparison was made between the apparent volumes of the ground quick-lime and of the dry hydrate produced. Under the same conditions, a dolomitic lime gave 193 per cent expansion with a deficiency of 20 per cent of water, of 210 per cent with the exact theoretical quantity of water, and of but about 20 per cent with an excess of water. The increase in volume is decidedly in favor of the white lime, the smaller expansion of the dolomitic lime being accounted for, no doubt, by the fact that the magnesia takes up very little water in the slaking process.

The *actual* increase is, as a matter of fact, more apparent than real. The calcium hydroxide produced from a weighed amount and accurately determined volume of calcium oxide will occupy a space but 35 to 40 per cent greater than the volume of the oxide. Few experiments have been made along this line and the above figures were obtained with a high grade white lime by the use of the Seger volumeter.

If allowed to stand in the air lime deteriorates by the process of air-slaking already described. It also slowly absorbs carbon dioxide, which renders it of little value for mortar. After slaking, if the paste is not to be used at once, it should be protected from the atmosphere, since moist lime hydrate changes very readily to the carbonate by the absorption of CO_2. Slaked lime is very commonly buried so as to be covered with several inches of soil, where it will keep for months without deterioration.

Owing to the susceptibility to deterioration of the high-calcium limes on the one hand, and the exceeding slowness with which dolomitic limes slake on the other, so-called "hydrated limes" are being put upon the market. The quick-lime is subjected to a partial hydration or slaking at once after burning and before being sacked or barrelled. The completeness of the hydration in the case of five Ohio* products ranged from 58 to 94 per cent, 100 being taken as the best that is possible on a commercial scale. Specially designed and patented apparatus and processes are being employed in the hydration of limes, but it is believed that such special equipment is not necessary, nor will the prep-

*S. V. Peppel, Bulletin 4, Ohio Geol. Survey, pp. 335 and 336.

aration of hydrated lime without doing so under a patent, make any person liable for infringement. So far as known, no hydrated lime is placed on the market from Iowa kilns.

The desirable qualities of hydrated lime are: (1) its convenience in use, for it is already pulverized and but little time is required to make a mortar by mixing the ingredients dry before adding the water; (2) its lasting qualities, as it will keep much longer without detriment than the unslaked product. Magnesian limes are more commonly prepared in this way, and the saving of time in their use is a very important commercial consideration. Hydrated magnesian limes are found by the Ohio Survey* to have specific gravities of 2.12 to 2.25. High-calcium limes run about 2.45. A series of tests with an Iowa white lime gives specific gravities from 2.2 to 2.32 for the slaked lime, while the quick lime is 2.08.

SETTING AND HARDENING.

In slaking, the lime takes water into chemical combination, and becomes the gelatinous hydroxide. When this hydroxide is put in place as a mortar, it is said to set. This preliminary set is due to the loss of the water used in mixing, which brings about a certain rigidity in the same way, so far as is known, that clay becomes hard on drying. Part of the moisture evaporates from exposed surfaces, but the larger proportion is in most instances absorbed by the porous brick or other masonry material with which it is used. The more rapid the set, that is, the more rapidly the mortar loses its water, the safer the construction, providing the proportions of sand and lime are such that shrinkage may be left out of account.

A second process begins at once when the lime is exposed to the air. This is the absorption by chemical combination of carbon dioxide by which the lime returns to the carbonate condition, as it existed in the original limestone. The process is a slow one and may require years for completion, but this depends largely on the surface that is exposed, the thickness of the layer and porosity of the mortar. A large number of chemical tests on small briquettes having a minimum cross section of one square inch, made with mixtures of sand as high as 6 to 1, and allowed to stand for a maximum period of one year, showed none

*S. V. Peppel, loc. cit.

in which carbonation was complete. This action is most rapid in the first few months until a crust of the carbonate forms on the exterior. The crust retards the process and at the same time protects the soluble hydrate within from being dissolved. The interior portions of large masses may, therefore, never reach this final condition in hardening.

Long contact of lime hydrate with finely divided silica is known to cause a reaction by which the silica combines with the lime forming a stable silicate of lime. The extent to which this reaction progresses depends on the physical and chemical qualities of the siliceous impurities in the lime or of the sand used with it. If these are very fine, chemical action is favored. Silicates, such as clay or feldspar, for example, are more susceptible to attack by the lime than is quartz sand. Hydraulic limes are apt, therefore, other things being equal, to give a more durable final product than the purer limes. In the same way, muddy or clayey sand used with lime, although less desirable at the start, will likely contribute to the durability of the mixture in time because of the development of these stable compounds by the caustic action of the lime. In the case of silicates, it is probable that other elements, especially alumina, also enter into combination.

Lime Mortar.

Sand.—Lime has a variety of uses in various industries but by far its most important application is and has been as a mortar in structural work, interior wall plastering, etc. For these purposes, slaked lime alone can not be used on account of the great shrinkage of the lime paste in setting and its lack of inherent strength when set. It is, at the same time, economical to add some foreign material which is cheaper than the lime itself. The filling material commonly employed is sand. Most sands are composed largely of quartz grains, although fragments of feldspar and of many other minerals are often found in varying amounts with quartz. There is often also more or less of earthy or clayey matter in sands.

In general, it may be said that the composition of the sand is not an important consideration. Any inert substance which does not shrink nor deteriorate may be used. Ground limestone, for example, or the pulverized sand from any durable rock will serve the purpose equally well.

The physical condition of the sand is, however, of considerable importance. The function of the lime is to serve as a binder to hold the particles of the aggregate together. If these particles are angular and rough, they afford good surfaces for the attachment of the lime. Sharp sand will therefore make a stronger mortar than one composed of rounded grains. Only sufficient lime is required to fill the voids and to form a thin film around each grain of the aggregate. The more nearly the voids are filled with the sand grains themselves, in other words, the smaller the percentage of pore space in the sand, the less the amount of lime needed. A sand composed of a properly proportioned range of sizes of grain will therefore not only give the strongest product but will do so with the least amount of lime. Few sands as they occur naturally are composed of the proper range of sizes to give the smallest pore space. It is sometimes not difficult, and often may be a matter of economy, to correct a poorly proportioned sand by screening or by the addition of suitably graded materials. The voids in a sand are determined readily with simple apparatus.* Separation into a series of sizes is quickly done by sieves of a number of different meshes. These two tests afford data as to how far a given sand departs from the ideal mixture of grains and indicate the size of grain and quantity to be added for correction.

The sand grains should be practically in contact throughout the mass so that the lime paste forms merely a plastic film filling the interstices. Such a mortar when it has attained its final hardness may properly be regarded as sandstone in which the cementing matter is lime carbonate. It differs from the natural stone only in its position and origin, being as strong, if properly made, and as durable as that quarried from natural ledges.

White limes shrink much more in drying than do dolomitic limes. For this reason is it more highly important that the proper proportion of sand be used with the former. The bonding or adhesive power of white limes is also less. This is evidenced in walls where the mortar separates readily from the

*Standard sand for Cement work, M. J. Reinhart, Proc. 3d Ann. Convention Iowa Association Cement Users, Ia. Eng., Vol. VII, No. 1, p. 34.

brick and can itself often be crumbled in the fingers. Such defects are believed to be due more to poor mixing and wrong proportions of sand and lime than to any inherent quality of the lime itself. On the other hand, dolomitic limes possess great adhesive strength and not only form a denser mortar by binding the sand particles firmly together, but contribute towards the stability of the wall by adhering to the brick or stone.

TESTS OF LIME MORTARS.

Although lime has been used as a mortar since very early times and is of late being employed in various other ways in structural engineering work, few records of tests of those physical properties which make it of value are to be found. The purpose of the following series of tests is to investigate several of the physical properties of lime mortars, covering the following points:

(a) The influence of slaking with increasing amounts of water;

(b) The increase in strength with increased setting periods, and, since in practice, limes are seldom used in a neat condition;

(c) The effect of varying proportions of sand on the strength of the mortar, and the rapidity of setting. There has also of late been considerable discussion as to the relative merits of the white or high-calcium limes, and the brown or magnesian limes.

To obtain definite data on these several points, the following plan was adopted in the beginning. Barrel samples of commercial limes were obtained from the principal producers in Iowa, and a few from bordering states. Samples of white lime were tested from Springfield, Mo., and Mason City, Iowa; of dolomitic lime from Viola, Iowa; Mason City, Iowa; Maquoketa, Iowa; and Eagle Point, Iowa.

While it was evident that the factors enumerated above were the important ones to be studied, with each lime it was necessary to carry on considerable preliminary experimenting in order to be able to lay out an exact systematic method of procedure. A provisional line of experiments was therefore initiated, using the white lime from Mason City. The quick-lime was slaked with percentages of water ranging from the amount which would produce a dry powder as a minimum, to a maximum of 300 per cent by weight. Slakings were then made with 100, 150, 200, 250, and 300 per cent of water, calculated on the basis of dry quick-lime as 100 per cent. From each slaking, series of briquettes were made with the following sand dilutions,* by weight:

One part sand to 1 of lime, $1\frac{1}{2}$ of sand to 1 of lime, 2 of sand to 1 of lime, and so on to 5 parts of sand to 1 of lime. Four sets of briquettes were made from each sand mixture to be broken at the end of four, eight, twelve, and sixteen weeks respectively. Ten briquettes were used in each set from which to obtain an average.

Briefly, then, from the lime paste obtained by slaking in each of *six* different percentages of water, briquettes were made with *nine* different dilutions of sand. Since four periods of set were to be allowed, with ten briquettes to be broken at the expiration of each period, a little arithmetical calculation will show that for each lime tested, according to this plan, 2160 briquettes would be made. As the work progressed, it was soon discovered, however, that this general scheme required more or less modification according to the peculiarities of each particular lime.

HIGH-CALCIUM WHITE LIMES.

Lime from Mason City, Iowa.

The limestone from which the Mason City lime is produced comes from the Devonian beds, and has the following analysis:

Water	0.51
Insoluble	.63
Alumina and iron oxide	.71
Lime (CaO)	54.59
Carbon dioxide	42.89
Magnesia (MgO)	.47
Carbon dioxide	.52
	100.32

Analysis of the commercial product:

	Quick-lime.	After slaking.
Insoluble	1.02	0.60
Alumina and iron oxide	2.98	2.80
Lime (CaO)	95.40	71.10
Magnesia (MgO)	.43	.40
Loss on ignition	0.00	25.60
	99.83	100.50

A sufficient quantity of quick-lime was slaked at one time to make the full number (360) of briquettes as planned for each

*A standard river sand was used throughout the tests, whose grains passed a 20-mesh (linear) sieve and remained on a 30-mesh sieve.

percentage of water. Precaution was taken in slaking to add the water in such quantities and to agitate the mass so as to facilitate the process and to obtain the greatest increase in volume with the amount of water employed. The lime paste was allowed to stand for twenty-four hours until all signs of heat had disappeared and then put into air-tight jars to be used as needed. All weights were calculated on a dry basis, the moisture being determined before each batch of both sand and lime was weighed out. In the case of the higher percentages of water, it was necessary to drive off by careful heating, care being taken to keep the temperature below boiling, some of the excess water, in order to reduce the paste to a workable consistency. One man did the work, using his judgment to obtain as nearly as possible the same consistency in every batch. Forty briquettes were made from each mixing. The briquettes remained in the molds until they could be safely removed, after which they were placed on edge on open shelves and allowed to harden for their respective periods.

The tensile strength test was adopted as a means of obtaining comparable results more because of its convenience and the uniform treatment to which each lime would be subjected, than as representing conditions which lime mortars would meet in actual use. As noted earlier, the principal function of a mortar is to serve as a matrix or adhesive to bind together particles of aggregates and sections of masonry structure. Adhesion, therefore, and crushing strength tests would give more direct results. Such tests have not as yet been made.

Records of tensile strength tests of lime mortars are to be found in the Report of the Secretary of War for 1896, Document No. 2, Volume II, part 5, on page 2839. These tests were made with paste slaked with 300 per cent of water, ratios of sand from 3.1 to 17.7 : 1, and setting periods of twenty-eight and twenty-nine days and three months. Average strengths range in the short time tests from sixty-four pounds with a ratio of 8.8 : 1 to twenty pounds per square inch with a sand-lime ratio of 17.7 : 1 and, in the three months tests from seventy-one pounds with a ratio of 8.8 : 1 to thirty-six pounds with a ratio of 17.7 : 1. Tensile strength has also been investigated by the Ohio Geological Survey.* The following table will indicate the results obtained:

*S. V. Peppel, Bulletin 4, p. 337.

Physical Tests of Ohio Limes.

Kind of Lime	Tensile strength of mortar after 7 days. Mortar made by adding 4 volumes of sand to 1 volume of quick-lime	Remarks
High-calcium or white lime	48.95	Water 20% less than theory for complete hydration.
	70.6	Theoretical amount of water.
	59.	100% excess. Product, moist powder.
	42.36	Broke badly. Defective briquette. 100% excess. Heat applied in slaking.
	48.95	200% excess. Moist, lumpy mass.
	65.90	Briquette cracked before going into machine. 300% excess. Smooth stiff putty.
Dolomitic or brown lime.....	24.48	Bad briquette. 20% less water than theory for complete hydration.
	77.2	Theoretical amount of water.
	58.	Bad briquette. 20% excess.
	81.90	40% excess.
	82.84	Sticky, lumpy, mass. 100% excess.
	68.	Bad briquette. Stiff putty. 200% excess.

The period of set allowed in these tests is entirely too short for valuable results. But one briquette seems to have been made for each percentage of water. It is evident that a much larger number should be used to obtain an average figure.

A similar line of experiments made by Mr. George S. Mills, of Toledo, Ohio,* affords results which bring out quite clearly the relative strength of the white and brown limes and the relation of strength to progress in setting and hardening of the mortar. The mortar was made with two parts sand to one of slaked lime by weight. The strength is expressed in pounds per square inch. From four to six breaking strengths were used for each period to obtain the average results given in the table:

	1 month	2 months	3 months	4 months	6 months	1 year
Dolomite lime..........	....	28.8	37.2	51.	83.	92.8
High-calcium lime......	30.7	36.6	39.2	39.	50.8	44.6

* Municipal engineering, Vol. 28, p. 6.

The Mason City lime is a hot lime, which slakes vigorously and requires constant attention when water is given to it. The quantity of water which would just leave the hydrate practically a dry white powder when it had cooled to the atmospheric temperature was found to be about 75 per cent of the weight of the dry hydrate.

The table below gives in detail the breaking strength of the briquettes made with Mason City lime. A Fairbanks Standard Testing Machine was used.

TABLE I.

Time of set in weeks	Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch		
		Average	Maximum	Minimum		Average	Maximum	Minimum		Average	Maximum	Minimum
SLAKED IN 75 PER CENT OF WATER.												
4	1 :1	48.4	51.4	38.5	1½:1	45.7	50.5	39.5	2 :1	54.5	64.4	46.1
8	....	50.6	56.3	47.5	....	40.7	44.5	35.0	....	54.3	63.3	48.0
12	....	56.1	60.4	45.0	....	47.1	50.0	44.3	....	48.5	52.5	46.0
16	....	53.9	50.0	42.0	....	46.2	49.4	40.8	....	52.0	55.9	41.2
4	2½:1	55.1	60.4	50.4	3 :1	50.6	56.2	41.9	3½:1	48.7	55.0	30.0
8	....	54.6	58.6	51.0	....	52.6	58.4	44.5	....	52.1	56.0	46.5
12	....	46.7	48.5	43.5	....	48.1	51.0	45.9	....	48.0	54.3	42.7
16	....	52.3	56.9	49.5	....	43.4	48.6	33.6	....	32.9	53.0	21.5
4	4 :1	47.2	51.4	43.5	4½:1	43.7	53.0	35.0	5 :1	43.6	58.4	38.0
8	....	47.8	57.0	37 0	....	41.8	52.5	37.0	....	45.9	50.0	34.3
12	....	43.6	49.5	33.7	....	42.6	46.6	38.4	....	42.5	51.4	28.6
16	....	41.5	49.0	28.8	....	44.6	50.0	33.0	....	53.1	55.7	50.0
4	5½:1	37.1	44.1	28.8	6 :1	36.0	39.6	34.6	....	....	....	....
8	....	37.8	45.0	32.6	....	35.9	39.0	31.0	....	....	....	....
12	....	38.5	44.1	33.3	....	33.1	39.4	29.8	....	....	....	....
16	....	38.6	40.8	34.9	....	35.4	41.6	30.0	....	....	....	....
SLAKED IN 100 PER CENT OF WATER.												
4	1 :1	47.3	56.2	39.7	1½:1	57.1	61.9	53.0	2 :1	55.9	73.6	45.4
8	....	56.4	64.8	48.9	....	60.5	68.7	48.5	....	72.3	94.7	55.1
12	....	64.9	76.7	52.5	....	64.4	85.8	45.4	....	76.2	89.8	54.1
16	....	62.9	73.3	53.6	....	73.2	91.6	55.6	....	67.9	83.6	53.1
4	2½.1	54:9	62.5	43.8	3 :1	49.9	65.6	40.9	3½:1	51.0	61.3	44.5
8	....	64.6	80.4	53.5	....	57.0	67.6	51.5	....	54.0	62.8	49.4
12	....	55.0	67.7	41.0	....	54.6	63.6	45.0	....	55.5	68.7	50.0
16	....	57.6	74.4	36.7	....	53.1	58.1	40.6	....	56.8	65.7	51.5
4	4 :1	52.8	59.7	41.2	4½:1	47.6	55.4	38.8	5 :1	64.1	75.4	52.5
8	....	53.8	57.0	50.0	....	49.6	53.0	44.5	....	68.1	74.5	65.0
12	....	52.2	58.7	45.4	....	54.4	58.0	48.5	....	63.7	69.3	57.0
16	....	49.6	58.6	43.0	....	48.7	52.0	43.0	....	65.8	72.5	59.0
4	5½:1	56.4	64.7	52.0	6 :1	53.7	59.2	49.5	....	....	....	....
8	....	56.7	62.0	51.5	....	52.5	54.5	50.5	....	....	....	....
12	....	60.4	73.0	53.4	....	54.7	60.0	49.0	....	....	....	....
16	....	50.4	59.4	41.0	....	47.8	55.0	31.3	....	....	....	....

