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MEASUREMENT OF PLASTICITY OF MORTARS AND PLASTERS

BY

WARREN E. EMLEY, Chemist
Bureau of Standards

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MEASUREMENT OF PLASTICITY OF MORTARS AND PLASTERS

By Warren E. Emley

CONTENTS

I. INTRODUCTION

Everyone knows that plasters, mortars, clays, and certain other classes of materials are plastic. They must be plastic or they can not be used for the purposes for which they are intended. On the other hand, few people realize the enormous influence which the degree of plasticity has on the economic use of the material.

Take the case of wall plasters, for example. About 70 per cent of the total cost of plastering your house is accounted for by the labor required to spread the plaster on the wall. If one plaster is more plastic than another, it means that the plasterer can cover more square yards in a given time with the former than with the latter, which, of course, will reduce the cost. Furthermore, the more plastic material entails less physical and mental fatigue on the part of the plasterer, and he is thereby led unwittingly to produce a better quality of work.

The material used for the final coat of wall plaster must have plasticity in a very high degree. In fact, the requirements are so severe that neither Portland cement nor calcined gypsum can be used by itself for this purpose; a certain amount of lime must be added to give plasticity. This means that dealers must carry in stock and deliver on the job two materials, and the plasterer must mix these two materials, whereas if either cement or gypsum had the desired plasticity, one material would be sufficient.

While lime in general is more plastic than cement or gypsum, different limes have different degrees of plasticity. Any kind of quicklime, when properly slaked, will produce a putty of very great plasticity. Unfortunately this material is difficult to handle by inexperienced operators, so that the phrase "when properly slaked" is of undue importance. On the larger operations, especially in cities, hydrated lime is rapidly replacing quicklime as a plastering material, because of its greater convenience and the fact that it is already slaked. Hydrated limes are divided very sharply into two classes, on the basis of their plasticity—the "finishing" limes, made from a kind of limestone peculiar to a small district in northwestern Ohio, and all other hydrates. As the art of making hydrate is improved, it is probable that finishing hydrates will be made elsewhere. In fact, this result has already been achieved in one or two cases, to be noted later. The plasterer was quick to discover the difference between the two kinds of hydrate and to take advantage of it. The result is that either putty made from quicklime, or Ohio finishing hydrate, is always specified to be mixed with the gypsum for the final coat of plaster, with the tendency strongly in favor of the hydrate.

In 1915 Ohio finish was being sold in Los Angeles at $26 per ton, as compared with $14 for the locally made hydrate. The owner who is building a home in Los Angeles is fully cognizant of the meaning of plasticity as expressed in dollars and cents.

Many investigators have attempted to develop finishing hydrates outside of Ohio. Several attempts have been made to improve the plasticity of Portland cement and of calcined gypsum. These investigators have always been handicapped by the lack of reliable means for measuring plasticity. It was necessary to make experiments on a large scale, so that enough material could be produced to permit a plasterer to spread it on a wall. The opinion of the plasterer was then recorded as indicating the plasticity of the material. The opinion of any man as to the amount of work which he performed to accomplish a given result is quite undependable. It will vary with his state of health and with his mental attitude, and the opinions of two individuals will seldom be found to agree. This method of procedure is therefore both unreliable and extremely expensive, so that most investigators have been compelled to abandon their researches without definite results.

Plasticity of a material is a property for which the consumer pays extra. The improvement of the plasticity of materials now on the market can readily lead to a saving of money to the consumer. For these reasons, the measurement of plasticity is not a question of academic interest only, but is of real practical importance to everyone who uses or pays for any mortar or plaster.

II. DEFINITION OF PLASTICITY

It seems strange that a property so important and so generally well known as plasticity should be so difficult to define that it has become the subject of endless discussion. Everyone who has made no special study of the subject can tell whether or not a material is plastic. But when one does make a special study of plasticity, the definition which he evolves is apt to be colored by the application of the material with which he is dealing, or by the viewpoint from which his research was undertaken.

A broad general definition, states that "plasticity is that property of a material, or combination of materials, by virtue of which it deforms continuously and permanently during the application of force." [1]

Unfortunately, this is not sufficiently detailed for everyday use. Its greatest fault lies in the fact that plasticity so defined is not comparable. According to this definition, a material either is plastic or it is not; it can not be more or less plastic.

Engineers, who approach the subject from the viewpoint of a solid, emphasize the fact that the deformation of a plastic material must be permanent, in contradistinction to the deformation of an elastic material, which is not permanent.[2]

Other investigators, starting from the viewpoint of a viscous liquid, find that a plastic material will sustain a slight initial load without deformation, while a true liquid will not.[3]

The users of plastic materials have their own ideas on the subject, and these ideas differ with different trades. Thus, a

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[1] Report of Committee C–7, Amer. Soc. Test. Mat.; 1919.

[2] Johnson, Materials of Construction, p. 1; 1915.

[3] Bingham and Green, Paint, a Plastic Material and not a Viscous Liquid, Proc. Am. Soc. Test. Mat.; 1919.

clay worker may speak of a clay as being too plastic, whereas such a term would appear absurd to a plasterer.

To arrive at a definition which can be used to establish a basis of measurement, it seems necessary, therefore, to confine ourselves to the particular uses, as plasters and as mortars, of the plastic materials. If such a definition enables us to evolve a machine which will correctly measure plasticity, then it is highly probable that the same definition and machine can be used for materials other than plasters and mortars, even though such use may involve a readjustment of generally accepted nomenclature. If a machine which is designed to measure the plasticity of plasters will not also measure the plasticity of sands or clays, with only minor changes to enlarge its scale, then there is something fundamentally wrong with the principle on which the machine was built and with the definition which dictated that principle.

From the viewpoint of a plasterer or mason, no dry material is plastic; it must be mixed with water to develop its plasticity. Mortar or plaster is usually applied to a surface which is more or less absorbent and which sucks the water out of it. The material loses plasticity at the same rate that it loses water. Therefore, the plasticity of a material depends directly upon its ability to hold its water against the suction of the surface to which it is applied.

Visualize a trowel full of plaster applied to an absorbent wall. The layer of the plaster in direct contact with the wall will lose its water (and its plasticity) immediately. Each successive layer, counting outward from the wall, will be able to hold its water a little longer than the one under it, because the water in each layer must percolate through an increasing thickness of material in order to reach the wall. That is, the time required for the wall to suck the water out of all the plaster will depend upon the thickness of the pat of plaster. When the water has been reduced to a certain proportion, the plaster is no longer workable. Some plasters can be spread out much more thinly than others. The plasterer measures this property quite accurately by noting the number of square yards of surface that can be covered by a given volume of plaster. The more plastic the material the greater the yardage.

The rapidity with which plaster of given thickness will lose its water will depend upon the ability of the drier layers next to the wall to obstruct the passage through them of the water coming from the outer layers; that is, upon the inherent ability of the material to retain its water. Thus the yardage is a measure of that factor of plasticity which was noted in the preceding paragraph. This factor has sometimes been considered as all important, and plasticity has been defined as being the ability to retain water against suction.[4]

Another factor which must be considered is the amount of work required to spread the plaster. Some plasters are notoriously sticky, while some work freely and smoothly under the trowel. This factor has sometimes been considered the most important, resulting in the definition that "that material is the most plastic which can be spread with the least work." [5]

Our definition, therefore, must contain two parts, as follows: (1) That material is the more plastic which has the greater ability to retain its water against the suction of the surface to which it is applied; (2) that material is the more plastic which requires the less work to spread it. A correlation of these two factors will be attempted later.

