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METHODS OF MEASURING THE PLASTICITY OF CLAYS.

By F. P. Hall.

ABSTRACT.

Probably the most characteristic property of clay is plasticity. Numerous methods have been proposed for measuring this important property. Criticisms concerning the more important methods are given in the first part of this paper. The second part is devoted to the presentation of experimental data collected with the use of the Bingham plastometer, an instrument that has been recently brought forward for measuring the plasticity of paints, greases, and other semirigid materials. The plastometer is a modified capillary-tube viscosimeter.

Plasticity has been resolved into its two components by Bingham, and the Bingham plastometer is supposed to give a measure of these two components designated as yield value and mobility. A certain equation has been developed by Bingham giving the relation between the two factors of plasticity of a material and the dimensions of the capillary of tube used in the plastometer. This equation, together with a modification, has been proven by Bingham to hold for paints, but in the case of clay slips with which we are dealing the equation does not hold true, as is shown in this article. This is due to an end effect which is not taken into account in the equations, and which we have not been able to evaluate. Thus we have not been able to express these two factors, viz, yield value and mobility in absolute units. But by using the same capillary we have been able to obtain some interesting comparisons of several types of clays and the effect of addition of certain materials and reagents to clay slips. We believe that by using the same capillary we can determine in a comparative manner the relative plasticities of clays.

CONTENTS.

I. INTRODUCTION.

1. NEED FOR A PRACTICAL METHOD.

Although plasticity is a property that is essential to the usefulness of clays, it is one for which, after ages of service, there is no generally accepted conception which can be crystallized into a definition. It is the property which makes clays workable. A material like mud, or dough, or putty that can be formed readily by simple, moderate pressure, and which will retain whatever shape is thus imparted to it, is called plastic. To the potter or the brickmaker, plasticity is practically the same as workability. It is commonly judged by the feel in the hands, or the way it behaves on the potter's wheel. But such methods are not capable of giving anything approaching a reliable measure of plasticity,[1] and it is becoming increasingly important to measure this property so that the plasticity of a clay can be expressed as a definite, quantitative value. It is obvious that it would be of advantage to a producer to be able to catalogue his different grades with a definite figure for the plasticity for each, and it would be an advantage to the purchaser to have such information in selecting clays for trial or for use. The importance of specifications for materials is rapidly becoming more apparent, and while it is conceivable that specifications for clays might be satisfactory without containing a direct plasticity requirement, it is reasonably certain that such a requirement would be included if a practical method for making the necessary measurements was available. Furthermore, in any scientific study of clays, for the purpose of classification or of utilizing the materials more advantageously in the ceramic industries, it is evident that a quantitative expression for plasticity would be useful. With these considerations in view, the Bureau of Standards has undertaken a study of this property. The work which is to be reported in this paper deals with analysis of the more important of the proposed methods of measurement which have gained some recognition, and particularly with a study of results that have been obtained in a somewhat extended series of experiments with the method of Bingham and Green.

II. DEFINITIONS.

While it is a simple matter to state, in a general way, what plasticity is, a more searching analysis is required to define the property in terms that are capable of mathematical expression.

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[1] "Mechanism of plasticity," by Bole, J. Am. Cer. Soc., 5, No. 6; 1922.

In other words, it is easy to define plasticity in such a way that it is possible to say whether a given material is of low, moderate, or high plasticity, but not so easy to define it so that it would be possible to determine just how plastic it is. Different investigators have devised methods of measurement conforming with their own conceptions of what it is, or possibly have, in some cases, devised a definition conforming to a proposed method of measurement. It will be noted in the discussion of the methods referred to in this paper that different methods measure different factors. It is possible that from a mathematical standpoint plasticity is a definite, hard and fast thing for which only one correct conception can be formed, and to which only one essentially correct definition can be applied. However, plasticity as a property is essential to materials used in a number of industries, and the term plasticity has a somewhat different significance in connection with different industrial operations. Therefore, the fact that a method may not measure plasticity according to the strictest interpretation of the term does not justify the conclusion that the method is of no practical value. That relation of factors which it does measure may be what is essential to a particular type of operation, and, therefore, it may serve a definite purpose. In the discussion of methods, which is given in this paper, it is the purpose to state what each one does determine rather than to show how nearly each one conforms to a definition which is assumed to be correct.

III. METHODS OF MEASURING PLASTICITY.

A considerable number of methods, some direct and others indirect, have been proposed for measuring plasticity, the indirect methods being based on the assumption that some other related but simpler and more easily measurable property would serve as an index to plasticity itself. The most noteworthy of the proposed indirect methods are those based on (1) colloidal content, (2) bonding power, and (3) the so-called viscosity of the clay slip.

1. INDIRECT METHODS.

(a) DYE-ABSORPTION TEST.

Clays exhibit many properties common to substances in the colloidal state, such as hydrolysis, absorption, shrinkage, ability to change from sol to gel form and vice versa. The colloidal theory[2]

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[2] "Theories of plasticity," Transactions of Am. Ceram. Soc., 11, p. 536; 12, p. 814; 14, p. 72; 16, p. 65; 17, p. 616.

is probably the most widely accepted explanation for the cause of plasticity, and the analogy between clays and substances in the colloidal state has led a number of investigators to look to the field of colloidal chemistry for a possible solution of the problem of measuring plasticity. Thus Ashley, assuming the plasticity of a clay to be inversely proportional to the grain size, reasoned that the clay with the highest colloidal content would be the most plastic.

Plasticity is not, however, entirely due to the presence of colloidal matter in clays, though the effects of colloids in increasing plasticity can not be denied. In determining the colloid content Ashley used the dye-absorption test. The absorption of a clay is usually determined by noting the loss of color of a dye solution, such as malachite green, and comparing it with another similar solution to which a standard clay has been added. It is known that different colloids have different absorptive powers toward a single dye and it is not reasonable to assume that the colloidal matter in all clays is the same; hence this method of determining the colloidal content is open to a serious objection In other words, in order for this method to be correct the colloidal matter in different clays would have to have the same absorptive power, and this is not the case.