TABLE I—CONTINUED.

Time of set in weeks	Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch		
		Average	Maximum	Minimum		Average	Maximum	Minimum		Average	Maximum	Minimum
SLAKED IN 150 PER CENT OF WATER.												
4	1 :1	41.0	48.3	33.8	1½:1	47.1	49.9	36.1	2 :1	45.0	53.2	38.0
8	....	40.9	48.9	37.0	....	47.6	64.6	36.1	....	46.9	56.7	40.4
12	....	45.8	55.3	34.0	....	50.8	59.8	40.4	....	52.1	68.3	39.0
16	....	47.6	55.7	39.2	....	57.5	74.5	40.8	....	62.0	81.6	51.5
4	2½:1	55:4	68.7	38.8	3 .1	60:7	68.7	45.7	3½:1	71.9	81.0	61.8
8	....	59.8	78.1	44.4	....	54.0	64.5	47.5	....	60.7	71.4	41.4
12	....	56.6	76.3	42.8	....	63.7	72.1	51.0	....	76.2	84.1	69.7
16	....	55.4	79.9	51.0	....	77.3	83.0	66.3	....	76.3	83.4	64.3
4	4 :1	60.5	67.7	53.5	4½:1	51.7	59.4	44.9	5 :1	46.0	51.5	40.4
8	....	63.9	74.5	59.4	....	58.9	62.6	53.1	....	47.5	51.0	45.0
12	....	69.9	76.8	60.6	....	61.1	64.3	49.2	....	49.6	48.2	42.0
16	....	59.5	70.7	49.5	....	60.5	68.4	53.1	....	60.2	75.5	42.3
SLAKED IN 200 PER CENT OF WATER.												
4	1 :1	45.0	60.6	37.2	1½:1	44.4	58.3	35.7	2 :1	45.2	54.6	38.5
8	....	45.5	62.8	44.3	....	51.0	65.6	43.9	....	57.3	69.7	45.9
12	....	45.2	61.8	42.6	....	40.0	57.1	34.7	....	50.6	61.2	40.0
16	....	47.4	53.1	41.2	....	48.5	67.0	36.4	....	53.4	62.8	46.5
4	2½:1	41.7	55.2	33.4	3 :1	46.9	57.1	37.0	3½:1	46.2	53.1	38.0
8	....	51.2	69.8	38.8	....	55.0	72.4	43.9	....	56.0	67.0	46.5
12	....	50.9	61.8	37.4	....	49.6	65.9	42.3	....	55.2	59.2	52.0
16	....	60.6	68.0	53.1	....	54.0	58.2	48.4	....	57.8	60.8	52.1
4	4 :1	40.6	44.9	38.0	4½:1	41.0	44.1	38.6	5 :1	43.8	46.0	39.8
8	....	47.7	57.3	38.8	....	53.2	63.1	38.8	....	46.3	50.5	42.6
12	....	52.9	60.0	47.5	....	52.2	57.4	45.5	....	53.5	59.6	38.0
16	....	53.0	57.0	45.5	....	54.9	57.1	53.0	....	52.7	54.5	47.0
SLAKED IN 250 PER CENT OF WATER.												
4	1 :1	35.4	37.6	33.2	1½:1	38.9	40:9	33:0	2 :1	37.9	41.0	33.0
8	....	43.2	49.0	36.0	....	45.4	53.2	35.4	....	48.6	56.1	44.1
12	....	38.0	43.9	35.0	....	41.2	46.4	36.8	....	47.4	55.5	42.8
16	....	40.0	45.2	36.0	....	43.9	50.0	36.5	....	51.8	58.9	42.0
4	2½:1	42.7	62.5	38.8	3 :1	52.6	61.0	42.9	3½:1	52.7	60.0	43.4
8	....	50.1	60.2	36.5	....	54.8	63.6	41.0	....	48.5	55.1	40.4
12	....	51.9	63.9	40.4	....	56.8	70.6	45.2	....	56.3	63.3	46.0
16	....	58.9	70.8	46.4	....	58.7	69.0	50.0	....	58.0	62.0	57.0
4	4 :1	43:2	64.0	35.0	4½.1	47.5	58.3	37.4	5 :1	50.2	55.4	30.5
8	....	43.4	48.0	35.0	....	50.9	58.0	35.9	....	56.6	62.2	42.4
12	....	53.0	56.6	49.0	....	54.5	60.0	45.5	....	56.9	61.6	53.0
16	....	51.2	54.0	42.0	....	....	....	....	....	....	....	....

TABLE I—CONTINUED.

Time of set in weeks	Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch			Ratio sand to lime	Lbs. Per Square Inch		
		Average	Maximum	Minimum		Average	Maximum	Minimum		Average	Maximum	Minimum
SLAKED IN 300 PER CENT OF WATER.												
4	1 :1	38.1	47.4	25.5	1½:1	35:6	48:4	26.0	2 :1	36.0	48.4	28.6
8	....	35.8	54.2	27.3	....	35.2	53.6	28.8	....	35.9	43.9	28.6
12	....	43.0	58.3	28.2	....	38.5	54.6	27.8	....	40.7	53.5	34.0
16	....	41.7	57.8	26.6	....	40.8	51.0	34.3	....	41.2	52.1	32.0
4	2½:1	41.8	50.0	35.3	3 :1	40.0	50.5	32.6	3½:1	42.4	50.0	33.3
8	....	46.2	51.0	40.8	....	40.2	53.0	30.6	....	52.1	58.1	45.2
12	....	51.1	60.2	39.6	....	46.1	51.0	36.0	....	52.5	55.0	45.9
16	....	56.8	63.8	50.0	....	47.8	54.0	40.0	....	46.7	58.0	35.0
4	4 :1	38.2	46.5	31.3	4½:1	39.7	43.5	32.8	5 :1	40.7	47.5	35.0
8	....	39.2	51.5	31 9	....	45.8	55.5	38.2	....	48.3	54.9	42.7
12	....	37.6	43.5	28.8	....	43.6	48.5	35.9	....	46.3	52.0	43.0
16	....	43.0	50.5	40.0	....	41.4	49.0	30.7	....	46.1	53.0	30.0
4	5½:1	37.8	44.5	34.0	6 :1	41.7	46.0	36.6	....	....	....	....
8	....	46.7	52.9	38.6	....	46.5	51.3	41.5	....	....	....	....
12	....	46.5	52.4	38.5	....	47.7	54.3	43.1	....	....	....	....
16	....	46.5	58.0	43.2	....	49.8	55.0	44.3	....	....	....	....

From these figures, three sets of curves can be constructed which will bring out in a graphic way the general trend of the results. One set, with sand-lime ratio and average tensile strength as co-ordinates; a second set using the setting periods and tensile strength; and a third, based on the percentage of water used in slaking and the tensile strengths.

Inspection of the table and of the accompanying curves will show that, in general, the strength increases with increase of sand up to 2: 1, 2.5: 1, and possibly 3: 1 in some cases, and that beyond these ratios it decreases. Considered with reference to the effect of different periods of set on the strength, little more is to be observed than an increase in all instances during the first two months. With the longer periods the change is not sufficiently pronounced to afford a characteristic curve.

It is evident that the lengths of time allowed for the lime to set were too short for the maximum strength to be attained. This conclusion is supported by chemical determinations of the carbon dioxide absorbed which show that carbonation is in no instance even approaching completion at the expiration of sixteen weeks. Sufficient time should be allowed for the longest period for all the lime to return to the carbonate condition. Then the

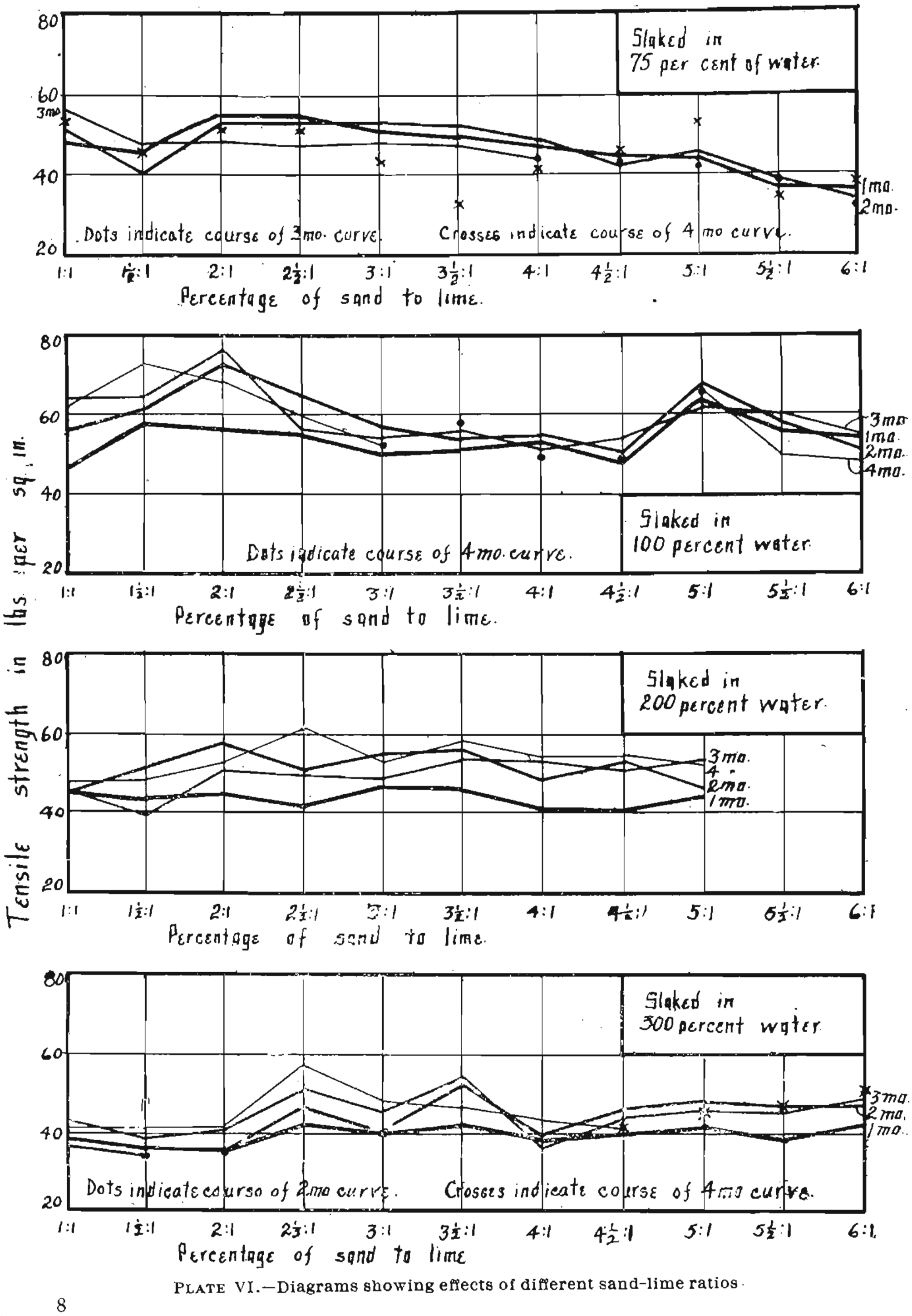

PLATE VI.—Diagrams showing effects of different sand-lime ratios.

curves constructed according to the first two methods mentioned above would indicate clearly the progress of the gain in strength according to percentage of sand and setting period.

Plate number VII shows the relation between the percentage of water used in slaking and the tensile strength of the briquettes. They are arranged in groups of four curves, each according to the whole-numbered sand-lime ratios. The general aspect of the five groups taken in conjunction with the tables, indicates a rapid rise in strength at 100 to 150 per cent of water, and as rapid a fall at 200 which continues through the higher percentages. It is to be noted that 100 per cent of water gives the highest strength with the 1 : 1, 2 : 1 and 5 : 1 sand dilutions, while with the two middle members of the series, 3 : 1 and 4 : 1, the highest strength is reached with 150 per cent. This may be but a coincidence, with results for only one lime at hand. The percentage theoretically necessary to hydrate the calcium oxide in the lime is but about 30 per cent of the weight of the dry quick-lime. The increase in strength with successively longer periods of time can also be traced from these curves. It will be further noted that the rapidity of increase is greater the higher the percentage of sand used.

The experience gained and the results accruing from the foregoing tests of the Mason City white lime suggested certain changes in the general plan of the experiments. In all the tests whose results follow, the longest setting period is made one year, and sets of briquettes were broken at the end of three, six, nine and twelve months. The percentages of water used for slaking are the even hundreds up to 300 per cent as a maximum, with the exception of the white lime from Springfield, Missouri, in which case 400 per cent of water was used, since it slaked to a dry powder with 100 per cent. The lowest percentage is in all instances the largest possible amount that would leave the slaked product a dry powder. Only the whole-numbered sand-lime ratios are used in the later tests.

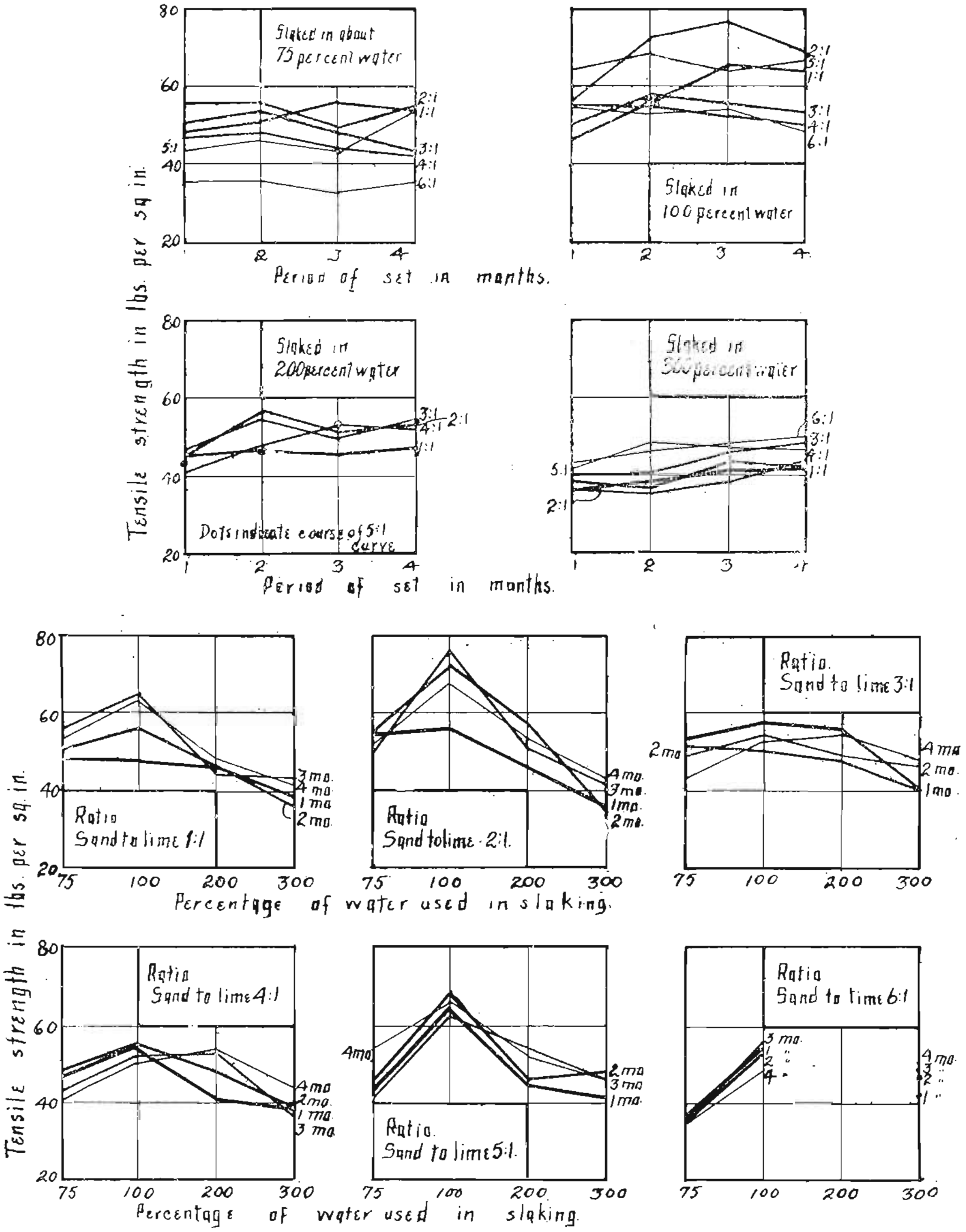

PLATE VII.—Diagrams showing effects of different setting periods and of different percentages of water.