Plastic materials may be distinguished among themselves according to their working qualities. This leads to a new and more limited definition of plasticity, in that a plastic material is one which works freely and easily under the trowel and has marked ability to hold its water. In distinction to this, there are sticky materials which hold their water, but pull and work "rubbery" under the trowel, and sandy materials which work harshly and dry out quickly. This gradation of plasticity—sticky, plastic, sandy—is the one generally accepted in the trade.

III. HISTORY OF PREVIOUS WORK

Work on the development of a means of measuring plasticity was started by this Bureau in 1909, and has been continued more or less steadily ever since. Altogether some 20 different instruments have been designed, built, experimented with, and eventually scrapped, each instrument representing one more step in our knowledge of the subject.

In the present state of general knowledge it is not difficult to build a machine and say that it will measure plasticity. The difficulty lies in offering convincing and acceptable proof that the

[4] Emley, Practical Method for Comparing the Working Qualities of Hydrates, Trans. Nat. Lime Mfrs. Assn.; 1915.

[5] Emley, Measurement of Plasticity, Trans. Nat. Lime Mfrs. Assn.; 1917.

machine will fulfill the claims made for it. For this reason it is thought advisable to go into the past history of the work, leading the reader up through successive failures, pointing out the sources of error in each case, and finally establishing in his mind the conviction that the present instrument will really measure plasticity.

The methods tried have been based upon seven fundamentally different principles: (1) Measurement of colloidal content; (2) measurement of viscosity; (3) compressive method; (4) range of plasticity; (5) rate of drying; (6) Carson blotter test; (7) present instrument for measuring plasticity.

1. MEASUREMENT OF COLLOIDAL CONTENT

Some years ago, when the chemistry of colloids first attracted attention, the theory was evolved that the plasticity of a material is directly dependent upon the proportion and kind of colloidal substance which it contains. Extended and successful efforts were made to measure the colloidal content of clays.[6] The methods employed consisted of deflocculating the colloidal matter by the addition of minute quantities of acid or alkali, or by measuring the quantity of organic dye which the colloidal matter could absorb.

Under Mr. Ashley's personal supervision, these same methods were applied to lime, but without success. The lime itself is so strongly alkaline in character that it was found impossible to deflocculate it with any reagent. The dye found most satisfactory for clays—malachite green—is an oxalate. It entered into chemical reaction with the lime and was immediately and completely decolorized. Some eighty other dyes were tried, but none was found which gave any assurance that the quantity of color removed by the lime was due to absorption and not to chemical combination.

If we concede that colloidal matter is merely matter in an extremely fine state of division, and agree that the finer the size of the individual particles the greater will be the area of their surfaces per unit of volume, then the measurement of the so-called "surface factor" becomes in effect a measure of the colloidal content. This surface factor theory is that the plasticity of a material is dependent upon the area of the surfaces of the grains. The sizes of the grains are determined as far as possible by sieves, and the finest particles are graded by elutriation.

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[6] Ashley, H. E., The Technical Control of the Colloidal Matter of Clays, B. S. Technologic Paper No. 23; 1912.

Unfortunately, this method is also inapplicable to hydrates. The grains are mostly so small that even the finest sieve is not of much use in separating them. Elutriation, which depends upon the carrying capacity of streams of water of different velocities, did not give definite results because of the solubility of the lime in the water.

It is well known that the plasticity of a lime changes quite rapidly when the lime is soaked with water. If the colloidal theory is correct, then this change in plasticity should be accompanied by a change in the size of the grains. It was therefore decided that there are too many difficulties in the way to permit measuring the sizes of these very small grains when the sizes are changing continuously and rapidly.

As a summary of our experiments with this method, it may be stated that the plasticity of lime may be, and probably is, dependent upon the sizes of grains, but the experimental difficulties in measuring these sizes have to date been insurmountable.

2. MEASUREMENT OF VISCOSITY

It is generally accepted that a plastic material is composed of inert solid particles suspended in a liquid medium. The viscosity of the liquid should determine the freedom with which the solid particles can move, and should therefore influence the plasticity of the mass.

On this assumption it was decided to investigate the viscosities of lime pastes. For this purpose it was first attempted to use a modification of the apparatus used by Arndt for measuring viscosities of melted silicates.[7] The instrument is illustrated by the accompanying drawing (Fig. 1). A plunger of known dimensions is immersed in the liquid, and then pulled out by the falling of a known weight. The viscosity is proportional to the time required to pull the plunger out of the liquid.[8] The instrument was found to be applicable only through a very limited range of viscosities. When the weight operating the plunger was set for thick pastes, it pulled the plunger out of thin pastes so rapidly that the time could not be measured with sufficient accuracy. The dimensions of the instrument were purely empirical; it was impossible to translate the results into absolute units. Hence, when the plunger

[7] Doelter and Sirk, Determination of Absolute Values of Viscosities of Melted Silicates, Monatshefte für Chemie, pp. 32 and 643; 1911.

[8] Emley, Tests of Commercial Limes, Trans. Nat. Lime Mfrs. Assn.; 1913.

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or the weight was changed, the results immediately became incomparable.

While the plunger viscosimeter was in use, a new instrument, based on an entirely different principle, was being designed. This instrument rotated a plunger or paddle immersed in the liquid, and measured the force required to turn it at a constant

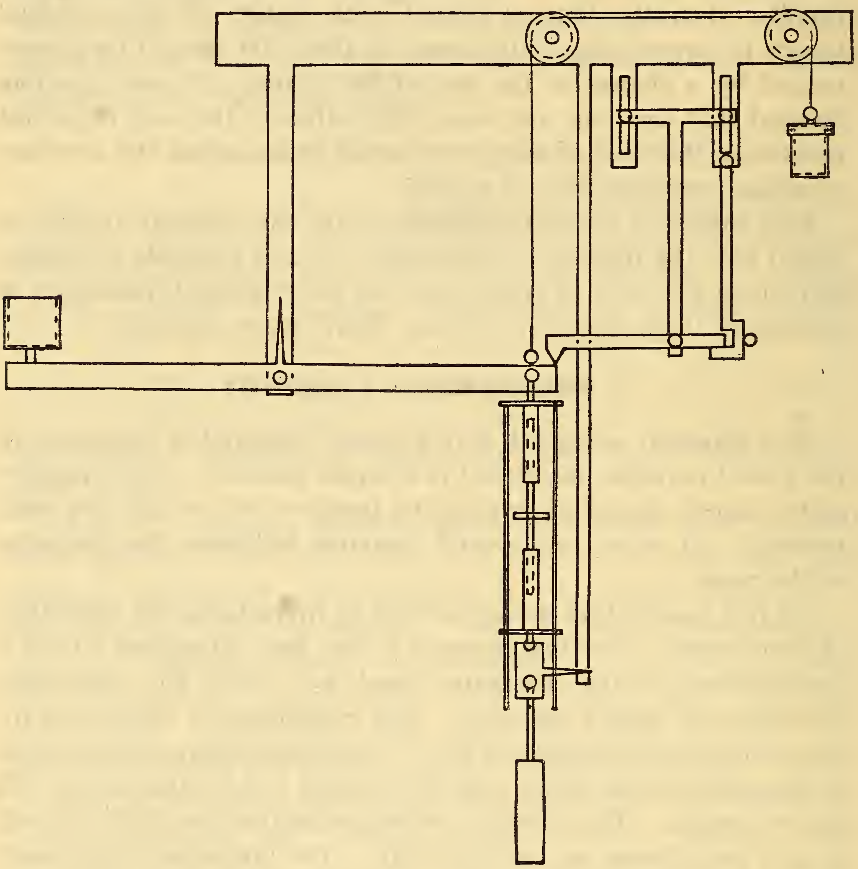

Fig. 1.—*Plunger viscosimeter*

speed. Its final design is indicated by the accompanying drawing (Fig. 2).[9] Great credit is due to Mr. Clark, the designer of this instrument, for the ingenuity with which he was able to overcome all of the difficulties previously encountered. In order to reduce friction to an absolute minimum, the paddle was mounted on jewel bearings. The necessity of mechanism to