(*b*) METHODS BASED ON BONDING POWER.

In the study of clays for a number of industrial purposes, the determination of bonding power, which is the ability of a clay to impart strength to a dried mixture made up in part of materials less plastic than itself, is extremely important. In most cases clays of high plasticity also have high bonding power, but, as is recognized by ceramists,[3] bonding power is not identical with plasticity and is by no means a reliable index to it. It is therefore not expedient to discuss the several proposed methods based on bonding-power determination.

(*c*) MacMICHAEL TORSIONAL VISCOSIMETER.

This instrument was first brought forward to determine the so-called viscosity of clay slips. It is at present used to determine the viscosity of liquids. It will be shown later that clay slips are not liquids but plastic substances. The torsional viscosimeter determines viscosity by means of a torsional balance, usually consisting of two concentric cylinders, one of which has an angular

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[3] A. V. Bleininger, B. S. Tech. Papers, No. 144, p. 17. J. W. Mellor, Communication No. 53 from Clay and Pottery Laboratory, Stoke-on-Trent, p. 1.

motion about their common axis. One of the cylinders is suspended by a fine wire, thus forming a torsional pendulum. In the MacMichael instrument the outer cylinder rotates at constant speed. The inner cylinder rotates until the torsional force in the suspending wire balances the viscous resistance, and then remains in a fixed position so that a reading may be taken. If, in the case of a viscous liquid, the speed of rotation of the outer cylinder is plotted against the angular deflection of inner cylinder, the result will be linear and the straight line will pass through the origin.

If a plastic substance[4] is tested the result will be linear at high speeds but the linear portion of the curve extended will not pass through the origin but will intersect the deflection axis at a finite point above the origin. Clay slips behave like plastic substances in this instrument. Tests made with it at the Bureau of Standards on a variety of clay slips showed that the results were not reproducible, due to what may be called a "puddling effect." Thus, as the outer cylinder rotates, that part of the slip immediately surrounding the inner cylinder changes in consistency as the stirring continues. Another difficulty in testing clay slips in this type of instrument is that of filling the outer cup to the proper height. In dealing with a substance that does not flow freely under its own weight it is very difficult to pour the substance into a container so that the entire surface will be at the same level.

This "puddling effect" observed in this type of instrument is likely to be present in any instrument designed for this type of substance as long as the agitation is local and does not extend to the entire mass. In a clay slip the particles are not free to move about; hence we have local agitation within the outer cup immediately surrounding the inner cylinder, and this agitation changes the apparent wetness of this part of the slip. This instrument in its present form can not be recommended for the testing of clay slips. The curves obtained by testing clay slips with it are very similar to those obtained with the Bingham instrument, which will be described in another portion of this article.

2. DIRECT METHODS.

(a) METHOD OF G. E. STRINGER AND W. EMERY.

It is known that plasticity varies with the proportion of water mixed with the clay. The possible plasticity is that which can be developed under the best known conditions. Messrs. Stringer and

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[4] G. S. J. Perrott and Reinhardt Thiessen, J. Ind. and Eng. Chem., p. 324; 1920.

Emery have measured the relations between the proportion of water in the clay mixture and the resistance the clay offers to changing its shape, and the deformation the clay can suffer without cracking. Their method is, briefly: A sphere of clay mixture is made 2 cm in diameter. This sphere is placed upon a glass slab and this placed under a vertical piston. Weights are added to the piston to cause it to descend upon the clay sphere. The descent of the piston is stopped when vertical cracks appear on the edge of the disc. The distance moved by the descending piston is taken to represent the amount of deformation the clay could suffer without cracking and the weight required to compress the clay sphere a definite distance is taken to represent the resistance the clay offers to changing its shape. They found, by this method, that as water is progressively added to a clay the plasticity, as determined by them, increases to a maximum and then as more water is added the plasticity gradually decreases. The chief difficulty with this method seems to be in making the clay sphere. Cylindrical test pieces are not as satisfactory as spherical ones. The results are expressed in plasticity units which are empirical. It is difficult to obtain concordant results and the method can not be regarded as satisfactory without modification. It was found that the greater the plasticity of the clay the greater the proportion of water required to develop the maximum plasticity. A ball clay required 30 per cent of water before becoming sticky, a kaolin required 20 per cent, while a very short clay required only 10 per cent of water to make it sticky.

(b) ATTERBERG PLASTICITY METHOD.[5]

This method is based upon the varying physical behavior of clays with different water contents. The range of water content over the workable stage is determined. The workable stage is bounded by two points which are arbitrarily fixed, one point being that at which the clay mass will barely flow, and the other the point at which the clay mass can no longer be rolled into threads. It is Atterberg's contention that the wider this range the more plastic is the clay. The results are expressed in a unit designated as the "plasticity number," which is empirical. This "plasticity number," along with the per cent water of plasticity, is supposed to determine the plasticity of the clay.

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[5] B. S. Tech. Papers, No. 46.

It is evident that in a method of this type too much is left to the judgment of the person conducting the tests. For comparative tests this method seems to have met with a fair degree of success.

(*c*) EMLEY PLASTICIMETER.

This instrument is described in Bureau of Standards Technologic Papers No. 169, by Warren E. Emley. F. A. Kirkpatrick and W. B. Orange used this instrument for testing clays and limes and made a report of the results in an article in vol. 3, Journal of the American Ceramic Society. The results are expressed in a term called the "plasticity figure," which is empirical, depending upon the dimensions of the instrument. Mr. Emley states that the consistency has little influence upon the plasticity. This is not consistent with the definition of plasticity as commonly given by the ceramist. The ceramist recognizes the fact that the plasticity is greatly affected by the water content of the clay mixture. There seems to be a difference in the definition of plasticity as given by the ceramist and that given by the plasterer. Hence the plasticimeter, while apparently giving good practical results with plasters, is not measuring the same property that is designated as plasticity by the ceramist. The plasticimeter measures the property of retaining water and the resistance to deformation under pressure that a substance possesses. It is yet to be proven whether or not these two properties are an index of plasticity.