WHITE LIME FROM SPRINGFIELD, MISSOURI.

The limestone from which the Springfield lime is made has the following chemical analysis:*

Lime carbonate ($CaCO_3$)	99.46
Iron oxide (Fe_2O_3)	.21
Silica (SiO_2)	.33
	100.00

Analysis of the commercial product:

	Quick-lime	After slaking
Insoluble	1.00	0.67
Iron and alumina ($Fe_2O_3+Al_2O_3$)	1.80	1.11
Lime (CaO)	94.70	73.20
Magnesia (MgO)	0.40	0.43
Loss by ignition	2.08	24.25
Carbon dioxide (CO_2)	Trace	......
	99.98	99.76

The Springfield lime is unusually pure and, as may be expected, slakes rapidly and with much heat. With 200 per cent of water, it was found difficult to prevent the lime from "burning". Up to 300 per cent of water, it was impossible to keep the paste thoroughly mixed on account of the generation of steam and the violence of the slaking action. 350 to 400 per cent works best and gives a uniform, well slaked product.

It is unfortunate in any investigation if the person beginning the work can not carry it to completion. Even though the training of the experimenters be identical, personal equation always enters, and sometimes to a sufficient extent in small matters of manipulation, and in the exercise of judgment, to produce unexplainable irregularities in results. In the present experiments it was necessary to place the work in new hands at times during their progress. Lack of uniformity in the data which follow can in some instances be accounted for only by such changes, and yet it is not possible to assign absolutely to this cause variations that appear. Notwithstanding all minor deviations from the rule, however, there are revealed certain general truths that are brought out in the results given.

In Table II are compiled the results of the tests of the Springfield lime and these are graphically shown in plates VIII, IX and X, which follow:

*20th Annual Rep. U. S. Geological Survey, Part VI (Continued), p. 415, also Bulletin 44, N. Y. State Museum, p. 924.

TABLE II.

SPRINGFIELD, MO., WHITE LIME.

Time of set in month	Tensile Strength in Pounds Per Square Inch																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
SLAKED IN 100 PER CENT OF WATER																		
3	96.20	112.0	67.0	93.95	107.7	81.7	68.24	77.6	49.5	56.71	60.0	50.0	61.40	65.0	58.8	48.21	55.0	40.00
6	113.70	121.0	102.0	88.23	105.5	72.1	75.40	96.1	61.5	75.60	82.1	69.2	63.06	68.9	53.4	46.56	50.5	41.60
9	109.40	130.0	97.0	97.03	120.0	79.9	72.74	86.7	61.3	65.70	87.5	45.2	60.70	74.0	50.0	42.81	48.1	38.40
12	114.18	137.0	95.0	95.58	104.0	86.1	70.45	82.5	61.2	62.75	75.5	53.9	51.07	67.6	46.1	40.36	48.5	34.65
SLAKED IN 200 PER CENT OF WATER																		
3	60.80	72.0	46.5	54.83	68.0	44.8	54.68	61.2	42.9	42.22	45.0	37.0	50.04	55.9	43.7	41.62	45.6	35.90
6	55.21	66.2	38.0	59.22	63.1	54.4	51.80	56.0	43.0	43.12	52.0	38.0	45.31	52.0	89.1	43.79	50.0	35.60
9	61.56	70.2	51.5	56.64	61.6	50.0	48.00	54.7	41.6	38.10	44.7	28.1	37.90	45.0	30.0	35.60	40.8	21.30
12	57.05	64.0	48.8	56.74	67.3	49.0	55.50	62.5	48.9	45.22	58.3	36.4	38.70	44.6	29.1	37.97	46.6	25.20
SLAKED IN 300 PER CENT OF WATER																		
3	40.60	50.1	33.2	44.71	54.2	35.1	53.27	59.1	42.9	48.35	54.6	41.0	46.00	51.5	40.0	47.92	56.7	48.10
6	45.68	50.4	33.2	49.37	59.4	38.5	51.13	58.5	42.4	46.94	57.0	40.0	43.65	51.0	38.5	45.79	51.0	37.10
9	44.90	52.6	35.8	45.25	58.5	38.0	50.69	54.9	45.1	48.53	55.1	44.7	38.94	45.0	29.2	50.50	54.8	47.10
12	42.55	53.2	22.7	50.25	57.8	35.7	62.58	73.6	49.4	49.03	57.7	43.2	39.37	46.9	25.5	45.01	48.5	40.20
SLAKED IN 400 PER CENT OF WATER																		
3	64.07	74.4	55.8	62.90	68.0	56.9	75.70	92.3	68.0	75.67	87.8	62.8	68.01	79.0	58.9	58.01	66.6	49.60
6	71.07	83.4	52.1	69.50	84.0	46.0	75.33	90.4	67.6	69.50	79.4	61.7	55.30	59.2	49.1	59.05	64.1	52.80
9	59.40	65.9	51.0	60.74	74.6	46.2	60.90	72.0	50.0	63.02	67.9	57.5	46.42	54.2	32.7	47.98	54.9	34 30
12	74.43	84.0	63.8	72.61	83.2	60.4	77.32	87.0	71.0	.....	....	....	49.74	53.9	42.3	54.67	61.2	45.60

The curves on plate VIII show that there is little change in strength after three months. In a few instances there is a slight gain, but in most cases the three, six and nine months' figures run close, followed, as a rule, by a falling off at the end of twelve months. Inspection will show that this falling off is most pronounced with the high ratios of sand, 4:1, 5:1, 6:1, where the decrease has frequently begun at the end of three months.

The diagrams according to percentage of water (Plate IX) are fairly uniform, all indicating a decrease in strength to 200 or 300 per cent followed by a rise with 400 per cent of water. This final rise seems erratic, and its meaning is not at present understood. It will be noted that the greater ranges between highest and lowest tensile strengths are found where the lower sand-lime ratios were employed.

Plate X brings out clearly the decrease in strength with increase in the amount of sand. This is most prominent in the lower percentages of water where a 1:1 mixture is the strongest. With the two higher percentages, 300 and 400, the average maximum strength is attained in the 3:1 and 4:1 mixtures. It is also conspicuous that the highest figures of all are reached with the lime when slaked with 100 per cent of water, which leaves it a dry powder.

MAGNESIAN AND DOLOMITIC LIMES.

EAGLE POINT, IOWA, BROWN LIME.

The limestone from which this lime is manufactured comes from the Galena beds of the Ordovician. Its analysis is as follows:

Insoluble	8.65
Iron and aluminum oxide (Fe_2O_3 and Al_2O_3)	3.15
{ Lime (CaO)	29.00
{ Carbon dioxide (CO_2)	22.60
{ Magnesia (MgO)	17.12
{ Carbon dioxide (CO_2)	18.85
Water	.09
	99.46

Commercial product:

Insoluble	2.01
Iron and aluminum oxide (Fe_2O_3 and Al_2O_3)	6.60
Lime (CaO)	58.19
Magnesia (MgO)	33.48
Loss on ignition	slight
	100.28

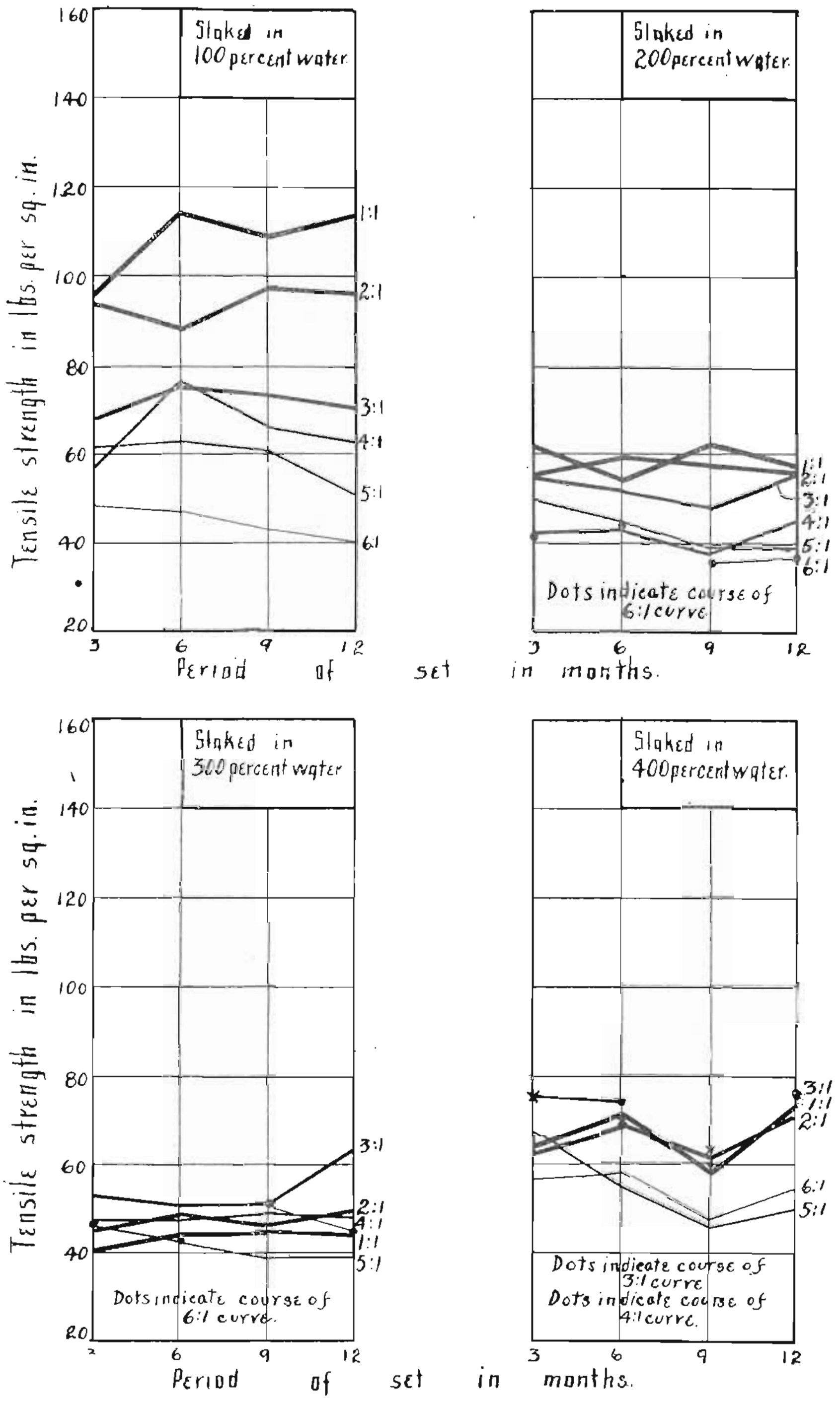

PLATE VIII.—Diagrams showing effects of different setting periods.

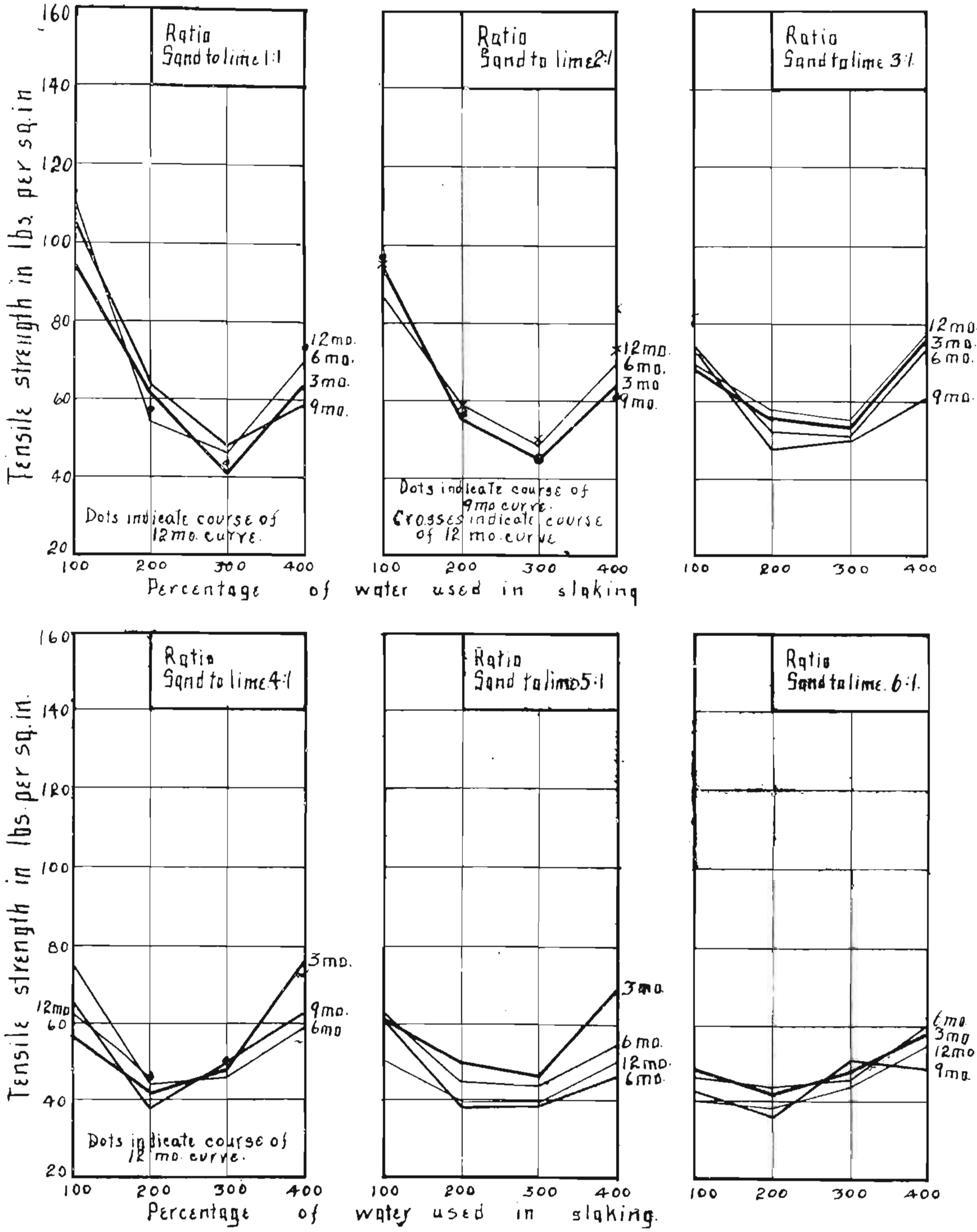

PLATE IX.—Diagrams showing effects of different percentages of water.

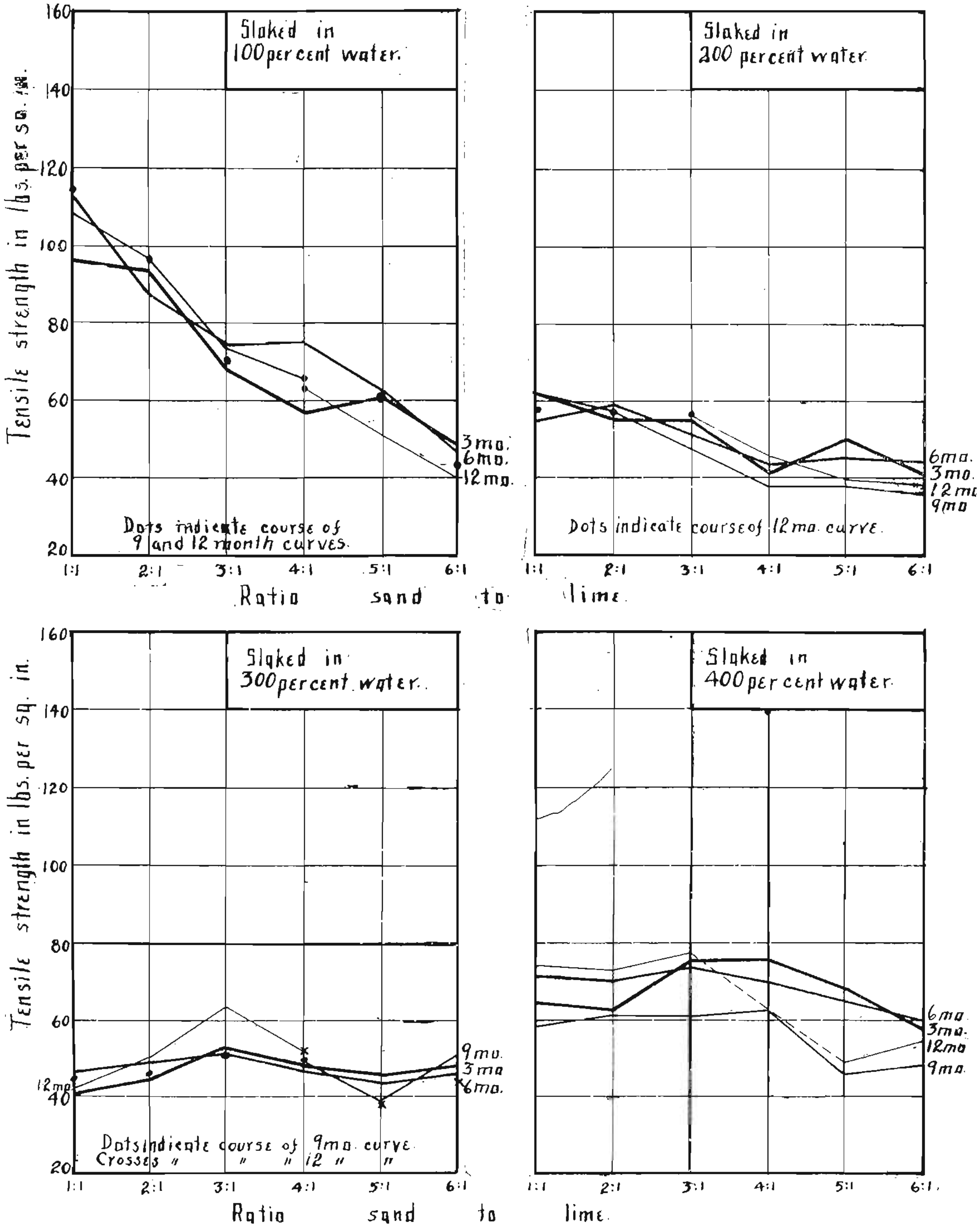

PLATE X.—Diagrams showing effects of different sand-lime ratios.