[9] Emley, The Clark Viscosimeter, Trans. Amer. Ceram. Soc.; 1913.

turn the paddle was eliminated by using a magnetic drive. Even the friction of a speed indicator was done away with, the speed being measured by optical illusion. This instrument provided means whereby the viscosities of lime pastes could be measured throughout their entire range from thin to thick. The results could be compared to the viscosity of water as a standard, or could be calculated in absolute cgs units.

Both the plunger and the Clark viscosimeters were used for some time, making slight changes in the design. Five different shapes of plungers were tried on the former. The Clark instrument was entirely rebuilt once, and was provided with two shapes of paddles.[10]

From these numerous experiments, it was finally concluded that, while the viscosity of the liquid medium may influence the plasticity of the mass, it is not the governing factor. It is quite possible, by properly proportioning the lime and water, to produce, from any two limes, pastes having the same viscosity. Any plasterer will confirm the statement that the plasticity is dependent upon the quality of the lime, rather than upon the quantity of water.

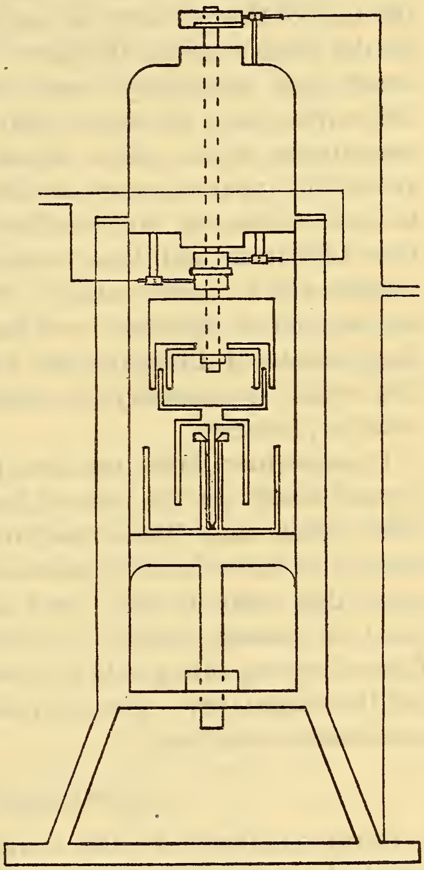

FIG. 2.—*Clark viscosimeter*

Of course, some exception may be taken to the conclusions reached, because the viscosity was not measured in the usual manner—the rate of flow through a capillary tube. Obviously it is impossible to force lime pastes, which contain large particles, to flow through capillary tubes. They can be made to flow through tubes of measurable dimensions, and this method has

[10] Emley, Effect of Consistency and Amount of Sand on the Properties of Lime Mortars, Trans. Amer. Ceram. Soc.; 1914.

[11] Bleininger and Ross, Flow of Clays Under Pressure, Trans. Amer. Ceram. Soc.; 1914.

been used on clays[11] and limes.[12] However, even by this method, no definite relation has been shown to exist between viscosity and plasticity.

More recent work on this line indicates that a plastic solid differs from a viscous liquid in that the solid is able to sustain a slight initial force before it begins to deform, but after deformation has begun, the solid behaves in the same manner as the liquid—the rate of flow through a capillary tube is directly proportional to the force causing the flow.[13] This brings in another factor which had previously been overlooked. Plastic bodies may differ from each other not only in their viscosities, but in the magnitudes of the initial forces required to start deformation. While the apparatus used by Bingham and Green is inapplicable to limes because it involves flow through a capillary, it is noted that Bleininger and Ross observed this same phenomenon, the existence of a "yield value." Probably measurements made by the method of Bleininger and Ross and interpreted according to the formula of Bingham and Green would supply the missing link which is necessary to connect the viscosity of lime paste with its plasticity.

It seems inevitably true that the viscosity of a lime paste will depend chiefly on the ratio of lime to water. When this ratio is held within such limits that the paste is workable under the trowel, we know from experience that plasticity is not dependent upon this ratio, to any great extent. Therefore the measurement of viscosity, while it would indicate the magnitude of one factor entering into plasticity, could certainly not be expected to tell the whole story. For this reason the measurement of viscosity was finally abandoned.

3. COMPRESSIVE METHOD

Our next attack on the subject was started from the viewpoint of the engineer, dealing with plastic solids. In Merriman's text book on the Mechanics of Materials, page 378, the statement is made that when a plastic body is subjected to increasing compressive loads it will first deform and eventually rupture. The rupture will occur along a certain well-defined plane. The angle which this plane makes with the vertical is a characteristic of the material, and, when considered together with the load

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12 Lazell, E., Private communication.

13 Bingham and Green, Paint, a Plastic Material and not a Viscous Liquid, Proc. Am. Soc. Test. Mat.: 1919.

required to cause rupture, affords a definite and reliable means for distinguishing between plastic bodies. The theory has been worked out mathematically to produce two formulas:

$$N = \cot 2\theta$$

$$S_0 = \frac{S \tan \theta}{2N}$$

θ is the angle which the plane of rupture makes with the vertical, and S is the load per unit of area required to cause rupture. These formulas enable us to calculate two inherent properties of a plastic material: N is the "coefficient of internal friction," and S_0 is the "unit cohesive strength." Translating these terms into ordinary usage, when N is high, the material is sticky; when N is low, the material is sandy; when S_0 is low, the material is short working. The conditions for maximum plasticity are an intermediate value for N and the highest possible value of S_0.

An instrument was built to measure the compressive strength of green lime pastes and mortars. It is shown in the photograph, Fig. 3. It operates on the same principle as an Olsen testing machine on a very small scale.

A great many experiments were made with this instrument, the results being published in three papers.[14] It was found that the method does give valuable information about the plasticity of lime, but, like the measurement of viscosity, it does not tell the whole story. The question of consistency again looms up like an insurmountable obstacle. With a very thick paste, S is large and θ is nearly zero. As the paste is thinned down by the addition of water, S decreases and θ increases, until, when the body changes from a plastic solid to a viscous liquid, S becomes equal to zero and θ to 45°. In other words, the plasticity of a material, when measured by this method, depends upon the ratio of lime to water, which is not true. The method was therefore abandoned.