(*d*) BINGHAM PLASTOMETER.[6]

If clay be suspended in water, the fluidity is lowered rapidly and in a perfectly linear manner. As the proportion of clay increases a concentration is reached at which the fluidity is zero as measured in an ordinary viscosimeter. Thus these instruments are not available for measuring the viscosity of a suspension above that critical concentration where the substance ceases to act as a viscous liquid. Prof. E. C. Bingham has developed an instrument for the investigation of substances of plastic nature. In using this instrument the rate of flow through a capillary tube under a definite constant pressure head is determined. The flow at several pressures having been determined, the volume discharged per second is plotted against the pressure producing the flow. For true viscous liquids the relation is linear and passes through the origin; for plastic substances the relation is linear at high

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[6] Proceedings, Am. Soc. Test. Mats., 19 and 20, Pt. II; 1919 and 1920.

pressures, but if this linear portion of the curve is extended to the pressure axis it will not intersect the axis at zero but at a finite point on the pressure axis. Figure 1 illustrates this difference between the two states of substances. The fact that with plastic substances the linear portion of the curve does not pass through the origin shows that with substances in this state a certain definite pressure must be exceeded before the substance will flow.[7] This definite initial friction value that has to be exceeded distinguishes the plastic state from the viscous state. The experiments by Bingham support the definition by Maxwell (Theory of Heat) that a plastic body is one in which the body is found to be permanently altered when the stress exceeds a certain value. The following relation between certain terms is given by Bingham and Green:

Solids (including plastic materials):	Liquids.
Rigidity (R) comparable with	Viscosity (η)
Mobility (μ) comparable with	Fluidity (θ)
$\mu=\frac{1}{R}$	$\theta=\frac{1}{\eta}$

By reference to Figure 1 the terms will be explained. The slope of the line (*a*) is determined by the fluidity of the liquid, while the slope of line (*b*) is determined by the mobility of plastic material, and the intercept of the line (*b*) upon the pressure axis is determined by the initial friction value of the plastic material. This initial friction value is also designated as yield value. Of two clay slips of equal mobility, the one having the higher yield value is the more plastic, while of two clay slips of equal yield value, the one having the higher mobility is the more plastic.[8]

Plastic clay in the form of a cylinder or cube, for example, will maintain its form, provided pressure due to weight does not exceed the yield value. Once the yield value is exceeded the material will flow. If the material is very mobile it will flow with ease; if not, a greater pressure will be required to keep the material in motion. These two factors, mobility and yield value, may be said to roughly define the plasticity of a substance.

The rate of flow of a plastic material through a capillary tube is dependent on the two factors of plasticity, namely, mobility and yield value—the dimensions of the capillary, and the pressure

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[7] According to the more complete theory of Buckingham, there can always be flow, due to slip at the lowest pressures. For a discussion of this phase of the subject, see Buckingham, Proc. A. S. T. M., 1921, p. 1155.

[8] E. C. Bingham, B. S. Sci. Papers No. 278; 1916.

applied. Bingham has derived an equation connecting these several factors and based on the following assumptions: (1) That the rate of shear in a given plastic material is proportional to the excess of shearing stress over a constant yield value, below which the material behaves as a solid, (2) no end effect at the entrance of the tube, and (3) no slip or seepage.

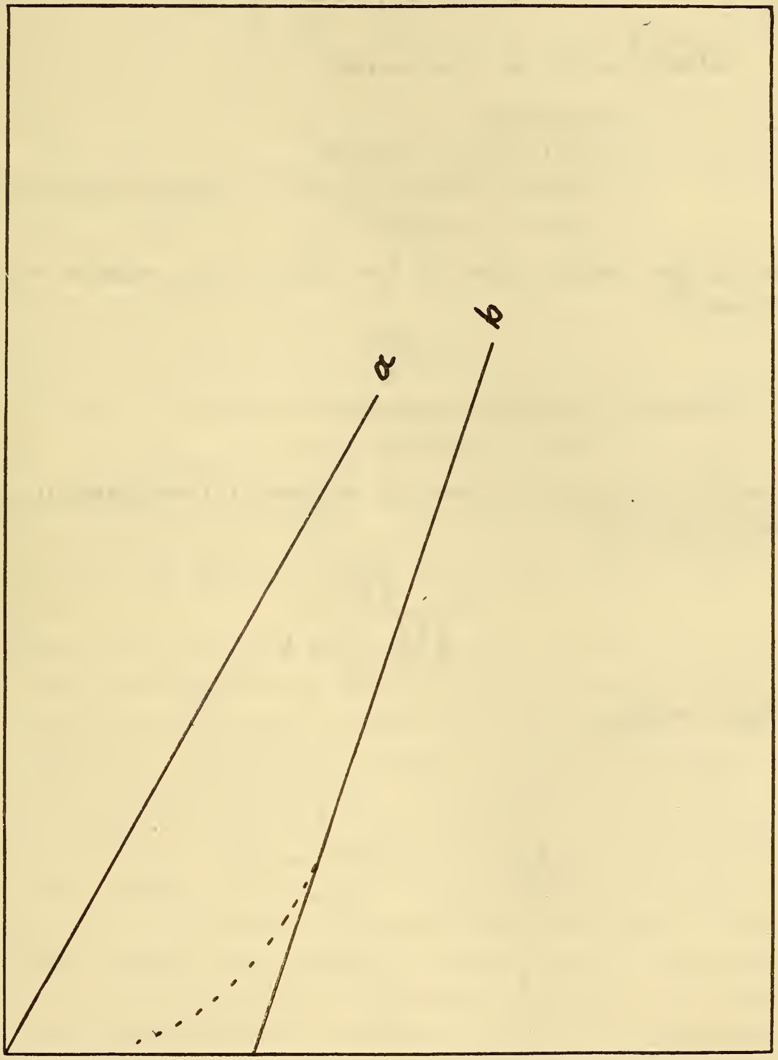


FIG. 1.—*Diagrammatic illustration of the difference between plastic and viscous flow.* Ordinates are flow values, abscissas are pressures.