The Eagle Point lime slakes sluggishly and gives a paste of a brownish color. With all percentages of water employed there was little heating up, and no steam was generated. Slaking proceeded best with 200 per cent of water and more rapidly than with lower percentages. 100 per cent gave a stiff paste, 200 one of a readily and conveniently workable consistency, while the 300 per cent paste was thin, and required the removal of the excess of water before use.

Table III includes the results of the tests of this lime. On plates XI, XII and XIII are plotted the data of the table.

The curves on plate XI again bring out the decrease in strength with age. It will be observed that the maximum strengths are attained at six and nine months, and that this almost universally falls off for the one year period. This falling off is most pronounced in general in the case of the higher sand proportions.

The influence of the amount of water used in slaking is shown on plate XII. It is impossible to make any generalized statements from the diagrams. As a rule the highest strengths are found with the lower percentages of water. In the case of the 2:1, 5:1 and 6:1 sand-lime ratios, however, this is reversed and the 300 per cent gives the highest figures.

As with the white limes, the curves based on the sand-lime ratio are the most characteristic of the set. The lowest proportions of sand gave in all instances the highest results. The decrease in strength with increasing sand is decided and rapid. The greatest range is seen to be with the lower percentages of water, the maximum tensile strength being shown by the "powder" slaked lime.

MASON CITY, IOWA, BROWN LIME.

The Mason City stone is Middle Devonian and belongs to the Cedar Valley stage. Its chemical analysis follows:

Insoluble	1.34
Iron and aluminum oxide (Fe_2O_3 and Al_2O_3)	2.07
{ Lime (CaO)	33.54
{ Carbon dioxide (CO_2)	26.35
{ Magnesia (MgO)	16.99
{ Carbon dioxide (CO_2)	18.68
Moisture	1.03
	100.00

TABLE III.

EAGLE POINT BROWN LIME.

Time of set in months	Tensile Strength of Briquettes in Pounds per Square Inch.																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
"POWDER SLAKED" IN ABOUT 75 PER CENT OF WATER.																		
3	88.85	120.0	73.0	94.90	110.0	80.0	90.92	104.8	66.7	84.26	98.0	74.0	72.60	82.5	60.0	57.30	61.0	55.8
6	157.90	176.0	130.0	99.60	125.0	75.0	106.67	116.2	95.2	90.97	104.9	80.0	73.32	92.8	63.9	57.50	66.0	50.0
9	155.30	181.2	130.1	96.50	105.0	82.0	96.95	107.6	74.3	74.89	81.9	66.7	78.62	93.1	66.3	64.78	77.0	52.0
12	159.03	182.8	120.1	99.10	119.7	76.5	98.82	112.7	89.5	68.91	92.1	49.5	69.90	84.8	57.6	47.39	56.3	34.3
SLAKED IN 100 PER CENT OF WATER.																		
3	110.70	135.0	85.0	100.04	110.0	82.5	90.41	100.0	80.0	80.67	96.8	60.0	80.40	96.0	70.0	50.70	55.0	40.0
6	148.54	169.4	116.3	96.51	103.9	75.0	95.90	122.0	84.0	82.60	93.0	68.0	74.28	87.6	47.6	50.43	56.4	39.6
9	154.08	208.2	119.7	113.31	132.0	97.1	94.38	110.0	71.4	87.90	104.9	72.8	86.20	98.4	63.7	62.20	72.8	52.4
12	135.38	159.4	105.2	107.32	127.5	89.6	93.08	110.1	80.2	73.85	92.2	50.5	70.71	88.1	63.1	49.10	58.4	39.6
SLAKED IN 200 PER CENT OF WATER.																		
3	97.70	115.0	70.0	89.90	109.0	72.0	100.60	105.9	95.1	64.60	73.5	61.0	67.90	79.2	54.5	62.31	75.0	53.0
6	87.54	97.0	73.3	78.11	92.7	68.6	85.94	97.2	64.5	55.10	62.5	40.4	73.27	87.2	58.8	57.72	62.1	48.5
9	112.66	124.5	94.1	87.96	110.0	85.0	104.05	113.2	89.6	66.40	75.5	58.8	72.48	87.4	59.2	65.80	75.0	55.7
12	90.46	107.2	73.5	85.31	99.0	75.0	80.88	90.4	67.3	57.70	65.7	50.5	73.38	84.4	60.2	59.58	67.0	52.4
SLAKED IN 300 PER CENT OF WATER.																		
3	119.85	145.0	101.1	112.16	126.3	93.7	86.80	98.0	70.0	73.57	81.6	70.0	80.10	100.0	68.0	68.87	77.0	60.0
6	124.25	132.4	103.0	113.21	132.4	94.2	86.50	101.0	74.3	78.31	92.4	70.5	88.92	101.0	77.7	78.12	84.2	70.3
9	140.24	160.0	125.0	114.12	126.6	100.1	99.19	120.0	79.1	81.24	92.6	71.1	87.02	95.1	75.7	74.25	90.2	56.0
12	134.40	152 0	105.9	111.95	119.2	101.0	91.60	98.0	75.7	79.17	95.0	66.0	70.71	88.1	50.5	66.16	75.2	58.4

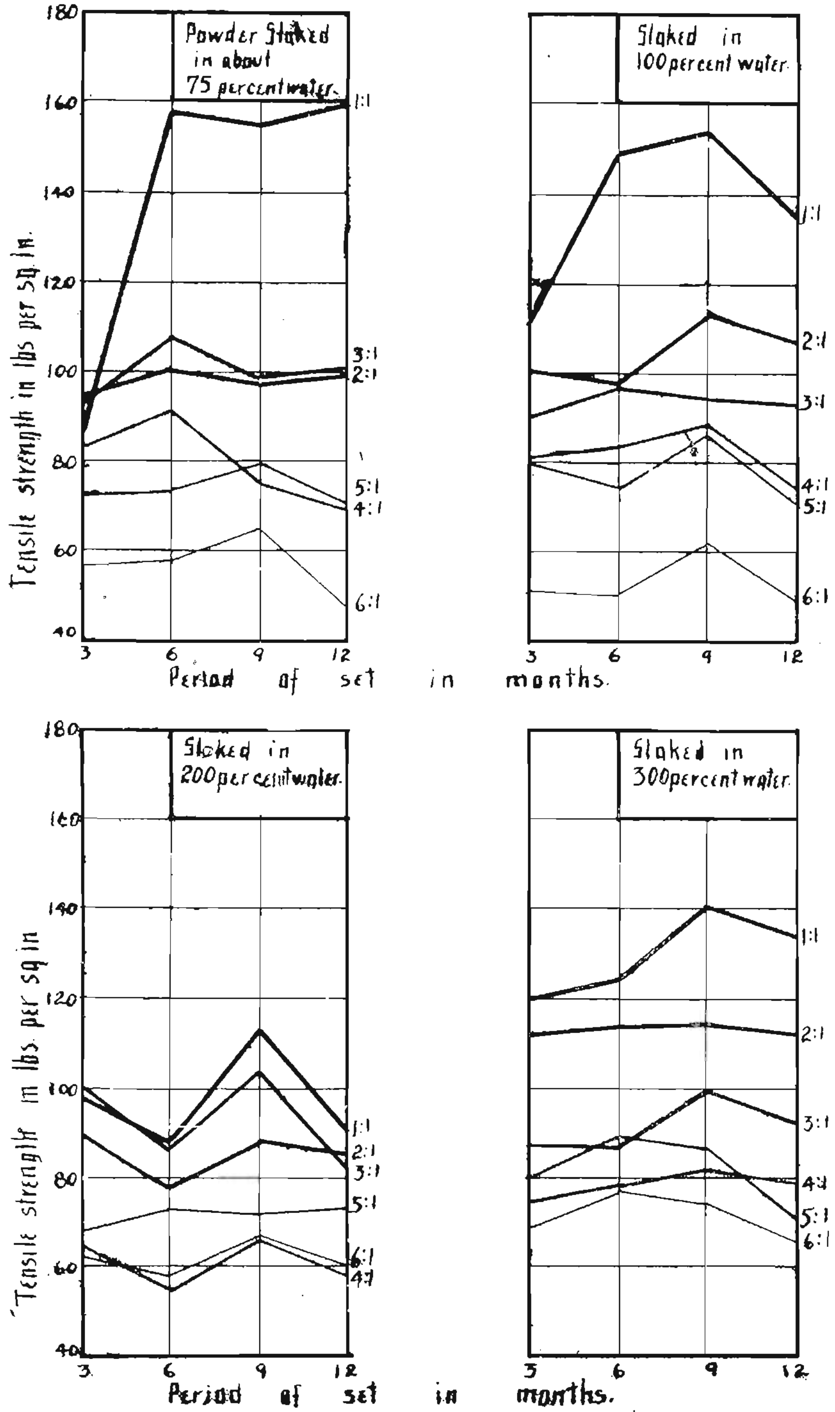

PLATE XI.—Diagrams showing effects of different setting periods.

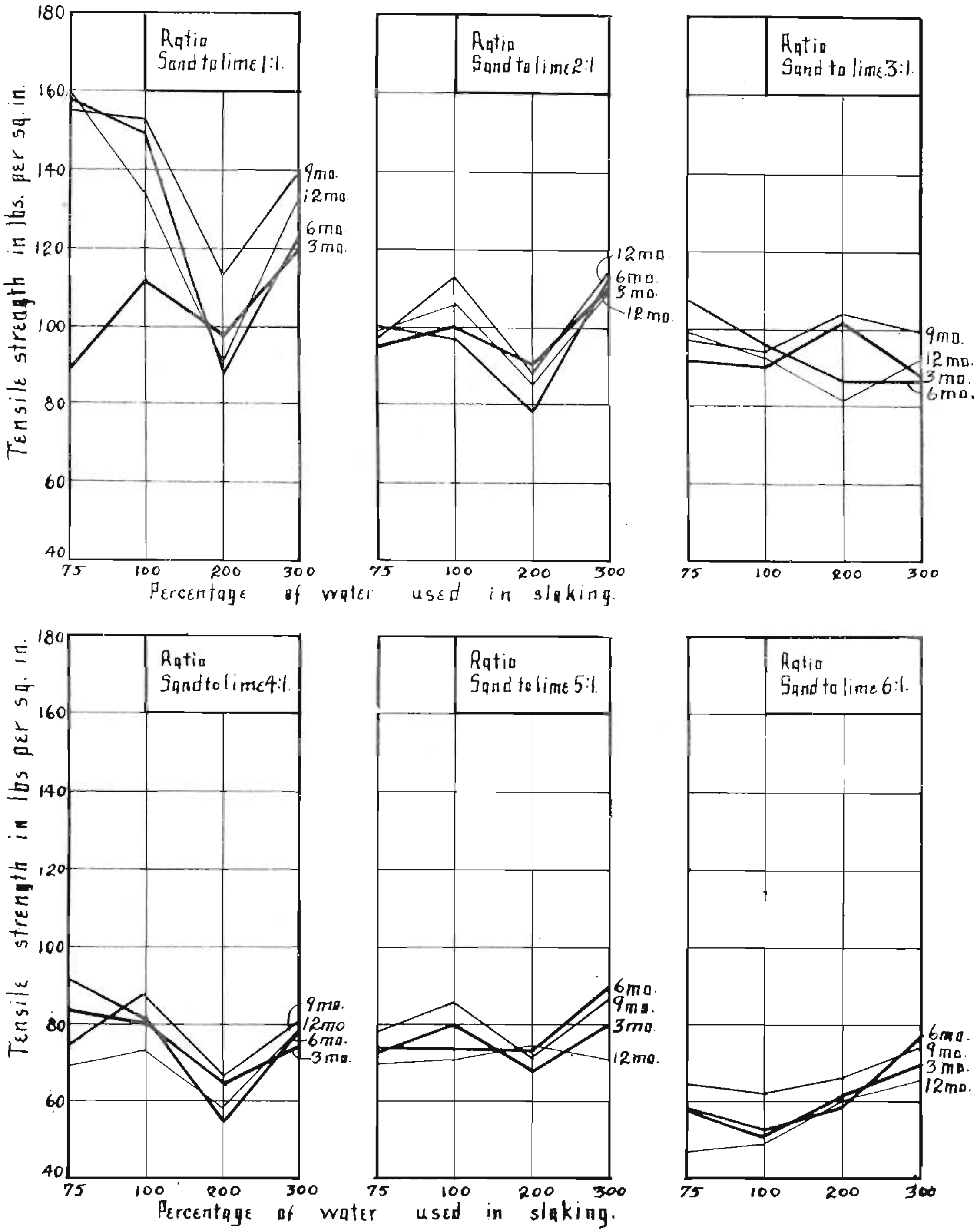

PLATE XII.—Diagrams showing effects of different percentages of water.

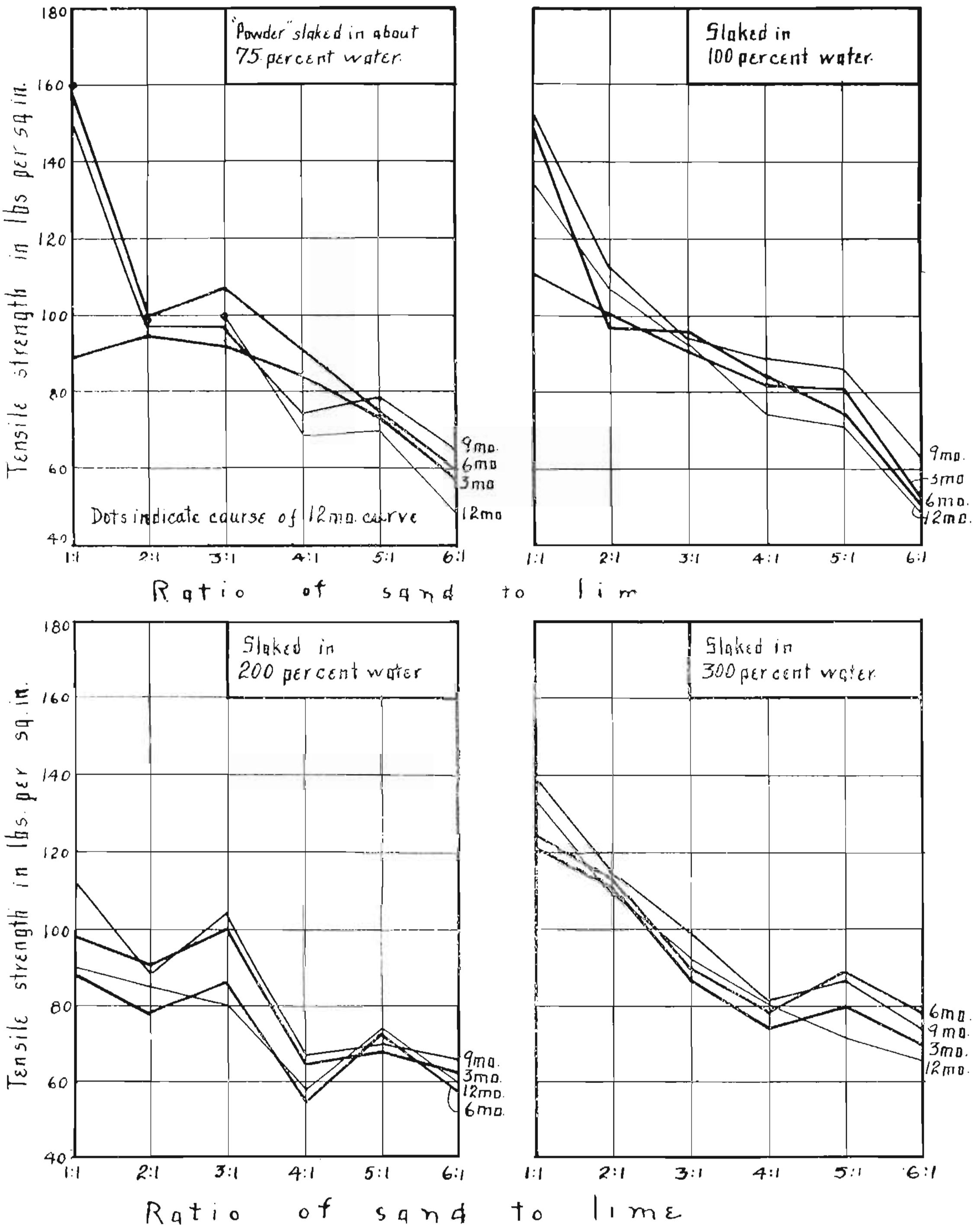

PLATE XIII.—Diagrams showing effects of different sand-lime ratios.