4. RANGE OF PLASTICITY

The experiments with the compressive method emphasized the previously known fact that plastic materials vary in the length of their plastic range. If increasing amounts of water are added to hydrated lime, the changes in consistency will occur in the following order: dry powder, damp powder, sticky

[14] Emley, Deformation of Plastic Bodies Under Compression as a Measure of Plasticity, Trans. Amer. Ceram. Soc., 1915; Measurement of Plasticity of Hydrated Lime by the Compression Method, Trans. Nat. Lime Mfrs. Assn., 1915; Compressive Method of Measuring Plasticity, Trans. Nat. Lime Mfrs. Assn., 1916.

mass which when molded is practically a solid, plastic material, liquid. Suppose a given hydrate changes from a solid to a plastic material when mixed in the proportion, 80 per cent lime, 20 per cent water. When the proportion is 50 per cent lime, 50 per cent water, the material changes from a plastic material to a liquid. Then the "plastic range" of this lime is $80-50=30$ per cent. It has been found by experience that, as a general rule, the more plastic the material the greater will be this range. This method has been employed for many years in the study of clays, under the title of the "Atterberg Plasticity Method."[15] The compressive method described above provided quite accurate means for determining the end points of the plastic range, and the results obtained from experiments with the compressive method could be used as data for the comparison of plastic ranges.

From a study of these data the following conclusions were drawn: (1) Limes as a class follow the general rule, the more plastic the lime the greater the range. (2) The end-points can not be determined with sufficient accuracy to permit differentiation between similar limes. Differences which are quite noticeable under the trowel can hardly be detected by this method. (3) The method is entirely inapplicable and misleading when it is used as a basis of comparison for dissimilar substances, such, for instance, as neat lime and lime mortar. This last conclusion, which really eliminates further consideration of the method, has been verified by other investigators.[16]

5. RATE OF DRYING

The quantity of water which must be mixed with a lime to render it plastic is conceivably a function of the size of grain of the lime and is to that extent a measure of its colloidal content. If plasticity depends upon the presence of colloidal matter, then the quantity of water required should be at least in some degree a measure of plasticity. This would probably be true if it were not for two factors: (1) The quantity of water is not definite for any given material; there is a range in the proportions of lime and water within which all mixtures are plastic. (2) Plasticity is not only quantitative, but also qualitative in its nature. It is impossible, by the mere addition of water, to bring all limes to the same degree of plasticity.

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[15] Albert Atterberg, International Reports on Pedology; 1911.

[16] C. S. Kinnison, Study of the Atterberg Plasticity Method, Trans. Amer. Ceram. Soc.; 1914.

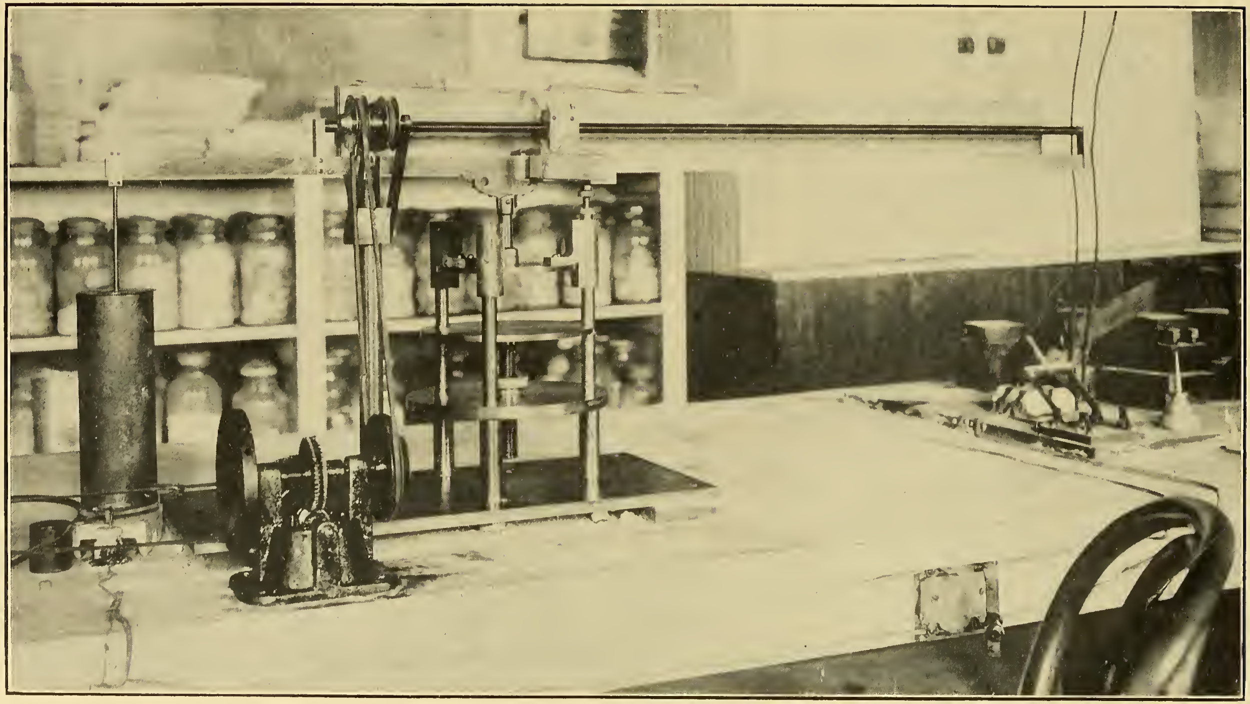

FIG. 3.—*Compressive machine*

Plasters are used by spreading them on absorbent surfaces. They must be mixed with enough water to make them plastic, and they must be able to retain that water against the suction of the surfaces on which they are spread. The length of time during which a plaster can hold enough water to maintain its plasticity will depend not only on the quantity of water originally present, but also on some inherent property of the plaster which gives it the ability to retain water.

An attempt was made to measure this property of hydrates. Pats of lime paste were spread on plaster blocks. The blocks sucked the water out of the lime. The rate of drying was measured by sticking a needle into the paste every few seconds. The method was found to give very promising results.[17] It was refined to some extent by molding the lime paste in the form of a wedge, so that the rate of drying could be followed up the wedge, and the thickness of the dried paste could be plotted against the time.[18]

From the reasoning given above, it will be understood that this method was not intended to measure plasticity. It measures the ability of the material to retain its water, which is only one of the factors governing plasticity. The method performed very much better than was expected; it differentiated sharply between Ohio finishing hydrates and nonplastic hydrates. This is taken to mean that the rate of drying is a measure of the most important factor governing plasticity. So predominant is the influence of this factor that the method forms a reliable basis for the comparison of different classes of materials

The ability to retain water, while the most important, is not the only factor governing plasticity. The measure of this ability permits distinction between classes of materials, but the other factors must be considered when attempting to compare materials in the same class.

6. CARSON BLOTTER TEST

During an informal discussion at the 1916 meeting of the National Lime Manufacturers' Association, Mr. W. E. Carson, who was then president, described a test which he had found satisfactory for the measurement of plasticity. This is essentially a duplication on a small scale of the action of a plasterer when spreading plaster on a wall. The wall is represented by a sheet

[17] Emley, Practical Method for Comparing the Working Qualities of Hydrates, Trans. Nat. Lime Mfrs. Assn.; 1915.

[18] Kirkpatrick, F. A., Circular Letter to Members of Committee C-7, Am. Soc. Test. Mat.; 1917.

of blotting paper; the trowel by a case knife or a spatula. This method was immediately investigated, pronounced satisfactory, and is at present in general use.