The equation of the straight line, on the assumption that the phenomena are not complicated by slip, seepage, or end effects, is:[9]

$$\frac{V}{t}=\frac{\pi\mu R^3}{4}\left(S-\frac{4}{3}f\right) \qquad (1)$$

Where $\frac{V}{t}$ = flow in cc per second.
μ = mobility.
f = yield value, dynes/cm.^{2}
S = shearing stress at the wall of capillary in dynes/cm.^{2}
R = radius of capillary, cm.

But as the shearing stress S has the following relation to the pressure P:

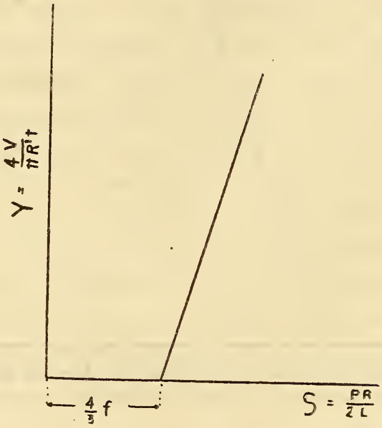
$$S=\frac{PR}{2L}$$

Where P = pressure in grams/cm.^{2}
L = length of capillary, cm.

Then by rearranging the terms in equation (1) we obtain the following equation:

$$\mu=\frac{\frac{4V}{\pi R^3 t}}{\left(\frac{PR}{2L}-\frac{4}{3}f\right)} \qquad (2)$$

Let $Y=\frac{4V}{\pi R^3 t}$



Since the mobility is a constant of the material and by equation (2), $\mu=\frac{Y}{S-\frac{4}{3}f}$ then the ratio $\frac{Y}{S-\frac{4}{3}f}$ is constant for any given plastic

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[9] For the derivation of this equation from Bingham's hypothesis, see Buckingham, Proc. A. S. T. M., 1921, p. 1155; or Bingham, Fluidity and Plasticity, 1922, pp. 223–225.

substance and Y is a straight-line function of S. If Bingham's assumptions are correct, then by plotting the factor Y against S for a particular substance, using several different sized capillaries, all of the resulting straight lines should coincide and the two constants, mobility and yield value, will be independent of the dimensions of the capillary.[10]

This theory is correct for paints and for some very fine-grained fat clays, but does not hold true for coarse-grained lean clays. Experimental data showing this to be true for several clays are presented in Figures 2, 3, 4, and 5.

Experimental.—In order to determine whether or not this theory applies to observations on clay slips, it was necessary to use several different capillaries with the same slip and then compare the results obtained with the different capillaries. As water content is a very important factor in determining the consistency of a clay slip, it is necessary to give this factor with every determination. The factor $\frac{w}{c}$ is used for this purpose and denotes the ratio of water to clay by weight. Time is also a factor in determining the consistency of a clay slip and this was kept constant by carrying out the plastometer tests three days after the slip was made.

Preparation of Samples.—In making up the slip the water and clay were weighed and mixed and the slip pressed through a 150-mesh screen in order to remove the grit that might clog up the capillaries. The slip was put into an air-tight container and allowed to stand for three days. The consistency of a clay slip changes during the first two days, probably due to the swelling of the gel colloids. The consistency changes more in the first day than later periods. The sample was again stirred and part of it was placed in the container of the plastometer for testing. Volume discharge through one capillary at several pressures was determined and these results checked and then tabulated. The capillary was changed and this procedure was followed using several other capillaries. All of the determinations on one slip must be made in one day because of the effect of time on the consistency of the slip.

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[10] This method of analysis of the plastometer results was suggested by Dr. E. Buckingham, of the Bureau of Standards.

By reference to Figure 2 we see that the results on the same slip using different capillaries are not the same and the straight portions of the curves do not coincide. Only a few of the results of tests on the English china clay are presented here. Tests on three slips of the English china clay are shown, using two capillaries in one case and three in the other two cases. Thus we see that in the case of the English china clay there is some effect or effects coming in which were not taken into consideration by Bingham in the development of equation (1).

By reference to Figure 3 we see that in the case of the English ball clay, that with a high water content the deviation is not great and is within the limit of experimental errors. As the water content decreases the results deviate considerably, as is shown by the two curves on the right of the figure. This deviation is too great to assume that it is due to experimental errors. There are other effects coming in that were neglected in the theory. Figure 4 shows the results of tests carried out on D. B. Georgia kaolin. We see that in this case we also have a deviation of facts from theory. In Bingham's original assumptions, on which he based his theory of plastic flow through capillary tubes, no account was taken of an end effect. This end effect we believe is the cause of the deviations between facts and theory. Small end effects are noticeable in the case of viscous substances when they are tested in a viscometer with short capillaries and are caused by shearing of the liquid before entrance into tube. Similar but much larger end effects occur with clay slips, especially with the lean clays. In the case of the clay slips it becomes greater as the water content is decreased. It is less in the case of the more plastic clays, and this may be due to the fact that these clays have a higher colloidal content and this colloidal material acts as a lubricant between the larger particles.