Analysis of the commercial product:

	Quick-lime	After slaking
Insoluble	2.32	.80
Iron and aluminum oxide (Fe_2O_3 and Al_2O_3)	6.03	9.80
Lime (CaO)	72.40	47.60
Magnesia (MgO)	15.23	19.20
Carbon dioxide (CO_2)	.10	3.50
Loss on ignition (CO_2)	3.36	18.70
	99.44	99.60

The Mason City lime slakes very slowly and considerable care was necessary to secure a uniform product free from lumps. By a proper adjustment of the amount of water supplied as it is needed, and its distribution throughout the mass by stirring, a homogeneous paste is, however, readily obtained.

In Table IV are arranged the data for this lime, which are also plotted on plates XIV, XV and XVI.

The curves on plate XIV show for the Mason City lime the same tendencies as do the corresponding curves on preceding pages. The diminution in strength with the longest time period, while not universal, is so common as to be unmistakable. This is more pronounced in cases where the higher proportions of sand are used.

Plate XV clearly shows the decrease in strength with increasing percentages of water. With few exceptions the maximum results come with the powder slaked lime from which the curves slope downward as the water percentages increase.

It will be noted also that the higher strengths correspond with the lower sand dilutions. With the powder slaked lime there is a decisive rise in all the curves at the 2:1 ratio and this is less prominently the rule with the other curves on the sheet. The length of the setting period appears to have no perceptible influence on this fact.

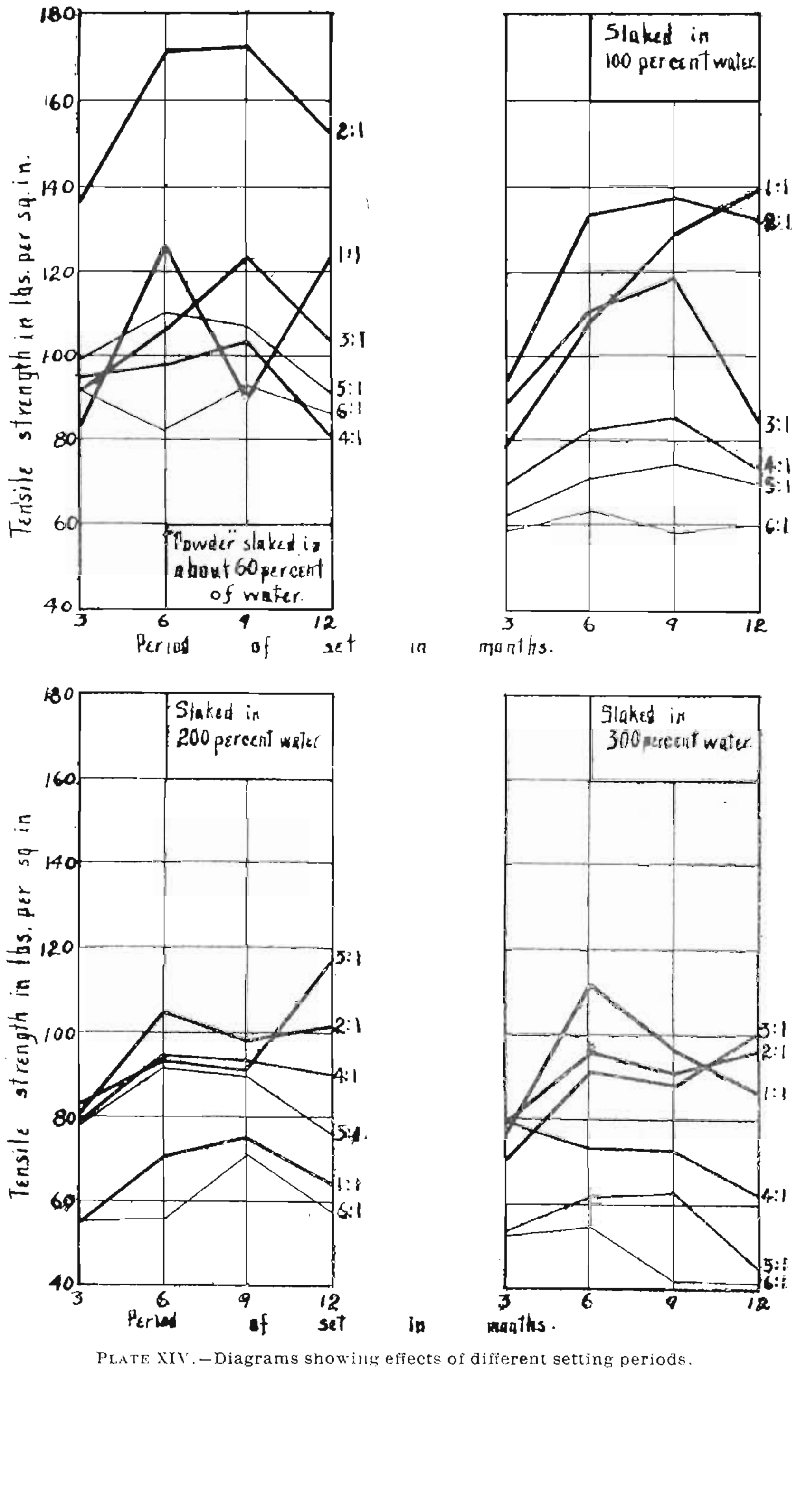

PLATE XIV.—Diagrams showing effects of different setting periods.

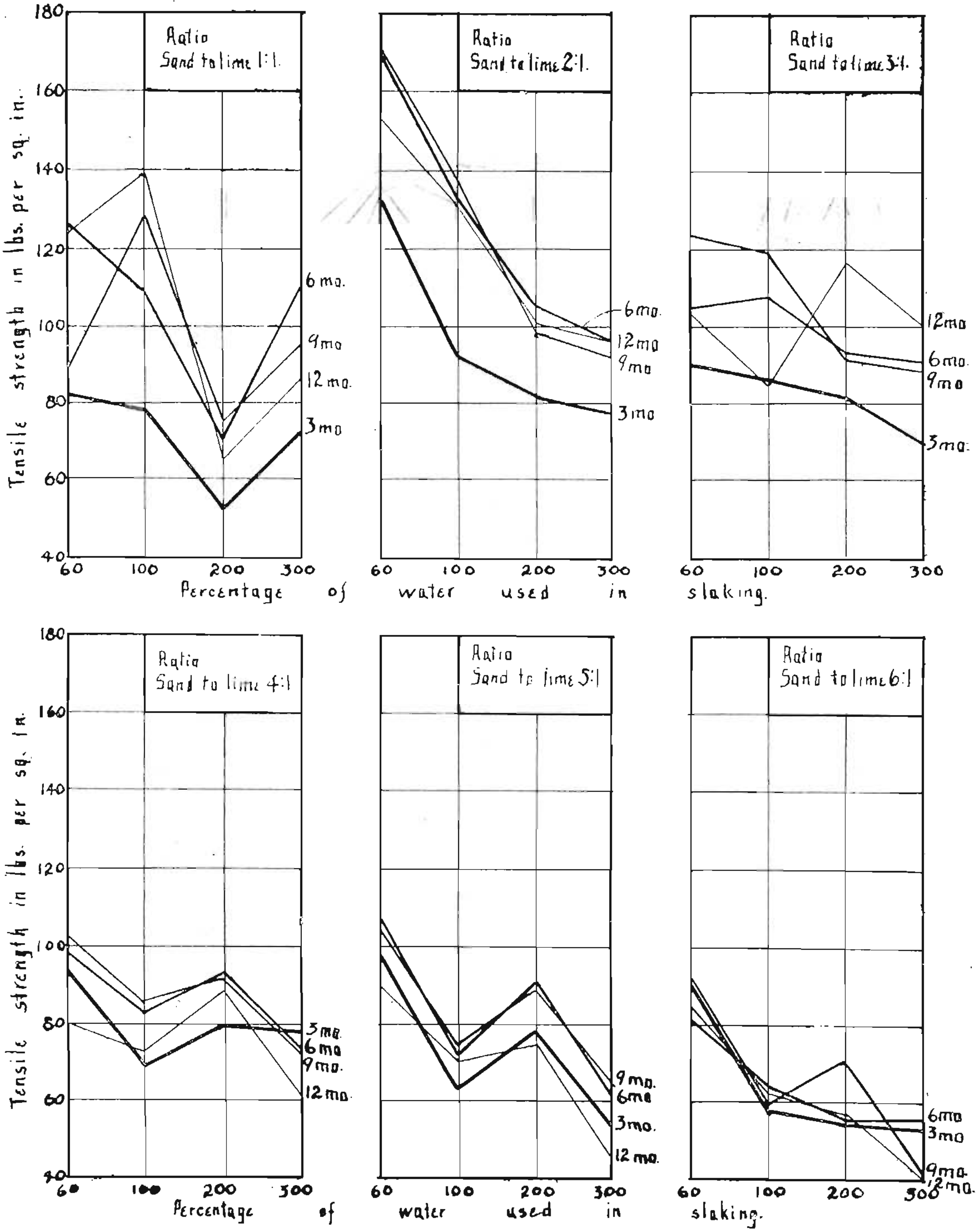

PLATE XV.—Diagrams showing effects of different percentages of water.

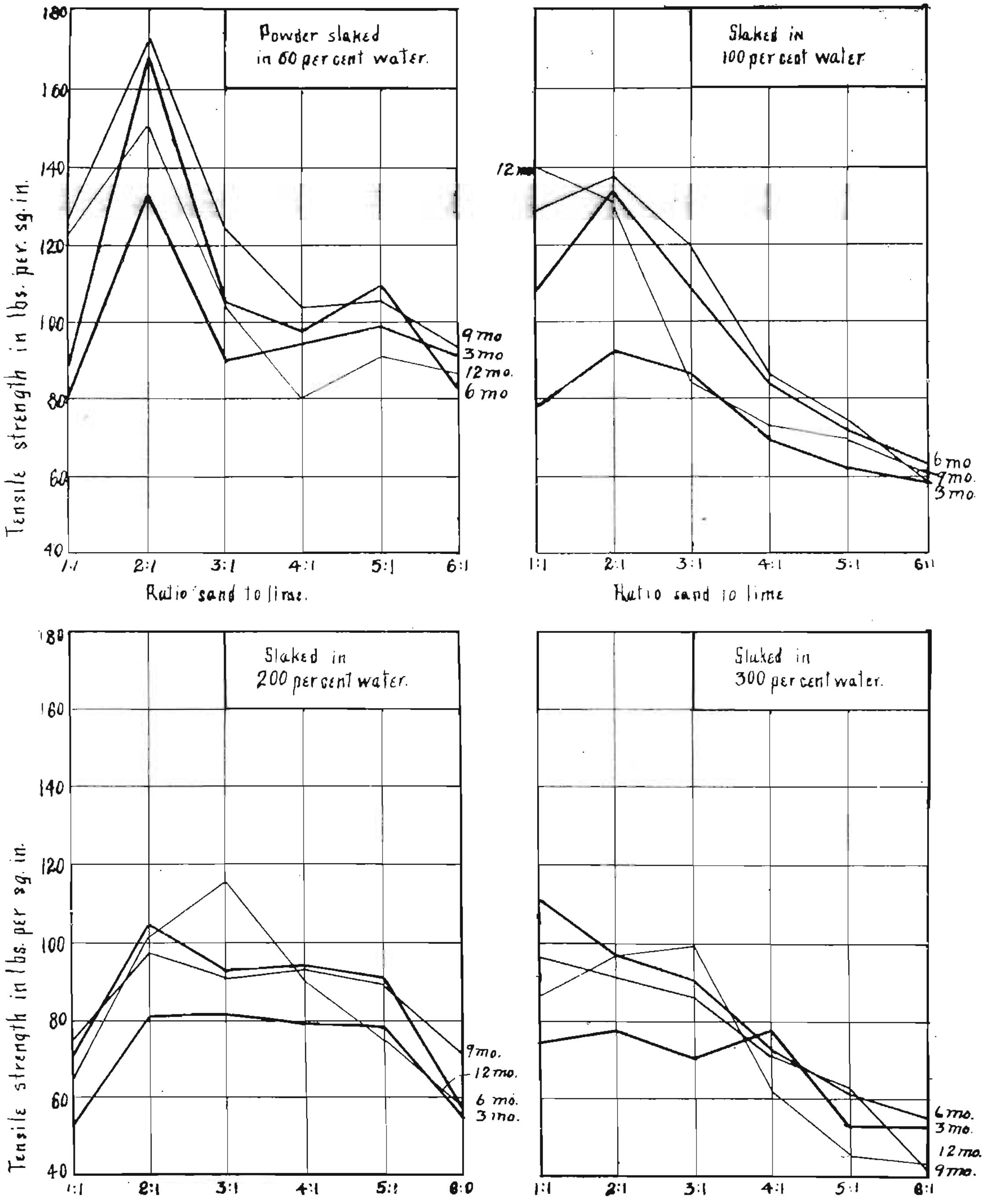

PLATE XVI.—Diagrams showing effects of different sand-lime ratios.

TABLE IV.
MASON CITY BROWN LIME.

Time of set in months	Tensile Strength in Pounds per Square Inch.																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
"POWDER SLAKED" IN ABOUT 60 PER CENT OF WATER.																		
3	82.24	97.1	60.0	134.35	182.5	110.6	90.22	96.1	77.4	94.15	108.9	86.5	98.9	109.8	86.5	90.49	110.6	75.7
6	125.57	165.0	80.0	170.92	184.0	156.0	104.56	117.0	90.0	97.5	109.0	82.0	110.37	122.0	98.0	82.3	90.0	71.0
9	89.4	128.0	50.0	172.45	186.3	150.0	123.48	144.2	100.0	103.16	122.5	91.2	106.61	122.0	90.3	91.72	101.9	79.9
12	123.98	146.5	98.0	151.58	168.0	136.2	102.73	129.3	83.8	79.65	88.0	65.0	90.9	107.0	42.0	86.45	104.0	76.2
SLAKED IN 100 PER CENT OF WATER.																		
3	77.83	95.6	50.0	91.91	107.1	79.2	85.84	98.0	77.7	68.62	83.3	58.0	61.86	68.0	53.0	57.55	69.3	31.3
6	108.14	161.1	79.5	133.23	150.0	93.7	107.87	134.7	80.6	83.45	103.0	57.7	71.44	84.0	58.0	63.31	83.0	53.5
9	129.26	158.1	102.0	137.47	156.9	112.0	118.7	144.5	95.1	85.39	98.0	68.6	73.64	96.9	54.1	57.93	67.0	51.5
12	138.72	166.3	112.2	131.9	150.0	107.0	84.29	108.8	64.7	72.5	93.0	60.0	70.45	80.2	61.4	60.41	77.4	49.5
SLAKED IN 200 PER CENT OF WATER.																		
3	53.64	81.0	30.0	80.6	102.3	64.3	81.4	96.1	74.3	78.98	91.1	66.0	78.49	90.3	59.4	55.4	65.0	48.0
6	69.63	95.3	49.8	104.72	121.8	94.1	93.3	112.0	75.0	94.0	120.0	75.0	92.2	103.0	81.0	56.39	73.7	40.0
9	74.7	88.5	63.5	97.78	127.5	84.7	90.98	113.8	73.2	93.35	117.1	71.5	90.8	102.0	75.0	71.4	85.0	59.0
12	64.49	78.1	46.8	100.91	121.0	70.8	116.64	131.0	99.0	89.82	99.0	77.8	75.91	92.8	60.6	57.79	68.0	49.5
SLAKED IN 300 PER CENT OF WATER.																		
3	74.66	93.0	58.8	77.01	87.0	64.0	70.44	78.4	59.6	77.69	88.2	64.4	53.23	58.8	44.1	52.99	60.0	40.0
6	110.65	129.6	85.7	95.64	110.0	75.0	91.3	104.0	72.0	73.3	80.0	63.0	60.56	77.0	50.0	55.46	65.7	45.0
9	96.01	104.9	93.0	90.66	100.0	74.5	88.11	111.7	68.6	71.65	81.3	63.7	62.3	74.5	52.0	40.59	48.1	29.4
12	85.75	103.0	64.6	95.99	116.0	75.0	100.19	119.6	87.2	61.8	76.0	51.0	45.2	54.0	40.0	40.52	48.5	29.7

MAQUOKETA WHITE LIME, A. A. HURST & CO., MAQUOKETA, IOWA, DOLOMITIC LIME.

EXCELSIOR WHITE LIME, O. W. JOINER & SON, MAQUOKETA, IOWA, DOLOMITIC LIME.

The Maquoketa limes are produced from the Hopkinton beds of the Niagara stage. The composition of these strata is shown by the accompanying chemical analysis of samples from each of the companies:

	O. W. Joiner & Son.	A. A. Hurst & Co.
Insoluble	.51	.58
Iron and aluminum oxides ($Fe_2O_3 + Al_2O_3$)	.47	.36
Lime (CaO)	30.56	30.88
Magnesia (MgO)	21.54	21.56
Loss on ignition (CO_2 and water)	47.16	47.13

Analysis of the unslaked commercial product (A. A. Hurst & Co.).