The simplicity of the operation and of the apparatus are great points in its favor. Anyone anywhere can procure a piece of blotting paper, a tin cup, and a table knife. Mix the lime with water in the cup. Use enough water to make a good plastering consistency, although this point is not very important. It is usual to let the paste soak overnight before testing it, in accordance with the custom of soaking hydrate overnight before using it. In the morning try to spread the lime out on the blotter with the knife and note "how it works."

In the hands of an experienced operator this method is perfectly trustworthy. Very small differences in plasticity can be detected.

While this method is excellent for regular routine work, such as checking up the quality of a day's output by the hydrate-mill foreman, or the comparison of two brands of hydrate, its use as an instrument for research is seriously handicapped. It is practically impossible to express the results in such a way that they can be understood by anyone else. This means that each operator must be taught personally by someone with experience, else he will have difficulty in recognizing the distinguishing characteristics. Having learned how to make the test, the operator must have considerable practice to gain the necessary assurance that his work is correct. The difficulty of expression makes it impracticable to record the results. It is impossible to test one lime and compare its behavior with that of another lime which had been tested a week before or by another operator. Comparisons can be made only when both samples are tested at the same time by the same operator.

IV. PRESENT INSTRUMENT FOR MEASURING PLASTICITY

The Carson blotter test enables one to measure the rate of drying of the lime, and also the work required to spread the lime on the wall before it has dried. These are the two factors of plasticity included in our definition and recognized by plasterers and masons. The former is much more important than the latter (as shown by the results of the wedge test), but the latter must not be overlooked.

In order to measure both of these factors at the same time, it was decided to build a machine which would duplicate the action of the plasterer. By designing this machine in such a way that the force exerted by the plasterer can be measured, it becomes in effect a blotter test refined so that the personal equation is eliminated and the results are recordable.

Such an instrument was built in 1916. A photograph of it is shown in Fig. 4. A few experiments with it demonstrated some mechanical imperfections, so that it was redesigned. The second design, and the principle upon which the instrument operates, were described in two papers,[19] but the second edition of the instrument was not completed and ready for operation until August, 1919. Its construction is illustrated by the photograph Fig. 5.

1. OPERATION

The operation of the instrument may be briefly described as follows: A number of interchangeable plaster blocks are provided to be used as base plates. These furnish the absorbent surface, corresponding to the wall in practice and to the blotter in the Carson blotter test. They are carefully made so that they all have about the same absorption, and are completely dried in an oven at 70° C after each experiment. The sample is mixed with enough water to make a good workable paste. The consistency of the mix is of some, though minor importance. This feature will be discussed later, under Results of Experiments. The paste is molded in the form of a cylinder 3 inches in diameter by 1½ inches high, using one of the plaster blocks as a base plate. The mold is immediately removed, and the plaster block carrying its cylinder of paste is placed in position on the permanent platform of the instrument. The whole is then moved upward by hand until the top of the paste just comes into contact with the bottom of the disk suspended above it, when the experiment is ready to begin. This operation must not occupy more than 1½ minutes from the time the first batch of sample is put into the mold to the time when the experiment is begun by throwing the switch to start the motor. The permanent platform which carries the sample is mounted on the upper end of a vertical screw. The motor turns this screw, which travels through a fixed nut, so that it moves upward as it revolves. The speed is such that the

[19] Emley, An Instrument for Measuring Plasticity, Tran. Amer. Ceram. Soc., 1917; An Instrument for Measuring Plasticity, Trans. Nat. Lime Mfrs. Assn., 1917.

specimen makes one revolution in 6½ minutes, and moves upward one-thirteenth of an inch in the same length of time. The upward motion presses the surface of the specimen against the disk. This disk is conical in form, mounted point downward on a vertical shaft. It is free to turn, but can not move upward. This conical disk is supposed to represent the trowel. Its sides make an angle of 10° with the horizontal, this being assumed to be about the angle that a plasterer's trowel makes with the wall. While the disk is free to turn, each increment of rotary motion requires an increasingly larger force to accomplish it. A cord connects the shaft of the disk to a pulley, to which a pendulum arm is rigidly attached. As the disk turns it winds up the cord, pulls the pendulum more and more away from the vertical and toward the horizontal, and thereby continuously increases the force required to produce further motion. The pendulum carries a pointer which moves over a circular scale, so that at any time the angle which it makes with the vertical can be read. The force which is being exerted to turn the disk is directly proportional to the sine of this angle. The force is also directly proportional to the weight of the pendulum; the magnitude of the scale readings can be changed by using bobs of different weights attached to the pendulum. Two bobs are provided, weighing 350 and 800 grams, respectively.

The upward spiral motion of the specimen against the disk results in a twisting moment, which tends to spread the specimen out on the plaster block. The pendulum provides means of measuring that part of the force exerted which is acting parallel to the surface of the specimen. The absorption of the plaster block gradually removes water from the specimen and permits measurement of the rate of drying.

From the drawing and photograph, it will be noted that three changes have been made in the instrument since it was built: (1) It was originally intended to permit the disk to move upward, and to measure the force required to cause motion in this direction. A large number of experiments with the first edition of the instrument demonstrated conclusively that the magnitude of this force is not interesting. This mechanism has therefore been locked so that it will not work, and it may well be omitted from further designs. (2) The design calls for a flat disk as well as a conical one. A large number of experiments were run with this flat disk, but it was found that the conical one is more satis-