By assuming that this end effect is equal to a resistance which would be produced if the capillary tube were made longer, we are able to reduce these deviations in some cases. One example of this is shown in Figure 5. The same values uncorrected are shown in Figure 4. The ratio $\frac{L}{R}$ is increased by adding a constant to the ratio $\frac{L}{R}$ for both tubes, and the curves are made to coincide. By reference to Figure 5 we see that this constant increases as the water content decreases. In other words, the end effect is greater

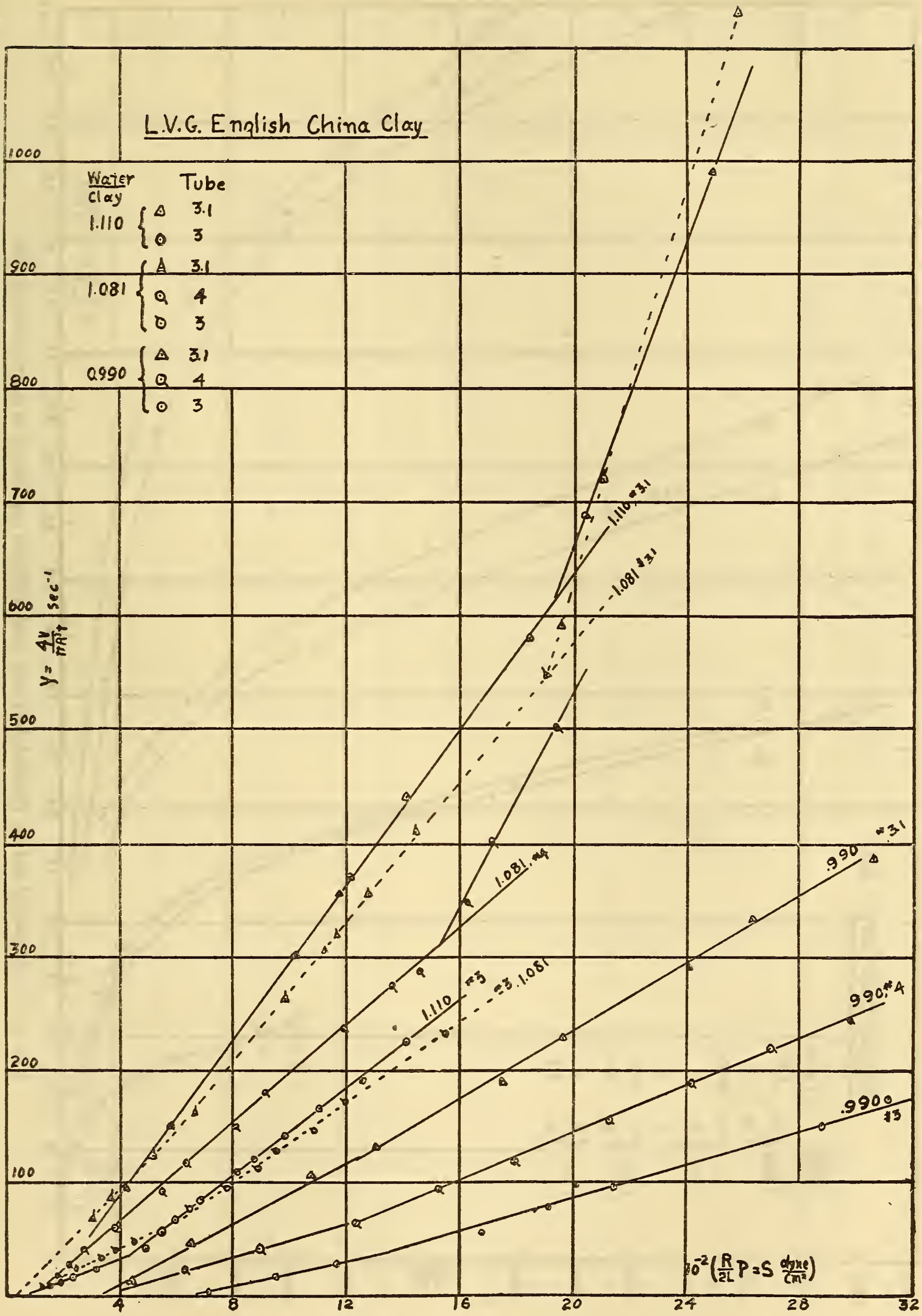

FIG. 2.—*Tests carried out on English china clay with different capillaries at three concentrations.*