Insoluble	.63
Iron and aluminum oxides ($Fe_2O_3 + Al_2O_3$)	2.10
Lime (CaO)	60.60
Magnesia (MgO)	35.73
Loss on ignition	2.30

The two samples of limestone analyzed come from the same horizon and compare very closely in composition. The treatment of the rock in the process of burning is exactly similar in both plants and the two limes are alike in appearance. Wood alone is used in the calcining process.

The quick-limes slake slowly, as is characteristic of the dolomitic limes, and the heat generated is relatively small in amount. The Joiner lime required somewhat less water for the first slaking than the Hurst product and, in fact, less than any of the other limes tested. This quantity, as shown in the table, is 50 per cent of the weight of quick-lime used. The results of the tensile strength tests of the two Maquoketa limes are compiled in tables Nos. 5 and 6 and are graphically represented by plates XVII, XVIII, XIX and XX, XXI, XXII, which follow:

TABLE V.

EXCELSIOR WHITE LIME, MAQUOKETA, IOWA.—O. W. JOINER & SON.

Time of set in months	Tensile Strength in Pounds per Square Inch.																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
"POWDER SLAKED" IN ABOUT 50 PER CENT OF WATER.																		
3	109.68	136.0	85.0	121.82	140.0	111.6	95.65	115.0	78.4	98.9	115.7	81.0	98.61	111.6	78.4	73.63	80.9	68.0
6	118.12	134.3	100.0	137.18	174.8	103.9	117.33	130.4	107.8	108.92	137.2	85.3	103.10	115.5	91.2	75.21	84.5	67.0
9	169.61	198.0	139.3	158.72	194.1	132.3	119.76	132.0	100.0	112.34	120.6	104.9	109.71	119.4	101.9	84.26	94.2	72.8
12	171.53	193.4	151.0	158.36	173.5	141.6	108.56	124.3	98.2	105.4	116.0	92.0	90.94	108.8	58.8	72.14	84.3	63.7
SLAKED IN 100 PER CENT OF WATER.																		
3	110.59	127.5	91.8	99.5	105.0	93.3	83.5	97.0	78.0	83.59	95.1	65.0	51.71	64.1	38.8	61.4	77.0	50.0
6	130.7	154.6	113.4	118.91	136.3	100.0	91.01	100.0	83.6	96.05	117.1	78.4	64.1	79.6	56.3	69.15	82.5	55.3
9	129.9	147.0	114.0	118.1	135.0	102.0	84.4	95.0	65.0	91.4	99.0	86.0	64.0	69.0	60.0	60.3	71.6	52.0
12	132.09	144.5	120.1	111.21	124.3	101.0	80.21	93.9	58.6	78.17	84.1	65.3	45.24	57.3	34.6	54.74	64.4	45.5
SLAKED IN 200 PER CENT OF WATER.																		
3	83.0	95.0	70.0	97.02	115.0	84.1	102.29	108.0	95.1	72.66	85.0	60.0	70.9	78.4	55.9	65.47	74.0	52.0
6	109.5	133.0	77.0	130.89	150.6	118.5	119.84	134.6	104.7	83.85	98.0	73.0	75.82	80.6	74.2	78.86	98.0	63.7
9	117.7	127.0	96.0	113.08	133.3	88.6	113.65	139.1	100.0	84.8	100.9	67.3	72.3	76.9	67.3	79.5	100.0	53.9
12	99.38	120.2	82.8	113.31	130.5	87.3	89.72	106.8	78.9	62.16	75.2	56.4	67.7	82.0	44.0	65.54	76.0	57.4
SLAKED IN 300 PER CENT OF WATER.																		
3	134.33	157.3	117.8	102.71	122.4	85.0	98.42	110.0	91.0	80.8	88.0	73.0	68.31	78.4	60.0	63.31	73.5	52.9
6	138.32	168.2	111.7	115.49	136.0	103.0	99.67	107.9	88.3	91.6	107.0	85.2	86.61	103.9	76.7	77.27	84.2	71.3
9	131.82	153.1	106.2	115.52	130.0	95.0	89.98	115.4	94.2	83.07	92.3	72.1	84.91	101.0	69.2	69.49	87.7	57.7
12	134.87	147.0	118.1	92.91	111.8	64.4	90.66	97.2	77.7	77.67	94.2	49.0	60.89	71.3	49.5	62.59	69.9	48.5

TABLE VI.

MAQUOKETA WHITE LIME, MAQUOKETA, IOWA.—A. A. HURST & COMPANY.

Time of set in months	Tensile Strength in Pounds per Square Inch.																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
"POWDER SLAKED"—ABOUT 70 PER CENT OF WATER.																		
3	112.6	135.0	70.0	143.87	157.7	117.5	121.58	133.0	115.4	105.29	120.0	100.0	104.74	130.0	85.0	98.39	115.7	88.2
6	140.05	197.0	100.0	213.52	243.9	178.2	125.0	141.0	102.0	115.38	133.6	97.0	126.38	112.9	108.1	110.81	125.00	93.1
9	159.38	176.7	145.2	191.56	214.8	170.1	125.83	139.2	110.8	131.45	144.1	124.5	113.53	138.8	90.7	102.47	115.7	90.2
12	150.03	180.6	121.8	182.98	210.0	158.0	129.89	147.5	108.9	122.16	146.5	96.0	118.26	138.6	78.4	104.70	118.0	87.0
SLAKED IN 100 PER CENT OF WATER.																		
3	128.43	144.0	110.0	130.14	153.0	110.0	130.0	140.0	120.0	115.93	126.2	100.0	101.64	111.7	86.5	97.66	110.6	82.5
6	178.95	204.1	151.0	156.75	177.0	144.9	143.36	173.4	120.0	134.16	158.4	120.8	123.92	142.2	109.8	105.92	121.6	98.0
9	184.29	213.2	150.0	167.36	183.6	146.9	154.3	168.0	137.0	144.5	162.0	111.0	137.56	152.4	125.7	119.94	140.6	105.8
12	185.85	212.2	164.8	157.91	170.0	130.9	144.47	161.6	132.3	123.05	133.7	94.9	128.16	137.4	117.1	108.1	116.0	96.0
SLAKED IN 200 PER CENT OF WATER.																		
3	105.01	120.0	80.0	105.09	136.5	89.1	99.82	121.0	88.0	91.04	110.6	87.7	103.62	120.0	85.0	87.72	90.0	74.8
6	134.66	163.2	117.0	125.20	151.5	101.0	108.18	125.7	93.9	96.85	115.7	73.5	106.53	117.3	93.1	83.4	100.9	65.7
9	152.84	173.4	131.6	124.70	141.6	96.8	108.3	120.0	93.0	94.54	115.0	84.5	85.26	95.2	77.7	92.1	99.0	82.7
12	146.05	164.9	121.6	114.51	145.3	89.7	102.34	111.2	93.9	101.1	112.1	87.9	97.18	118.2	70.7	95.19	112.1	82.0
SLAKED IN 300 PER CENT OF WATER.																		
3	100.7	125.0	90.0	86.49	94.1	70.0	82.25	95.0	63.7	....	....	....	....	....	....	....	....	....
6	126.8	134.0	115.0	98.07	117.0	84.2	95.50	113.8	89.1	....	....	....	....	....	....	....	....	....
9	123.22	136.7	113.2	112.6	136.0	95.0	95.90	108.0	85.2	....	....	....	....	....	....	....	....	....
12	124.9	138.1	113.4	99.27	131.9	79.3	91.91	114.3	78.6	....	....	....	....	....	....	....	....	....

Joiner lime.—Plate XVII brings out very well the change in strength with increasing period of set. The powder slaked lime attains its maximum strength at nine months with the marked exception of the 1:1 ratio in which case the curve continues upwards to the end of a year's time, and gives the highest figure of any mixture in the set. The other percentages of water give characteristic and fairly uniform curves, showing a maximum strength at six to nine months and a falling off or weakening after nine months' set.

The curves on plate XVIII are somewhat irregular but exhibit quite clearly the decrease in strength with increase of water for slaking. In general, the slope is down from the "dry" slake through all higher percentages, although, in a number of instances, there is an unaccounted-for rise from the minimum at 100 or 200 per cent. The position of the curve groups on the diagrams indicates the lowering strength with larger sand dilutions.

Plate XIX emphasizes the weakening effect of sand dilutions higher than 1:1 and 2:1 mixtures. In the majority of instances even proportions of sand and lime afford the greatest strengths, although a higher figure for 2:1 is not unusual. Higher ratios than these two, however, produce a marked falling off in tensile strength for all four time periods.

Hurst lime.—The curves of plate XX run conspicuously uniform and show in general, the greatest strength at nine months. The usual lowering in strength at the end of twelve months is to be noted. As a rule this lime attained its maximum strength with 100 per cent of water as shown on sheet XXI. The highest figures of the set are reached, however, by the powder slaked lime and a sand-lime ratio of 2 to 1.

On plate XXII is brought out the relation between the strength and amount of sand used. With the powder slaked lime, 2:1 gives the highest results, while with the other percentages of water for slaking the trend of the curves is universally downwards as the sand increases.

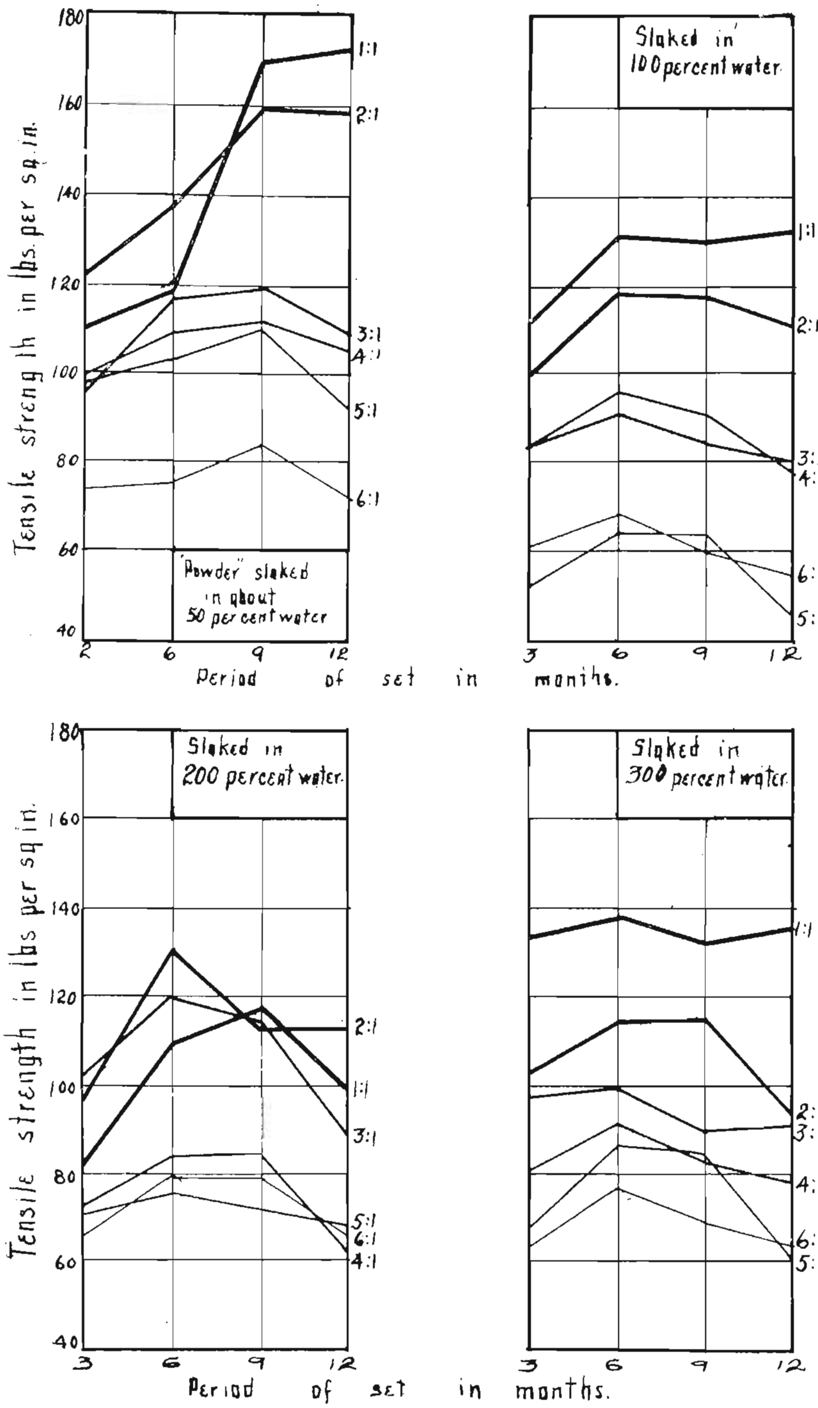

PLATE XVII—Diagrams showing effects of different setting periods

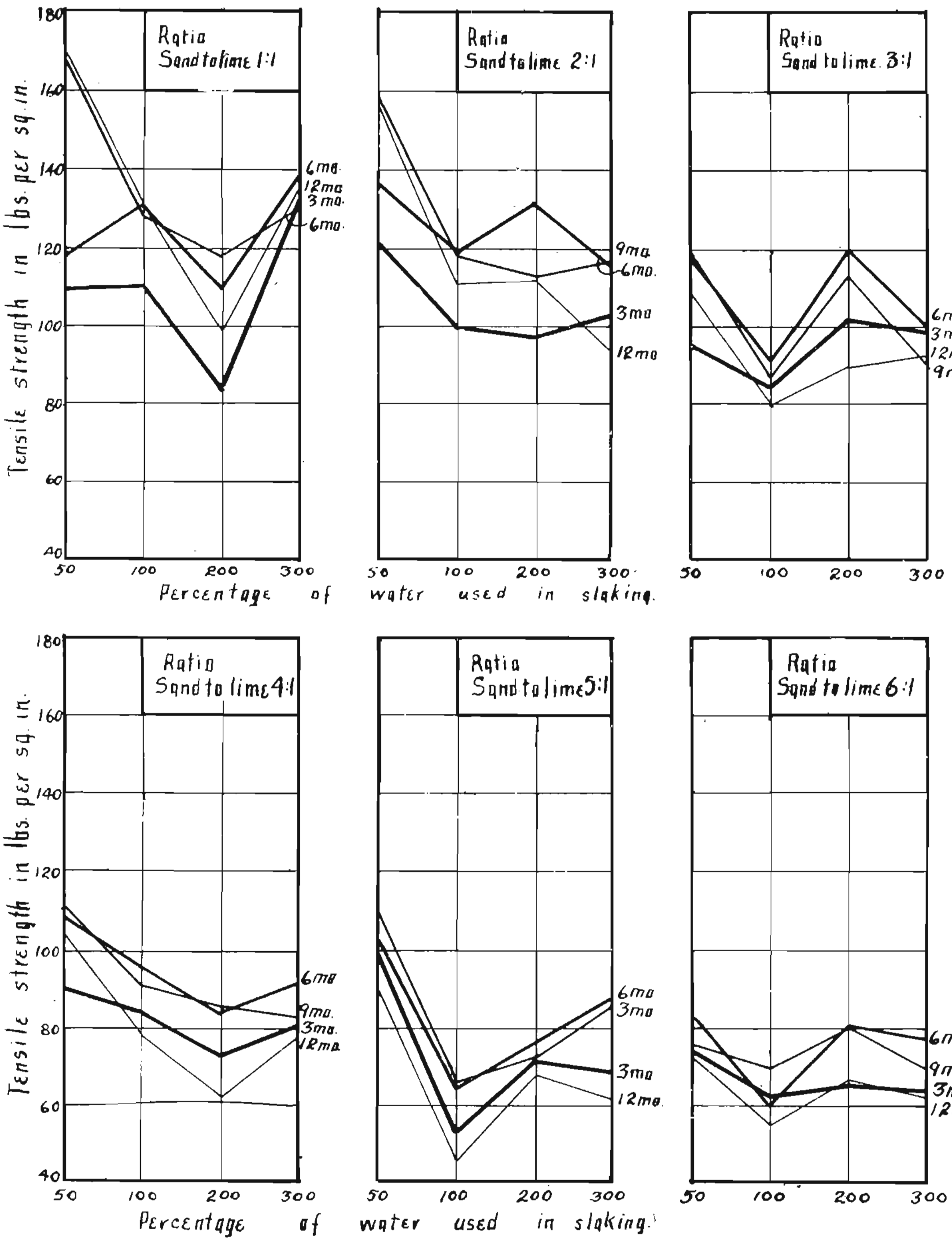

PLATE XVIII—Diagrams showing effects of different percentages of water.