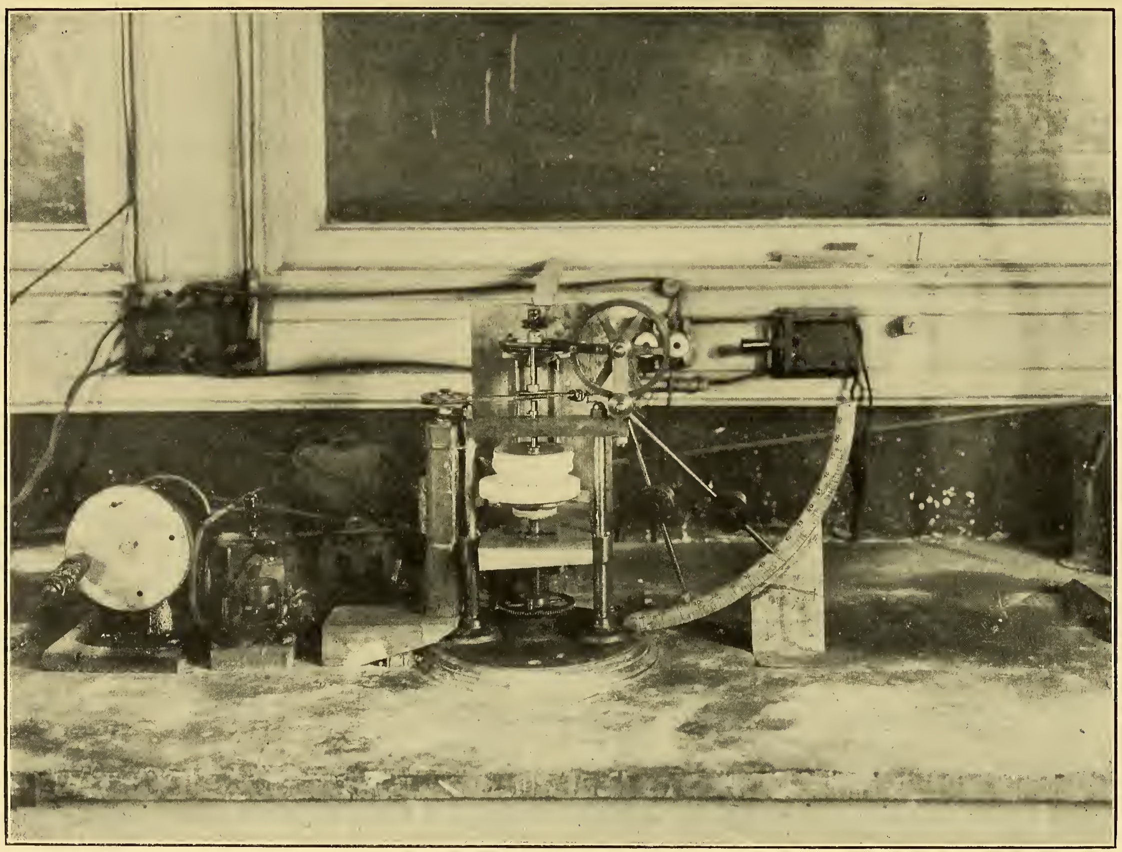

FIG. 4.—*Plasticimeter, original design*

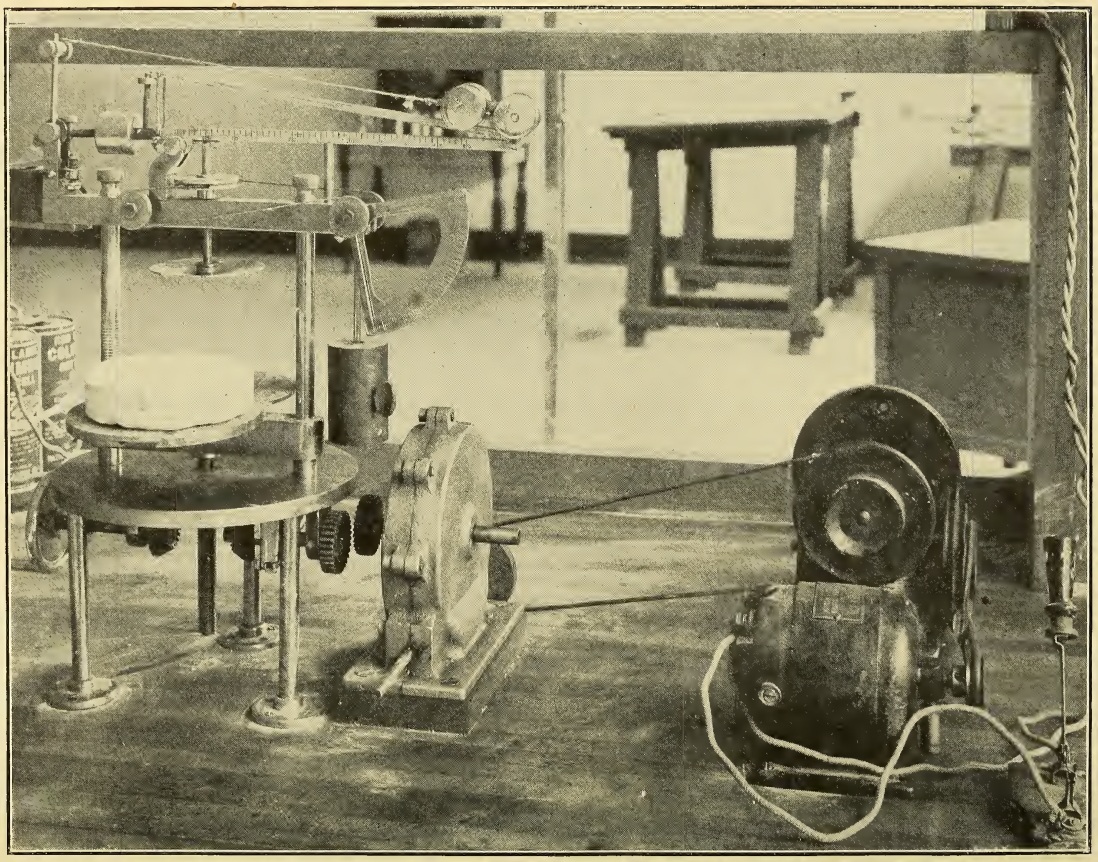

FIG. 5.—*Plasticimeter, present design*

factory for plasters and mortars, though the former may possibly give some valuable information about clays. (3) The original design calls for a speed of 3 rpm. This was found to be much too fast for plasters, and the speed now in use—one revolution in 6½ minutes—has been finally adopted as satisfactory. It may be found necessary to increase this speed when dealing with materials which set very quickly (unretarded calcined gypsum, for instance), but determinations made at different speeds are not comparable.

2. METHOD OF RECORDING RESULTS

While the instrument is in operation, the specimen is continuously drying out. This, together with the continuously increasing area of contact between the specimen and the conical surface of the disk, results in a continual increase in the force tending to turn the disk. The pendulum gradually swings out over its circular scale. The results of an experiment are expressed as the relation between time and force. The time is counted in minutes, beginning with the time when the first lot of the specimen was put into the mold. Since one bob only is used during any experiment, the force is recorded as the sine of the angle which the pendulum makes with the vertical. It is convenient to express the results in the form of a curve, using time as the abscissa and force as the ordinate. A large number of experiments, conducted during a period of three years, have enabled us to recognize the typical curves of plastic and nonplastic hydrates. The former will start to rise late and will continue to rise gradually. The latter will start to rise early and will continue to rise abruptly. The shape and position of this curve constitute criteria of plasticity which all of our experiments have shown to be infallible.

3. INTERPRETATION OF RESULTS

If, for example, one is conducting experiments to improve the plasticity of a material, each change in the manufacturing process can be followed up by the instrument and the curve obtained can be filed away for future reference. This ability to refer back to previous results is of great practical importance. Herein lies the great advantage of the instrument over the Carson blotter test.

The use of a curve to express results, has, however, many disadvantages. It requires some little study of a curve to deduce its exact meaning, and its use is therefore inconvenient. While the comparison of two curves usually enables us to tell without doubt which lime is the more plastic, the relative degrees of plasticity are still indeterminate. An attempt has been made to draw an arbitrary line across the curve sheet and state that when a curve lies to the right and below this line the hydrate can be used as a finishing lime; when a curve lies to the left and above the line, the hydrate is nonplastic. This attempt has thus far been entirely successful, but there is always the possibility of a quibble about the position of the arbitrary line. If one curve crosses another in two places, as frequently happens with similar materials, it is impossible to tell from the curves which of the two substances is the more plastic.

For these reasons, many attempts have been made to find numerical expressions for the curves. It must be emphasized that these attempts are merely for the sake of greater convenience, and that the curves remain as the final criteria.

4. NUMERICAL EXPRESSION OF RESULTS

It will be remembered that the speed of the machine is constant. The abscissa representing time can, therefore, by a suitable change in the scale, be made to represent distance. The area under the curve then becomes the product of the force and the distance through which it acts, which, by definition, is the work done. If we accept the old statement that that lime is the most plastic which can be spread on the wall with the least work, then the area under the curve is a direct measure of plasticity—the less the area the more plastic the material.