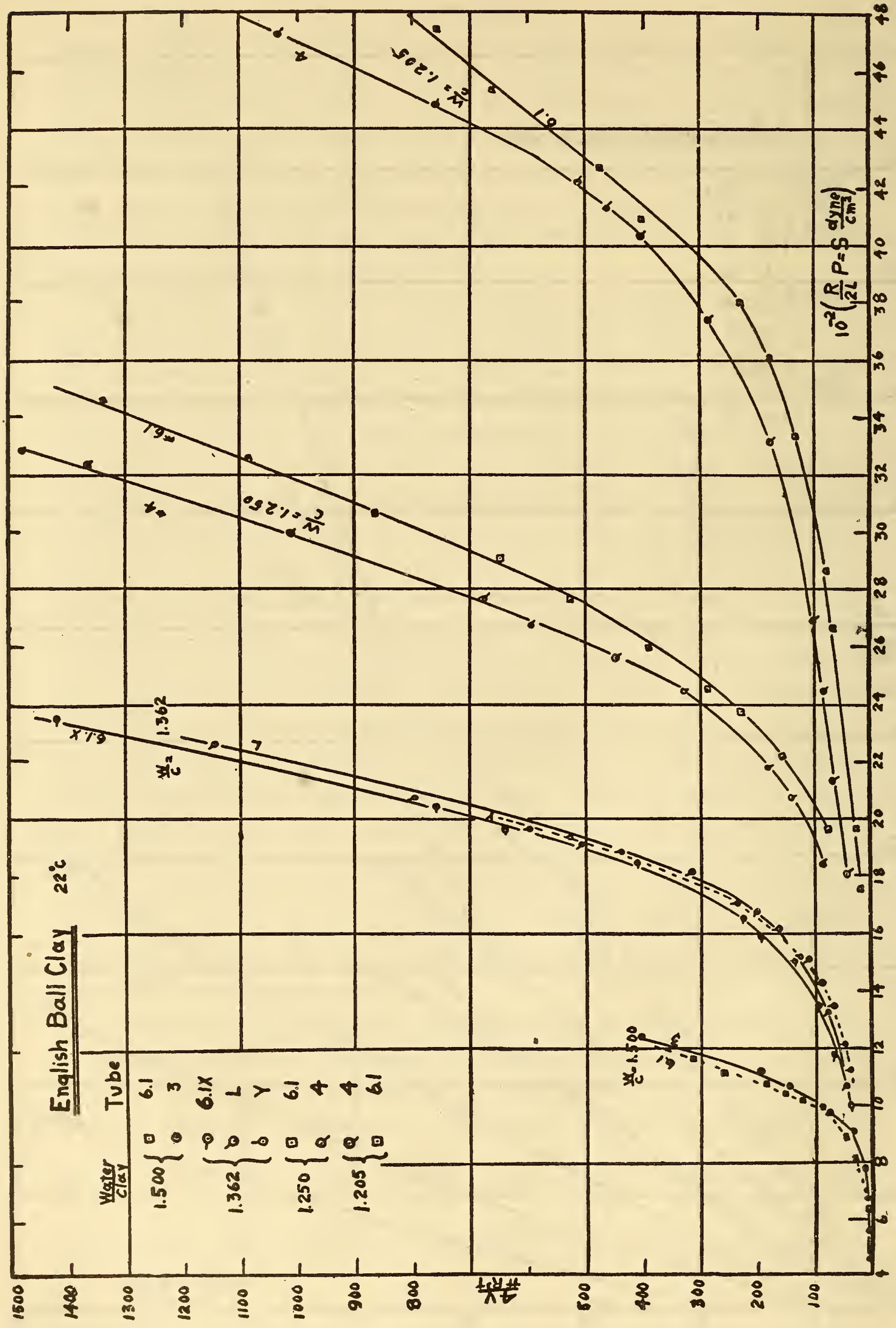

FIG. 3.—*Tests carried out on English ball clay with different capillaries at four concentrations.*

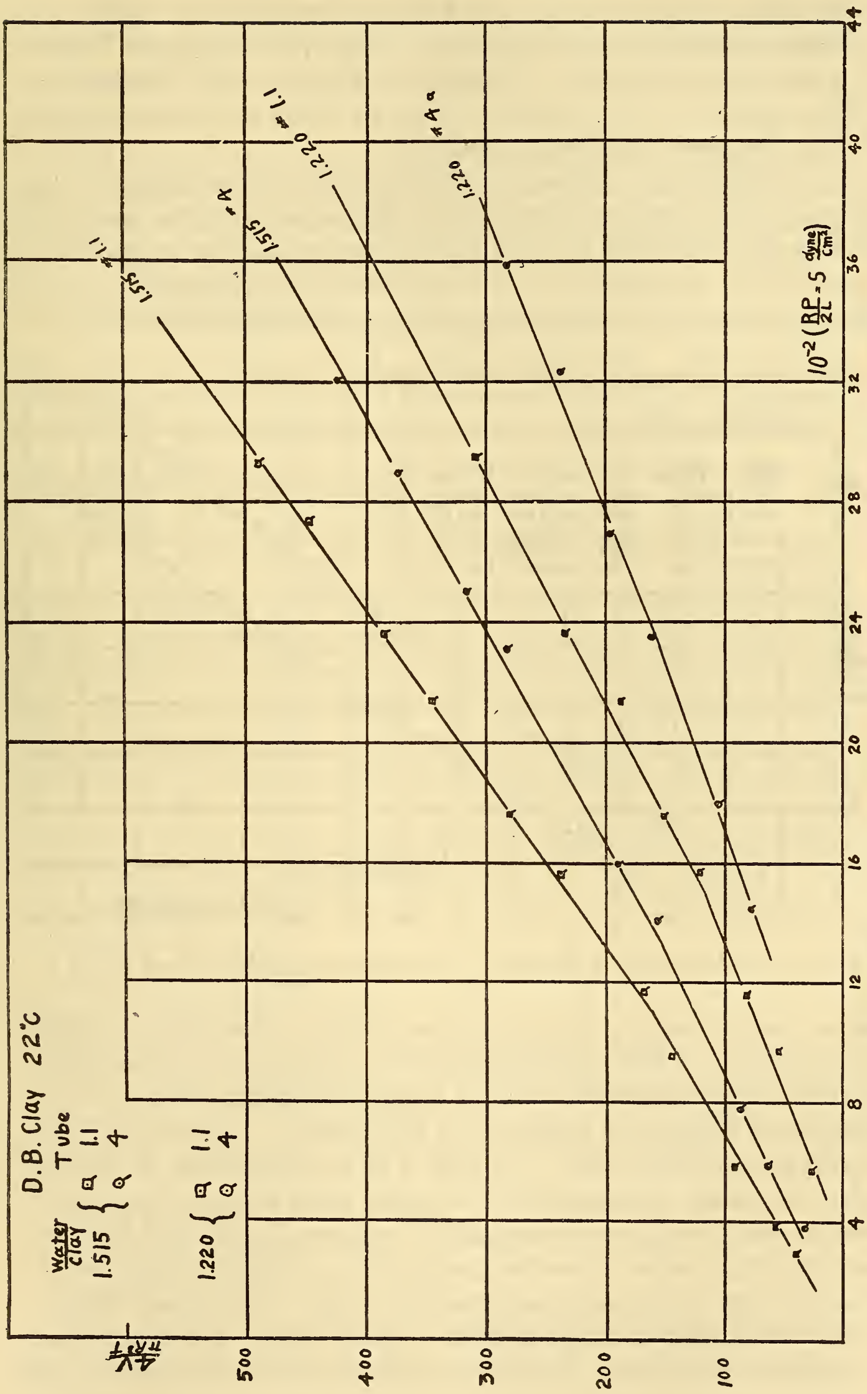

FIG. 4.—*Tests carried on D. B. Georgia kaolin with different capillaries at two concentrations.*

with lower water content. We have not been able to reduce all of these results by this assumption. The values shown in Figure 2 can not be reduced to identical values by this assumption. There seem to be other effects coming in which are not accounted for by Bingham's original assumption.