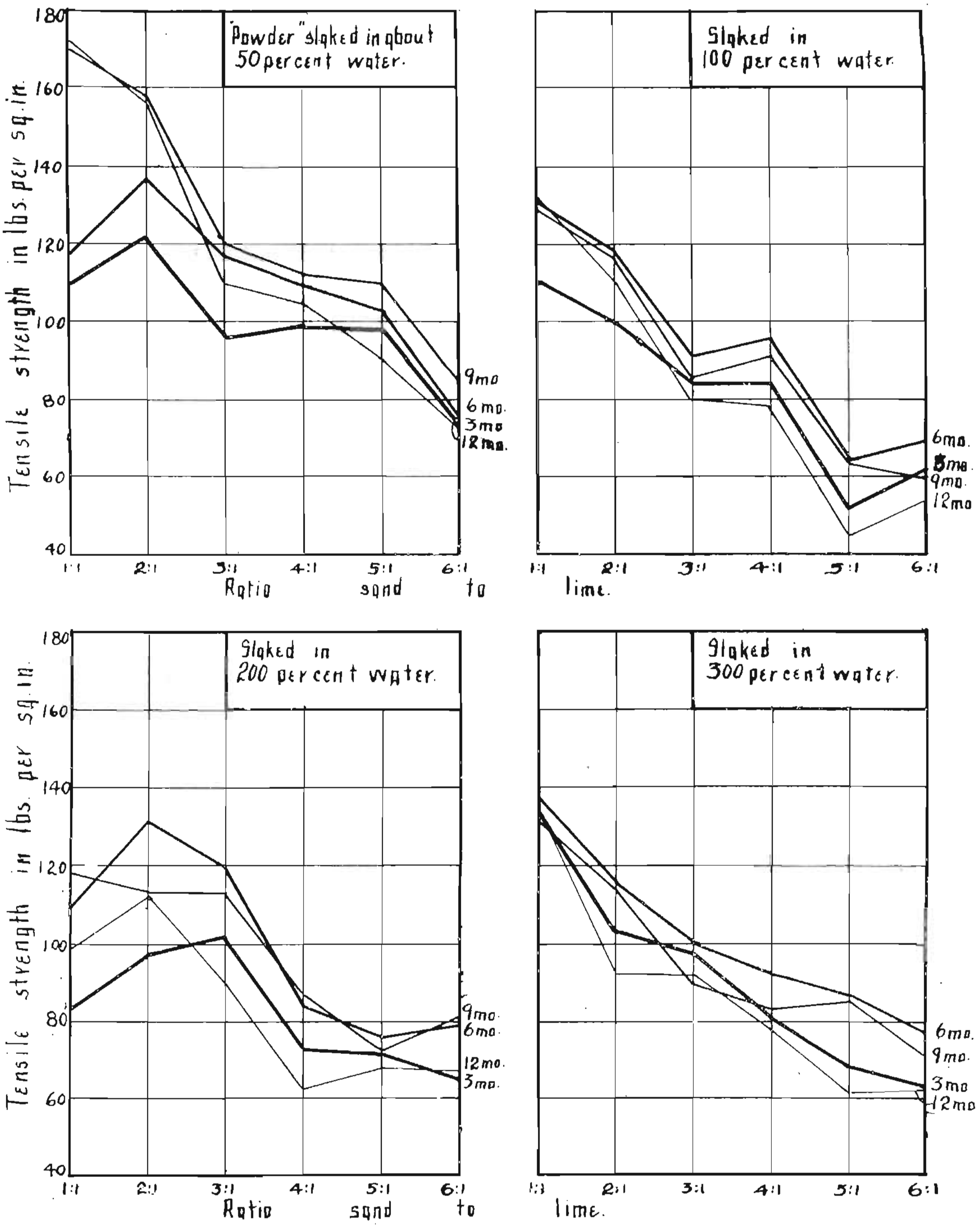

PLATE XIX—Diagrams showing effects of different sand lime ratios.

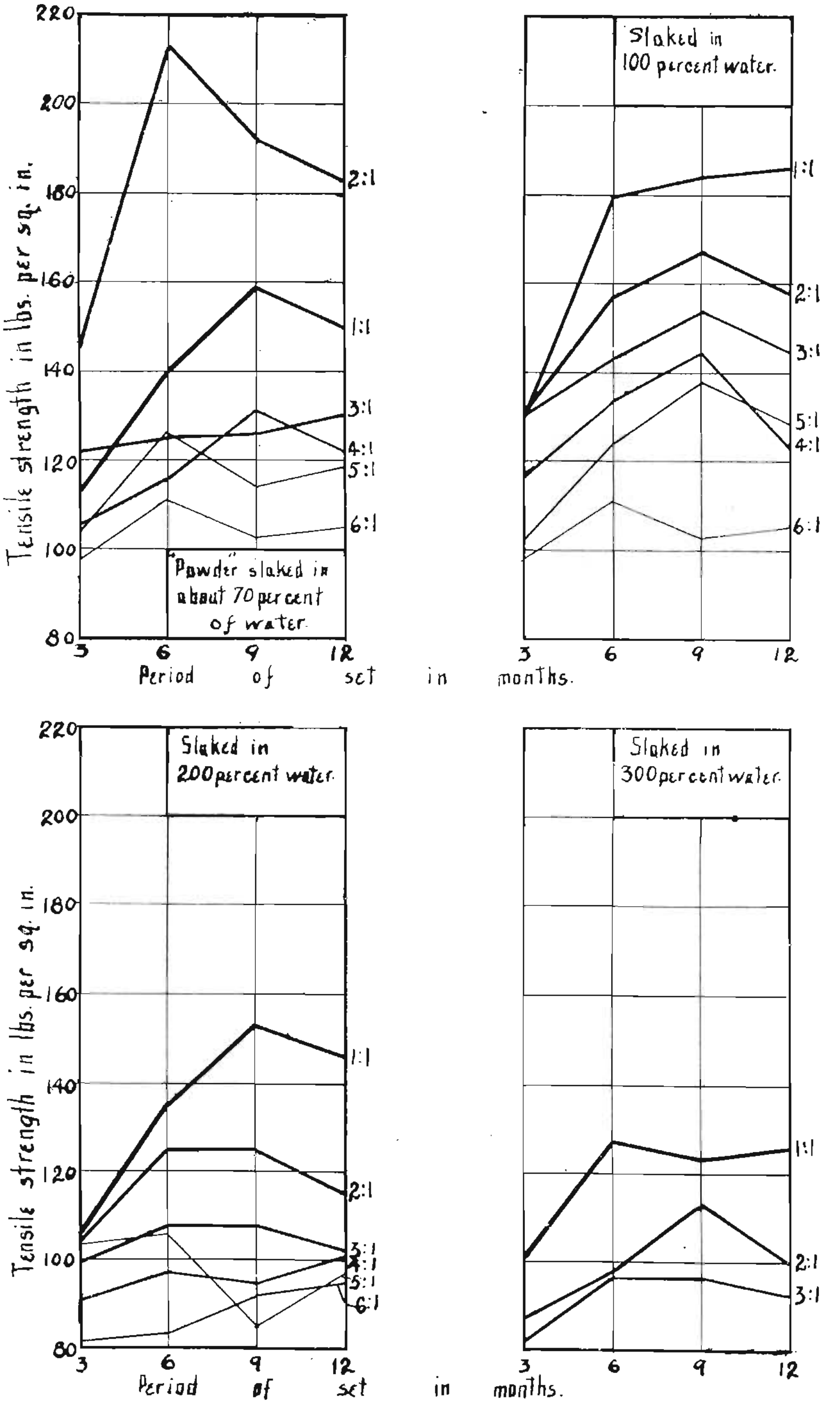

PLATE XX—Diagrams showing effects of different periods of setting.

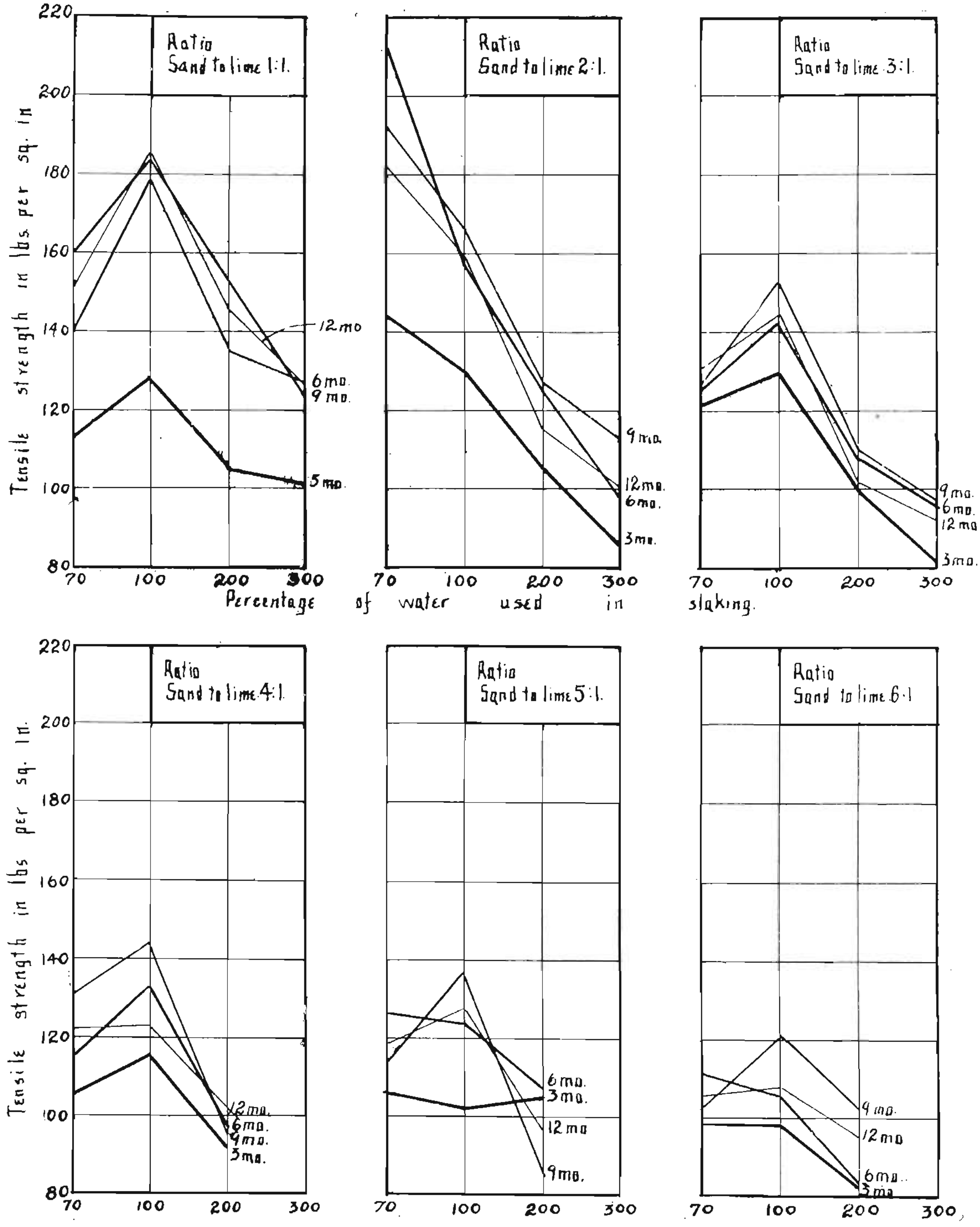

PLATE XXI—Diagram sshowing effects of different percentages of water.

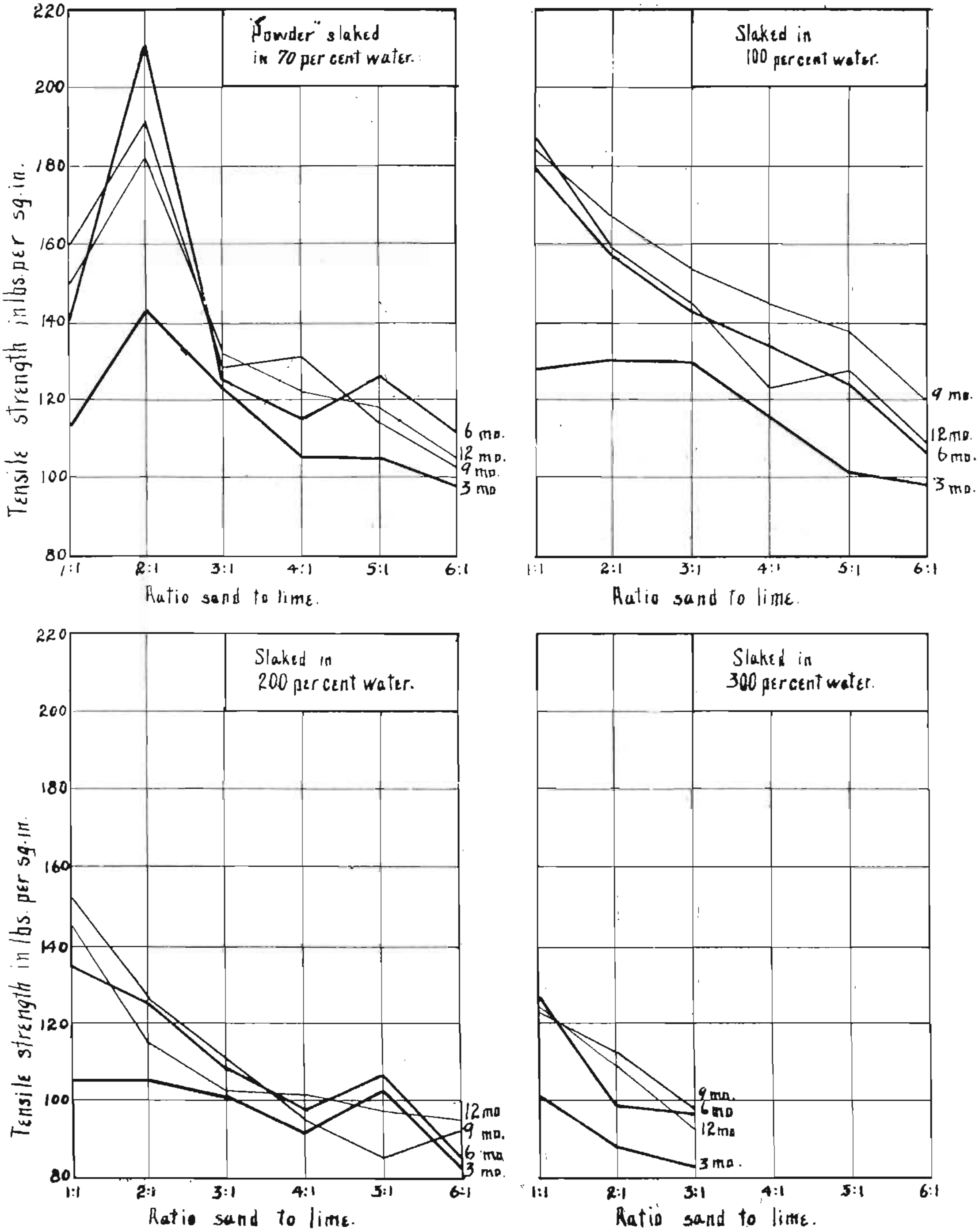

PLATE XXII—Diagrams showing effects of different sand-lime ratios.

NEW PROCESS LIME, VIOLA LIME WORKS, VIOLA, IOWA.

The Viola lime was manufactured from the Le Claire beds of the Niagara stage. The plant is now idle. The stone is highly magnesian and produces a lime of the following composition:

	Quick-lime.	After slaking.
Insoluble	1.20	1.00
Iron and aluminum oxides ($Fe_2O_3 + Al_2O_3$)	1.40	1.00
Lime (CaO)	66.80	45.20
Magnesia (MgO)	27.10	29.28
Carbon dioxide (CO_2)	.70	2.02
Loss on ignition, less CO_2	2.50	21.75
	99.70	100.25

The commercial product takes water slowly and no slaking action becomes noticeable for some time. About five hours was required for complete slaking in 60 per cent of water, the mixture heating but slightly. With the higher percentages of water the time required is still greater and in all cases the slake is very cool. The lime does not melt to a paste as is usual, but remains in a more or less granular condition. The results of the tests of the Viola lime are tabulated in Table VII and plotted on plates XXIII, XXIV and XXV.

A comparison of the data obtained in these tests with the results from the other limes of the whole series reveals two notable departures. The breaking strengths are on an average higher, the maximum being nearly 50 per cent greater than the closest competitive value. They are remarkable also in that the strength almost without exception increases to the end of twelve months and this increase is most rapid, as shown by the sharpness of the curves on plate XXIII, when slaked with 100 per cent of water, which gives the highest breaking strength of the set. The steepness of the curves between nine and twelve months is in many instances so marked as to render of extreme interest the question, how long such an increase would continue. A properly designed series of tests should be made along this line.

Plate XXIV shows that the lime develops its greatest strength when slaked in 100 per cent of water, while on XXV is plainly shown the decrease in tensile strength following the addition of proportions of sand greater than one and two to one of lime.

TABLE VII.

VIOLA "NEW PROCESS LIME."