Unfortunately, this area could not be directly measured. There was no right-hand end to the curve, no stopping place. The force continued to increase with the time indefinitely. An attempt was made to remedy this defect by setting an arbitrary time limit. The work done during the first five minutes was established as a basis for comparison.[20] The results were extremely gratifying, so much so that this method was on the point of being adopted as standard. Further study of it, however, brought to light two serious fallacies: (1) In a majority of cases the curve could not be continued for five minutes. Either the specimen ruptured or else the force ran off the scale. It was necessary, therefore, to extrapolate the curve in order to measure its area for five minutes. This is of doubtful expedience in any

[20] Kirkpatrick and Orange, Tests of Clays and Limes by the Bureau of Standards Plasticimeter, Jour. Amer. Ceram. Soc., March, 1918.

case, and in cases where the specimen ruptured it is positively wrong. (2) It requires very little work to spread pure sand, if the operation can be completed before the sand has dried out. This method would therefore show sand to be one of the most plastic materials, which of course is absurd. The trouble here is not with the method, but with the definition. That material which can be spread with the least work is not necessarily the most plastic. The thinness to which the material can be spread, the time during which it can be worked, its ability to retain water (all of which terms are synonymous), is a more important factor in plasticity than is the quantity of work done on the material. While it requires less work to spread sand than lime, the sand dries out so quickly that it can not be spread to the same thinness nor worked for the same length of time and is therefore less plastic.

It is absolutely necessary, therefore, to find a right-hand end to the curve, not an arbitrary one, but one which depends upon the inherent character of the material. This has been accomplished with the second edition of the instrument. By using a slower speed and a heavier bob, it has been found possible to reach the point of rupture of every specimen thus far examined. The force does not continue to increase with the time indefinitely. A point is eventually reached where, due to the largeness of the force and the dryness of the material, the specimen breaks. This break is plainly visible, and is indicated in the results as the point where the curve abruptly ceases to rise.

Having now a definite end point to the curve, it is a simple matter to compare the quantities of work which these curves represent. Here again the argument leads to absurdity. The work done on sand is very much less than the work done on lime, yet the lime is more plastic.

Reverting back to the preceding discussion, it will be remembered that plasticity is dependent upon two factors, the time during which the material can be worked and the work required to spread it during that time. Of the two the former is the more important. By considering only the area of the curve we have neglected the first and more important factor. Mathematically it can be stated that plasticity varies directly as the time and inversely as the work. The work, however, is represented by the area, force multiplied by time. A combination of these two statements would indicate that $P = K\frac{T}{FT} = \frac{K}{F}$, or the plasticity varies inversely as the force and the time element is completely eliminated. This, again, is absurd. The trouble is that our mathematics have given equal values to time and work, whereas we know that the former is more important and should carry more weight than the latter. The T in the denominator should not be able to cancel completely the T in the numerator.

5. ADOPTED METHOD OF EXPRESSING RESULTS

We have not been able to determine the relative importance of time and work. We have been able to establish the fact that the former is of far greater importance than the latter—is, in fact, the predominating factor. If we consider two plasters, one of which can be worked on the wall for 30 minutes and the other for

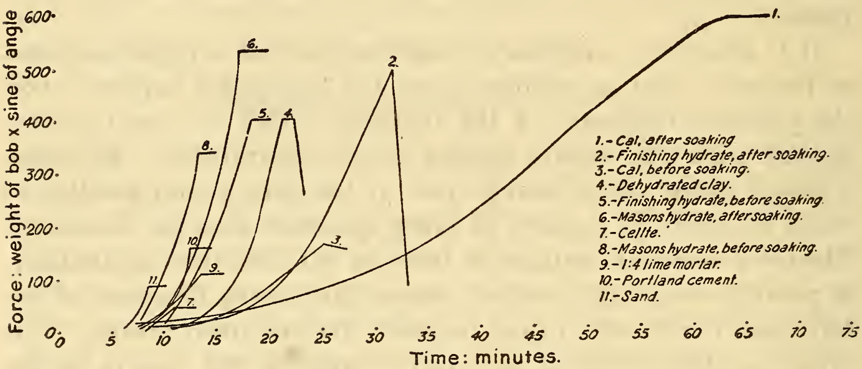

FIG. 6.—*Plasticity curves of miscellaneous materials*

only 15 minutes, there is no doubt that the former would be generally accepted as the more plastic, regardless of the relative quantities of work required to spread the two. If, on the other hand, two plasters can be worked for exactly the same length of time, then that is the more plastic which requires the less work to spread it.

Acting on this theory, plasters have been divided into classes according to the length of time during which they can be worked, and the plasters within each class have been ranked according to the work required to spread them.

As a matter of convenience, 5-minute intervals have been fixed as a basis of classification. The curves of some miscellaneous materials are shown in Fig. 6, and the results are classified in the table given below.

V. PLASTICITIES OF MISCELLANEOUS MATERIALS

The following table calls attention to certain facts. Before soaking, the finishing hydrate is not much better than the nonplastic. Soaking raises the finishing hydrate three classes, the nonplastic hydrate only one class. Materials in the 20-minute class or better can be used as finishing plasters, those below the 20-minute class can not.

TABLE 1.—Relative Plasticities of Miscellaneous Materials

Class	Relative force required to spread	Material	Class	Relative force required to spread	Material
30-minute	14	"Cal"[a] soaked overnight	10-minute	12	Celite
	51	Finishing hydrate, soaked overnight		13	Nonplastic hydrate, not soaked
25-minute	20	"Cal" not soaked		15	1 : 4 lime mortar
20-minute	37	Dehydrated clay		16	Cement No. 1
15-minute	24	Finishing hydrate, not soaked		16	Cement No. 2
	34	Nonplastic hydrate, soaked overnight	5-minute	3	Cement No. 3
				5	Very fine sand

[a] "Cal" is a proprietary material which is intended to be added to concrete to accelerate its early hardening.

EXPERIMENTAL EVIDENCE.—"The proof of the pudding is in the eating." The principle upon which the plasticimeter operates appears to be fundamentally sound, but if the results obtained by its use are erroneous, the theory will not be able to hold its own against the facts. On the other hand, criticism of the theory must be expected; but, if it is shown that the results obtained are correct, this will afford the best possible means of substantiating the theory.

In order to prove that the instrument does give correct results, experiments have been conducted along two different lines—a determination of the effect of consistency upon the plasticity of lime pastes and a determination of the effect of the quantity of sand on the plasticity of lime mortars.

VI. EFFECT OF CONSISTENCY UPON PLASTICITY

It was noted above that consistency has little influence on plasticity. If a lime paste is not plastic, no amount of water which may be added to it can render it so. The converse of this is also true; a plastic lime remains plastic, regardless of the quantity of water which may be added to it. Of course, these statements are true only when the material is really plastic—when it does not approach too closely to either the solid or liquid conditions. Any plasterer will verify these statements, and they can be corroborated with a trowel at any time.

The consistency does, however, have some influence. Obviously, the time required to dry the water out of a plaster, while it depends chiefly on the ability of the plaster to retain water, must be somewhat dependent upon the quantity of water originally present. Experience shows that a wet paste will have somewhat, though very little, better spreading qualities, than a drier one made of the same material.