It is Bingham's contention that the slope of the straight line portion of the pressure-flow curve is determined by the mobility of the material tested and that the intercept of this line on the pressure axis is determined by the yield value of the material. We believe that in the case of these clays an end effect affects both the slope and intercept of the plastometer curves. Therefore, the slope and intercept of the pressure-flow curve will not give us the values of the mobility and yield value of a plastic material unless the end effect and slip can be evaluated or eliminated. Thus far we have not been able to do either. In fact, it is not reasonable to assume that all plastic substances will act alike when tested in the plastometer, and the opposite assumption is supported by the fact that the results of L. Livshis[11] show that cooking fats do not act as paints when tested in the plastometer and that the results of Porst and Moskowitz[12] with corn-product starches are not entirely consistent with Bingham's equations. In the case of cooking fats there seems to be

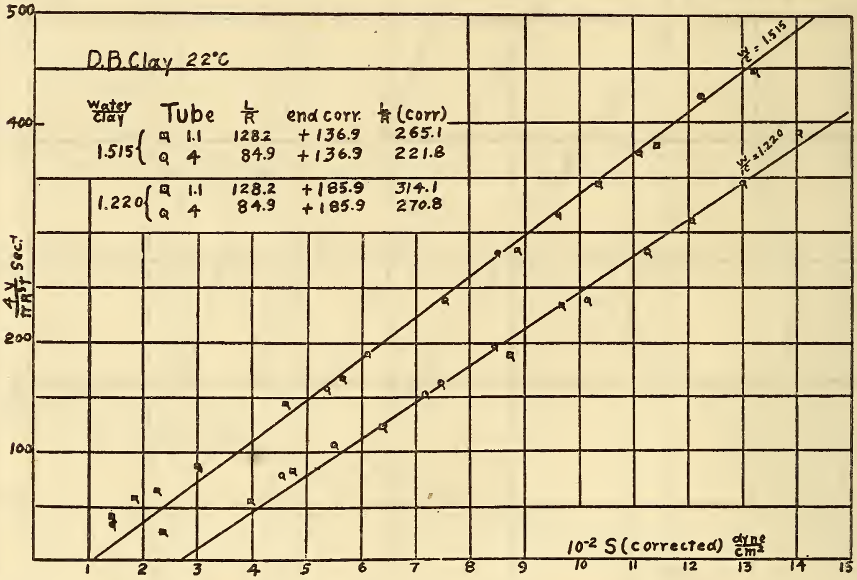

FIG. 5.—*Effect of increasing the ratio* $\frac{L}{R}$. *The uncorrected values are shown in Fig. 4.*

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[11] Unpublished manuscript of L. Livshis

[12] J. Ind. and Eng. Chem. 14, No. 1.

an end effect that affects the slope and intercept of the pressure-flow curves. Bingham's[13] observations on clay slips can not be reduced to absolute values by using the equations which he later derived for paints.

While we have not been able to reduce the observations on clay slips to absolute values or values independent of the capillary, we have obtained some interesting information by using one capillary with several slips and then comparing the results. Figures 6, 7, 8, and 9 show these results.

We will not consider yield value and mobility, for we have not been able to determine these values for clay slips. We will consider the slope and intercept of the pressure-flow curves as obtained by the use of the Bingham plastometer. Given some particular clay and capillary we can vary the slope and intercept of the pressure-flow curve by varying the water content of the clay slip that is to be tested, but for a given clay we can not alter the functional relation between the slope and intercept. This was illustrated in Figures 2, 3, and 4. Figure 6 shows the result of varying the water content of several clay slips until the intercept of pressure-flow curves is the same, using the same capillary in every case. The slopes of the straight line portions of the pressure-flow curves vary over a wide range. It is our belief that, the intercept being the same, the clay giving the steepest slope will be the more plastic. According to this idea of plasticity the relative plasticities of the several clays shown in Figure 6 are as follows:

English ball clay (most plastic).
Tennessee ball clay.
Kentucky ball clay.
Florida plastic kaolin.
South Carolina kaolin No. 1.
South Carolina kaolin No. 2 (least plastic of series).

Figure 7 shows the effect of varying the water content until the slopes of the pressure-flow curves are the same, using the same capillary in every case. The order of relative plasticity in this case is:

English ball clay.
Tennessee ball clay.
Kentucky ball clay.

Figure 8 shows the results of observations on mixtures of clay and bentonite, and clay and flint. Bentonite is a hydrous alumi-

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[13] E. C. Bingham, B. S., Sci. Papers, No. 278; 1916.