Time of set in months	Tensile Strength in Pounds Per Square Inch.																	
	Sand to Lime 1:1			Sand to Lime 2:1			Sand to Lime 3:1			Sand to Lime 4:1			Sand to Lime 5:1			Sand to Lime 6:1		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
"POWDER" SLAKED IN ABOUT 60 PER CENT OF WATER.																		
3	116.5	138.7	104.0	130.8	152.0	100.0	107.2	122.6	89.6	101.9	113.4	92.3	103.7	120.7	88.0	81.5	91.5	75.4
6	149.5	168.6	124.5	149.4	174.5	122.4	139.8	163.2	117.0	122.9	152.8	102.9	113.9	134.2	90.7	84.6	95.4	74.1
9	119.6	142.1	95.2	134.8	157.7	110.3	122.4	150.0	103.9	110.8	124.2	92.2	94.8	108.4	82.2	77.6	85.7	61.9
12	....	....	....	163.5	184.7	138.8	151.7	176.0	120.2	125.2	140.3	107.6	113.6	122.6	102.8	93.3	107.7	83.7
SLAKED IN 100 PER CENT OF WATER.																		
3	156.4	199.0	106.05	167.7	198.0	132.0	127.3	163.2	105.0	148.4	180.6	116.5	120.7	140.1	102.8	....	....	....
6	154.2	200.0	132.3	211.4	244.9	176.5	175.4	208.0	100.0	163.1	212.0	130.0	120.3	143.5	92.6	....	....	....
9	200.4	269.5	145.0	209.2	253.0	180.6	186.8	213.1	163.6	153.3	185.1	144.5	111.2	127.6	83.8	....	....	....
12	282.1	301.9	255.6	249.7	278.2	191.6	183.9	206.1	165.9	161.6	178.4	151.9	127.2	150.0	103.7	....	....	....
SLAKED IN 200 PER CENT OF WATER.																		
3	145.7	185.4	103.0	139.8	157.0	112.0	111.0	124.2	95.1	72.1	100.9	70.5	65.1	71.4	57.1	72.1	89.4	63.4
6	160.4	202.0	111.1	164.8	189.3	140.0	137.7	182.5	107.0	93.4	105.6	80.2	75.1	95.3	75.4	67.0	77.6	56.1
9	157.9	185.9	121.3	153.4	173.5	142.6	134.0	159.2	118.6	97.9	122.3	87.4	74.4	83.0	66.3	69.1	77.6	60.6
12	165.1	189.5	142.7	149.6	161.6	127.3	153.1	176.5	128.9	105.7	118.4	90.2	88.4	102.8	73.6	74.3	83.8	65.7
SLAKED IN 300 PER CENT OF WATER.																		
3	118.4	143.0	102.0	143.8	159.6	114.3	119.7	132.7	106.3	84.1	90.7	77.8	90.4	107.6	60.0	83.5	91.5	75.4
6	155.7	187.7	118.5	159.8	181.5	132.4	110.1	128.0	86.9	90.8	104.8	78.2	91.3	103.8	76.9	78.7	87.7	70.7
9	144.1	182.3	94.6	154.5	166.7	133.2	97.9	114.0	84.1	78.8	101.9	46.7	92.9	103.9	81.5	73.5	87.5	56.7
12	206.9	229.0	165.0	176.2	210.9	153.0	101.2	128.4	85.9	107.7	119.2	83.7	90.0	101.9	80.6	90.2	99.0	76.9

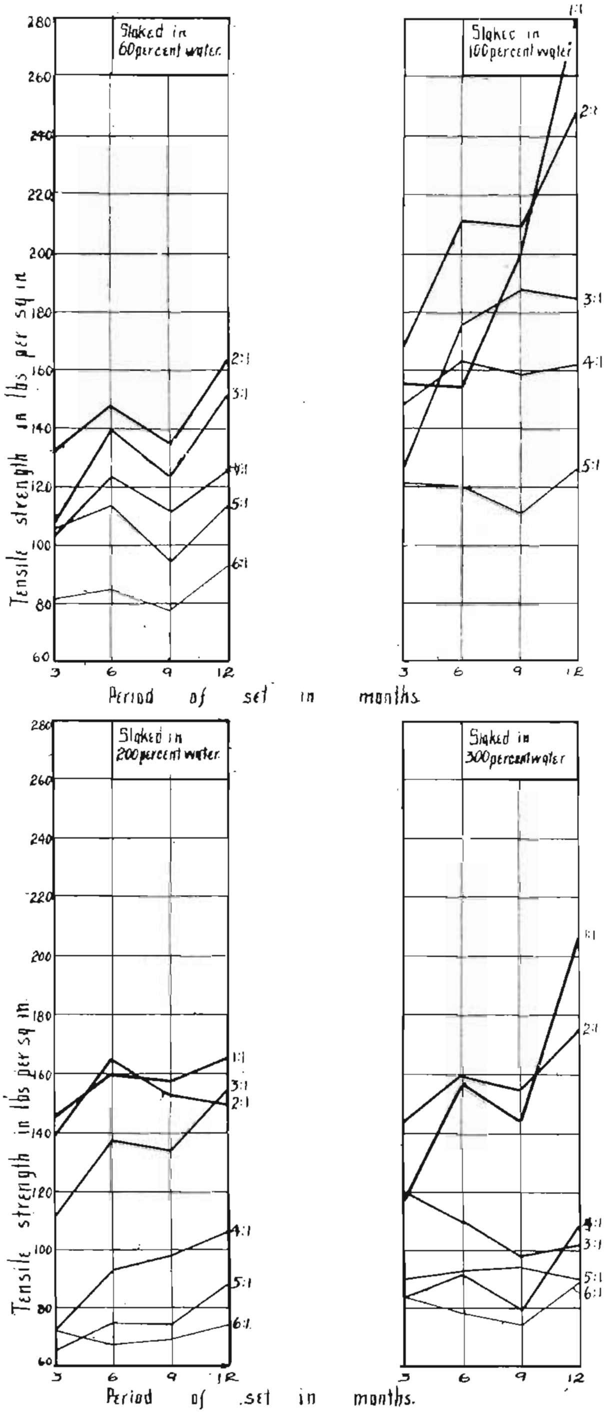

PLATE XXIII—Diagrams showing effects of different periods of setting.

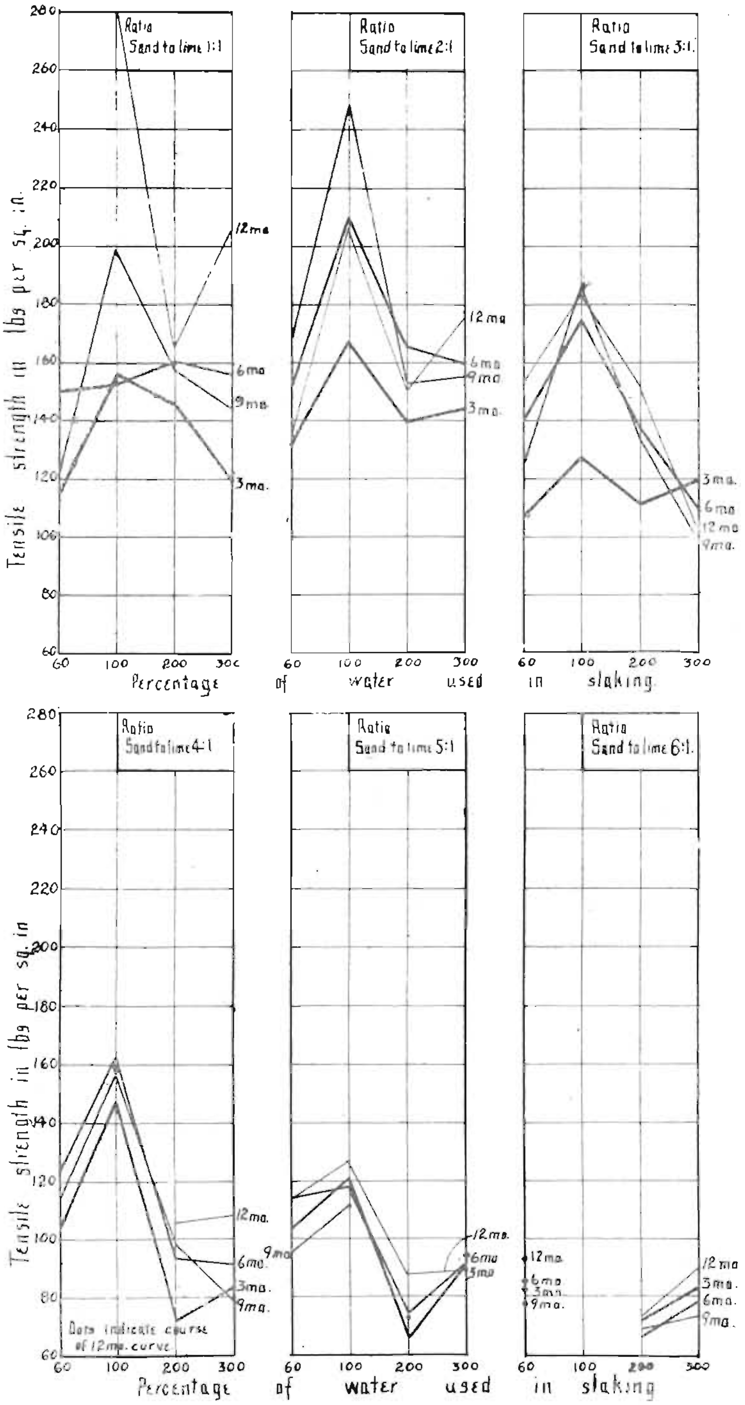

PLATE XXIV—Diagrams showing effects of different percentages of water.

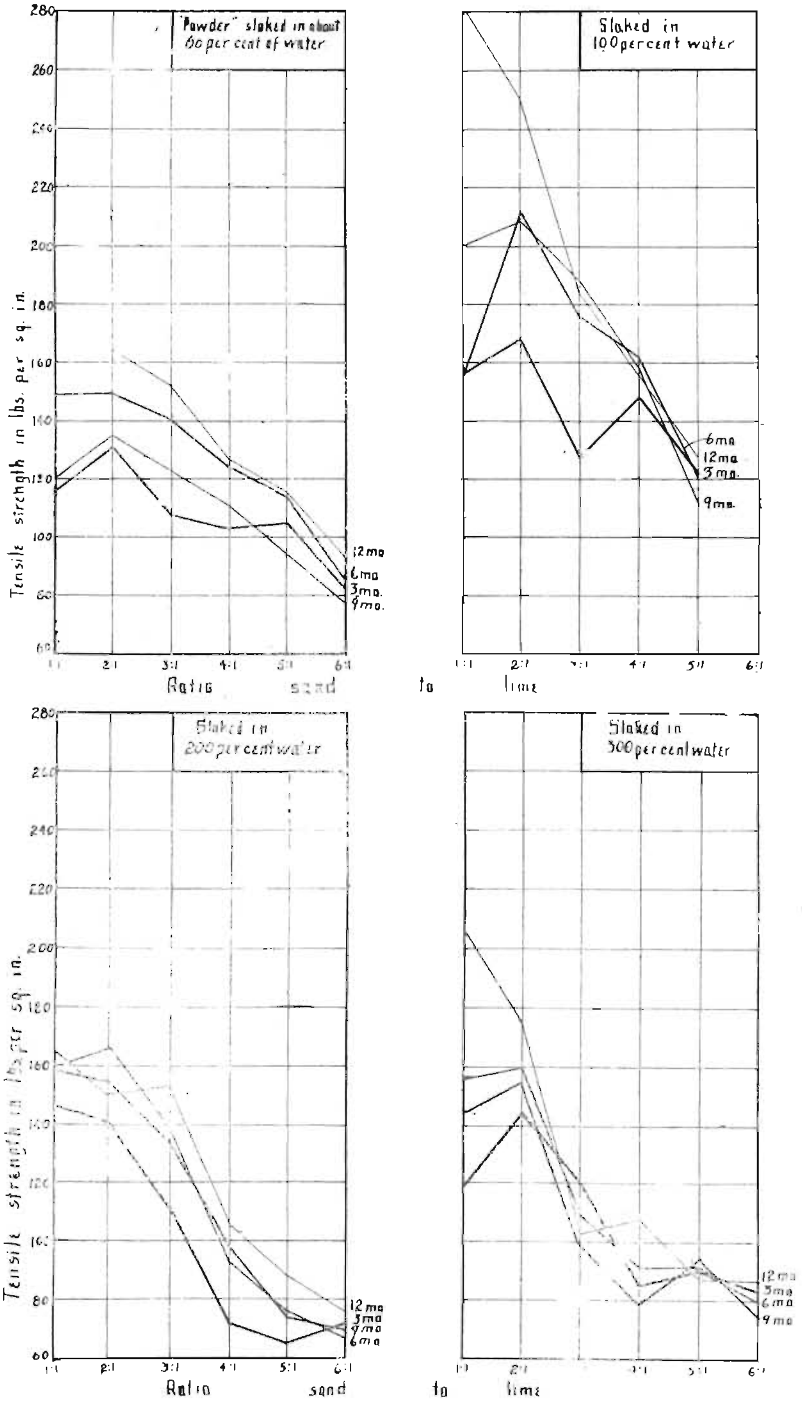

PLATE XXV—Diagrams showing effects of different sand-lime ratios.

RESUMÉ.

While the foregoing series of tests are far from exhaustive and serve to open up and suggest many questions that might be profitably investigated, the results obtained are, it is believed, sufficient to base upon them a few generalizations. Some of the statements which follow are of facts that have long been regarded in practice but which have not before been proven by systematic experiment. The limes tested are types of high grade products and may be regarded as representative examples of pure white limes and of the magnesian or dolomitic class. The results, therefore, are to be limited in their general application to these classes and are not to be construed as holding good for the impure or hydraulic limes.

(a) The maximum strength reached within a year's time, is attained at the end of a setting period of six to nine months duration. This is most pronounced where the higher percentages of sand are employed. The notable exceptions to this rule are found with the *lowest* sand-lime ratios, the *lower* percentages of water used to slake, and are most conspicuous in the strongly dolomitic limes.

The cause for the diminution in strength after nine months is not known and results of chemical analyses to determine the amount of carbonation at the end of each of the four periods indicate that this process is in no instance complete at the end of a year's time. Carbonation has progressed to a minor extent only during the first six or even nine months. The change that occurs during the *setting* of the mortar is considered to be largely the crystallization of the lime hydrate. It is possible that such crystallization may produce a bond that is stronger than the carbonate. The process of carbonation displaces the combined water of the hydrate and may as a result actually diminish the cohesive strength of the mortar. If this be true, we would expect such loss in strength to continue till a minimum value is reached, which would either remain constant, or, as the amount of carbonate becomes greater than that of hydrate and carbonation approaches completion, increase again. It is within the range of probability that the ultimate final strength, which might require years for attainment, would be greater than that reached in the first few months of setting. A set of long-time tests, properly designed, should yield valuable information along these lines.

(b) In general, the greatest strength comes with the lower percentages of water used in slaking. Equal amounts by weight of water and of dry quick-lime give in the majority of cases, the highest results. Higher proportions are detrimental to tensile strength. This is more especially noticeable in the white limes.

The generation of a considerable amount of heat, and consequently steam, seems essential in the slaking process, as explained earlier. Too little water leaves hydration, and therefore expansion in bulk, incomplete and the unslaked lime remaining receives its necessary moisture either slowly from the atmosphere or from the water used in mixing for use. The latter slow hydration is not accompanied by the necessary rise in temperature or increase in volume. Too much water prevents the formation of steam and maximum increase in bulk, and therefore retards the slaking. A high excess may keep the temperature so low that combination between water and quick-lime may be evidenced by few if any signs of slaking whatever, for hours after immersion. It would be expected, therefore, that such a percentage of water as would produce the most vigorous slaking action and leave a satisfactory moist paste would afford the best results when tested. This amount varies with different limes as noted in the consideration of each set of results. In every instance, however, the percentage giving the highest strength was that amount which gave the best slake and produced the most workable paste.

(c) As a rule, the highest strength is given by the lowest proportions of sand, the curves being about equally divided between equal parts by weight of sand and dry quick-lime and two of sand to one of lime.

Economy in the use of lime demands that as little as possible be used over that required to fill the voids and to coat each grain of sand with a thin film. The sand particles should be in practical contact with each other throughout. The percentage of pore space in the standard sand used in these tests is essentially 40 per cent. (It will be recalled that this sand is a clean, rounded river sand and represents an average grade and quality such as is obtainable along the streams of Iowa.) Theoretically, therefore, a volume of slaked lime equal to 40 per cent of the total space enclosed by the sand is required to fill the open pores among the grains. If the lime could be confined to the pore spaces alone, still permitting the sand particles to touch at all possible points, such an amount of lime could be added without increasing the apparent volume of the sand, but this is not practically possible.

As noted on an earlier page (page 103), white lime hydrates range in specific gravity from 2.12 to 2.32, and the magnesian averages 2.45. Assume an average for white limes of 2.22 and 2.65 for quartz sand. To be equal in volume to the voids in the sand there would be required in round numbers by weight 36 per cent of the dry lime hydrate. That is, with each sixty-four pounds of sand should be mixed thirty-six of slaked lime (estimated dry) to just fill the space among the grains. There would be required of the average dolomitic lime about thirty-nine in each one hundred pounds of mixture to eliminate the voids in such a standard sand. A liberal allowance would be 40 per cent by weight in each case.

The results of the tests show the highest strength with a 1:1 or 50 per cent mixture. As lower ratios of lime and sand were not employed, it is impossible to do other than speculate on the possible results from such mixtures. It seems probable that mixtures as low in lime as theoretically required to fill the voids may show higher strengths than the lowest proportion used in the foregoing tests. This limit of the series could profitably be extended to include even the neat lime so as to make the results conclusive. As the lime paste is ordinarily used in practice, it contains from 50 to 65 per cent of free moisture, the white limes carrying the larger amounts. In order to make calculations on the dry basis in mixing with sand, it is necessary to evaporate the water from a small sample of the paste, weighing before and after to determine its percentage. Practically, also, sands as they come from the bank contain a considerable percentage of fine material which decreases the voids. River sands range in the neighborhood of 35 per cent. The amount of voids can likewise be determined as directed in an earlier portion of this chapter.

(d) The white limes require more water to slake properly, generate more heat in slaking, slake much more rapidly and reduce to a more uniform paste than the magnesian limes. The dolomitic limes set and harden more slowly but in many cases attain strengths so much greater than do the white limes as to be almost out of comparison. They will, therefore, stand greater dilutions of sand and still be sufficiently strong to meet the requirements of practical use.