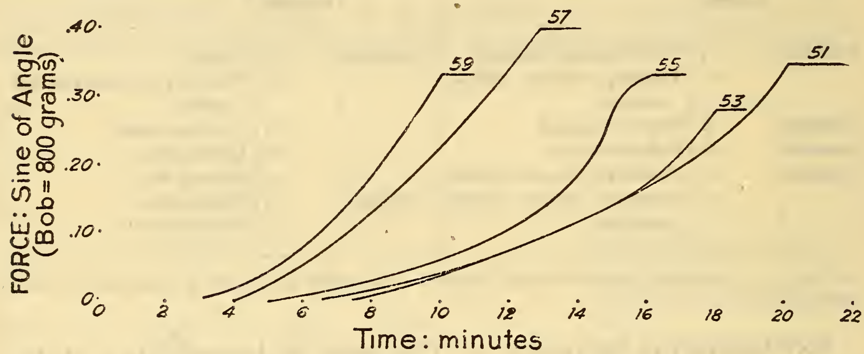

Fig. 7.—*Effect of consistency on plasticity*

To illustrate this effect, and at the same time obtain some idea of its magnitude, a series of specimens were tested, all made of the same lime, but with different proportions of water. The results are shown by the curves, Fig. 7, and are tabulated as follows:

TABLE 2.—Effect of Consistency Upon Plasticity

Per cent lime	Per cent water	Class	Force	Per cent lime	Per cent water	Class	Force
51	49	20-minute	34	57	43	10-minute	23
53	47	15-minute	14	59	41	10-minute	33
55	45	15-minute	28				

Evidently, the wetter the consistency the more plastic the material. In practice the consistency must be at least dry enough so that the plaster will not run off the trowel. The wettest specimen included in the above series is possibly a little wetter than could be readily handled. It is impracticable, therefore, to make from this hydrate a paste which would have the same plasticity as that shown by the finishing lime in Fig. 6.

The instrument corroborates our experience as to the effect of consistency in every respect.

Consistency is not of very great importance. Changes due to consistency can practically never be of sufficient magnitude to render a nonplastic hydrate plastic or the reverse. For this reason consistency as judged by the eye will usually be close enough for practical purposes.

In cases where greater accuracy is desired, as when comparing similar hydrates, the consistency must be considered and accurately measured. We have found it convenient to use the Southard vicosimeter [22] for this purpose. This is a modification of the "slump test" which has been in general use on concrete for some time. The molded cylinder is 2 inches in diameter by 2½ inches high. A sample of plaster gaged ready to put on a wall was tested and found to slump one-half inch; that is, when the cylinder of paste was removed from the mold, it deformed of its own weight until it was only 2 inches high. This was taken as the "normal consistency." In all plasticity experiments the material being examined is mixed with enough water so that it will show a slump of one-half inch when tested in the Southard viscosimeter.

VII. EFFECT OF PROPORTION OF SAND UPON PLASTICITY

The quantity of sand which is added to a lime paste to make a plaster is governed almost entirely by the plasticity. The mortar mixer adds as much sand as he can without making the mortar so lean that it can not be worked successfully.

It is usually claimed, but never conceded, that a dolomitic hydrate will carry more sand than a high-calcium hydrate. Certainly the dolomitic hydrate has the advantage of greater plasticity in the neat paste. As hydrate is replaced by successively larger amounts of sand the mixtures become leaner. Their plasticities approach each other and finally become equal when all of the hydrate has been replaced by sand. Since the plasticity of the sand is lower than that of the lime, it is evident that the replacement of lime by sand will cause a continuous decrease of plasticity. At a certain point it will be found that the plasticity of the mixture is so poor that it can no longer be used for the purpose intended. This point indicates the sand-carrying capacity of the lime. It is obvious that, in order to measure the sand-carrying capacities of different limes, it is essential that the sand

[22] Report of Committee C-11, Am. Soc. Test. Mat.; 1919.

be uniform for all tests. A standard sand, to be used in testing plastering materials, is a necessity. It is worth noting that the process can be reversed, and, by the adoption of a standard lime, can be used to measure the lime-carrying capacity of different sands.

Probably the sand-carrying capacity will be found to vary with the purpose for which the material is to be used. It was noted above that a lime must be in the 20-minute class or, better, to be used for finishing. Possibly a 15-minute mixture of lime and sand

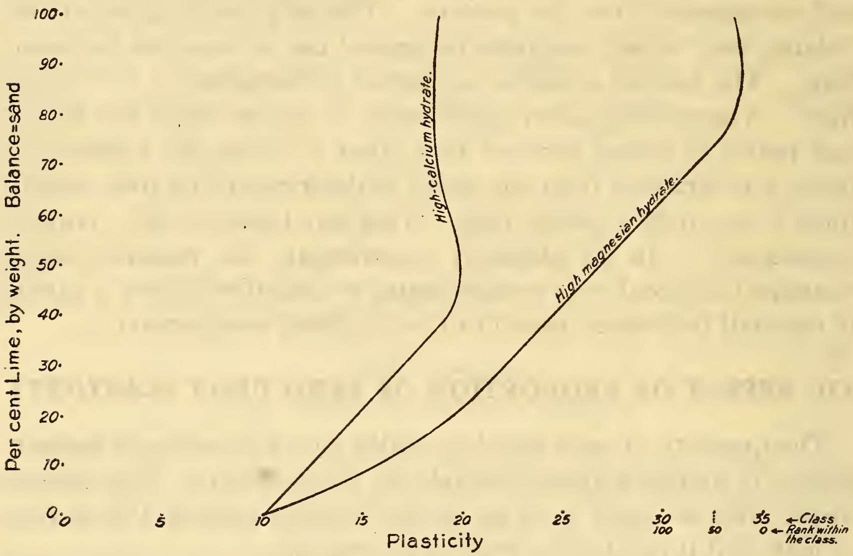

Fig. 8.—*Effect of proportion of sand on plasticity*

will be satisfactory as a scratch coat on metal lath, while for brown coat we may be able to go still leaner, to the 10-minute class.

Fig. 8 shows the plasticities of all proportions of lime and sand. It offers definite proof that the dolomitic hydrate does carry more sand than the high-calcium hydrate. It shows that a mortar made of dolomitic hydrate is more plastic than one made of high-calcium hydrate, regardless of the proportion of sand, up to that point where they are both so lean that there is little difference between them. It shows that the addition of a small amount of sand to a high-calcium hydrate slightly improves its plasticity, a fact which is frequently taken advantage of in practice.

VIII. CONCLUSION

An instrument has been devised that will measure plasticity. We now have a tool with which to work on the important investigations into the cause of plasticity and the improvement of plasticity.

At the instigation of J. J. Earley another instrument is now being built which is much simpler in design and on a much larger scale than the present machine. It is proposed to use this new plasticimeter to attack the problem of the plasticity of concrete.

The instrument is available for use in writing standard specifications for lime and gypsum.

The investigation has been conducted during such a long period of time that it is difficult to make due acknowledgement to all whose thoughts and work have been included in the final product. Those who have contributed the most are, probably, J. J. Earley, W. E. Carson, E. E. Eakins, A. V. Bleininger, P. H. Bates, F. A. Kirkpatrick, W. B. Orange, S. K. Kaczorowski, and C. H. Bacon.

WASHINGTON, January 15, 1920.