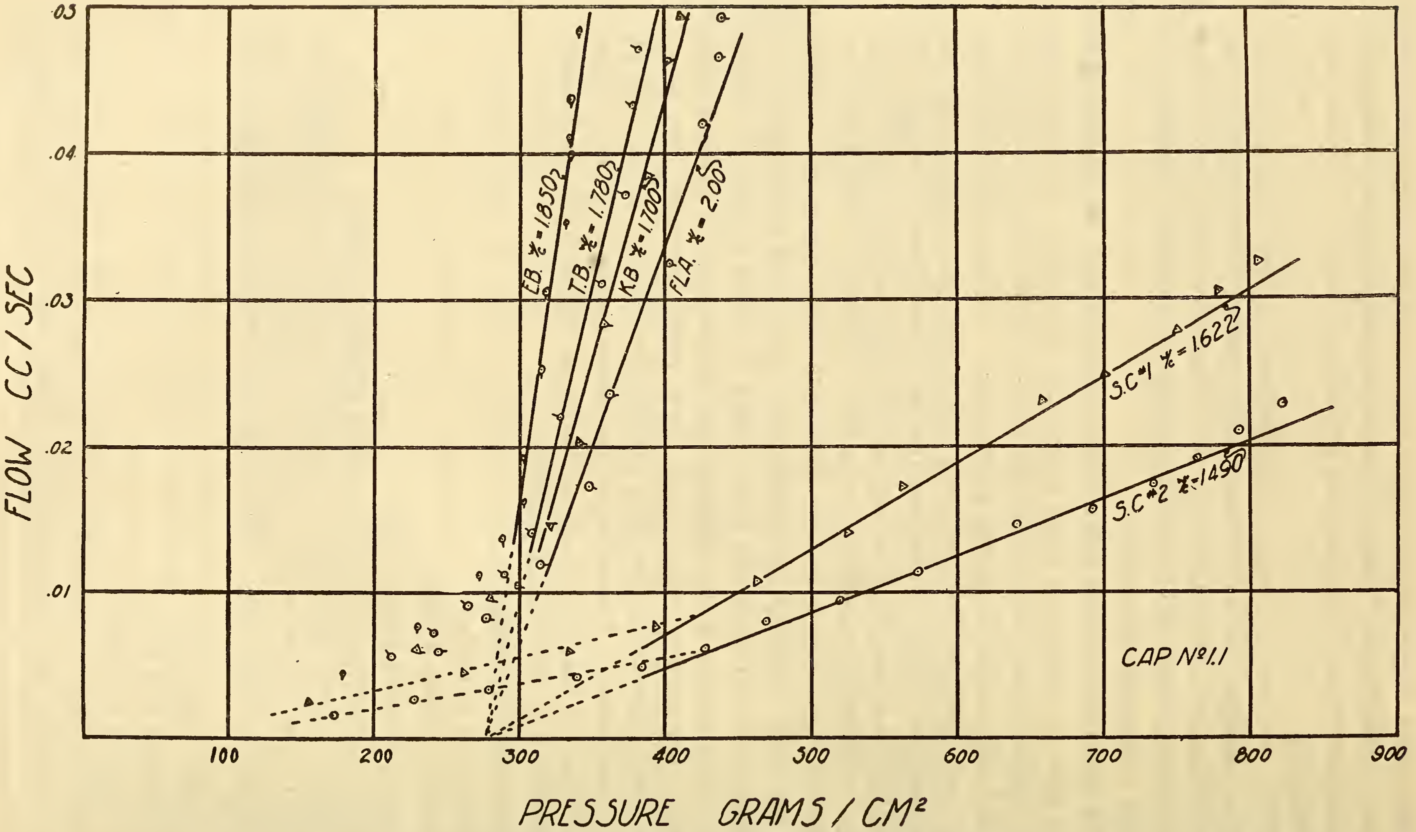

FIG. 6.—*Comparison of different clay slips using the same capillary.*

The concentration has been varied until the pressure-flow lines have approximately the same intercept on the pressure axis.

num silicate in a very finely divided state. When bentonite is added to English china clay the value of the intercept is increased and the slope of the pressure-flow curve is changed very little.

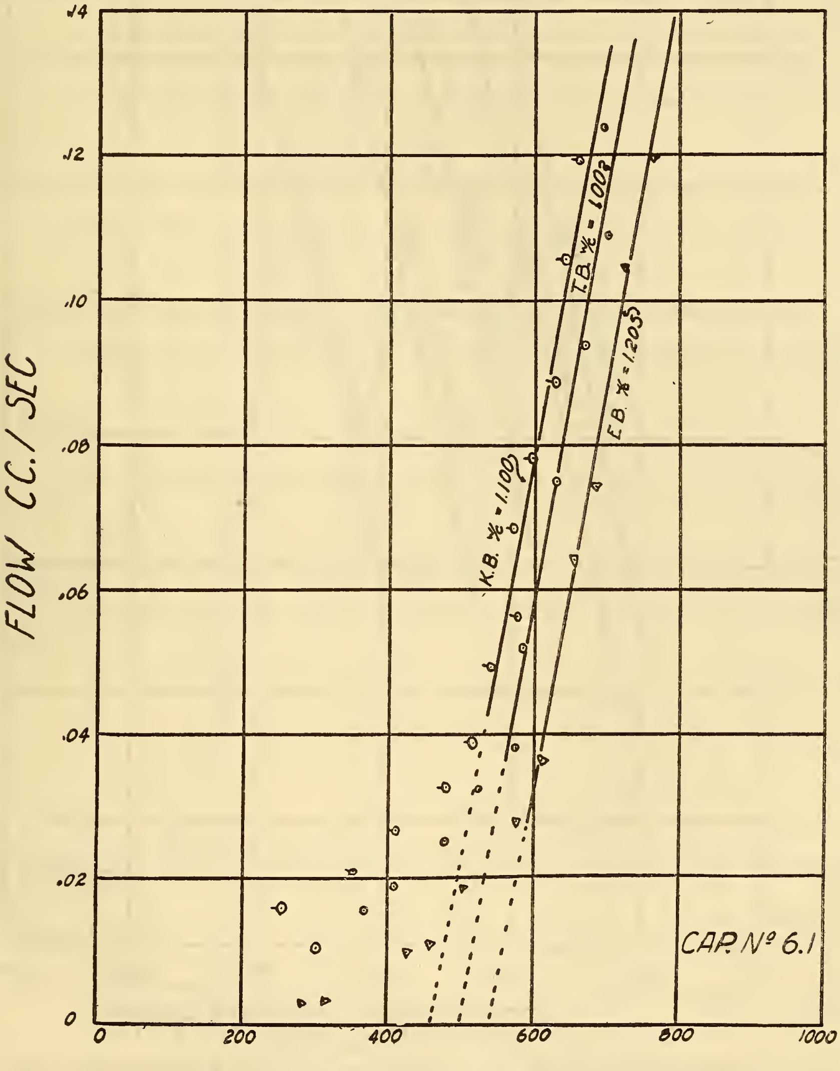

Fig. 7.—*Comparison of different clay slips using the same capillary.*

The concentration has been varied until the pressure-flow lines have approximately the same slope.

In other words, the bentonite increases the plasticity of the china clay. The addition of bentonite to a lean clay increases the colloidal content of the mixture and at the same time increases the plasticity of the material. The addition of flint has the opposite effect. This is shown in Figure 8, where an addition of 10 and 15 per cent flint decreases the value of the intercept.

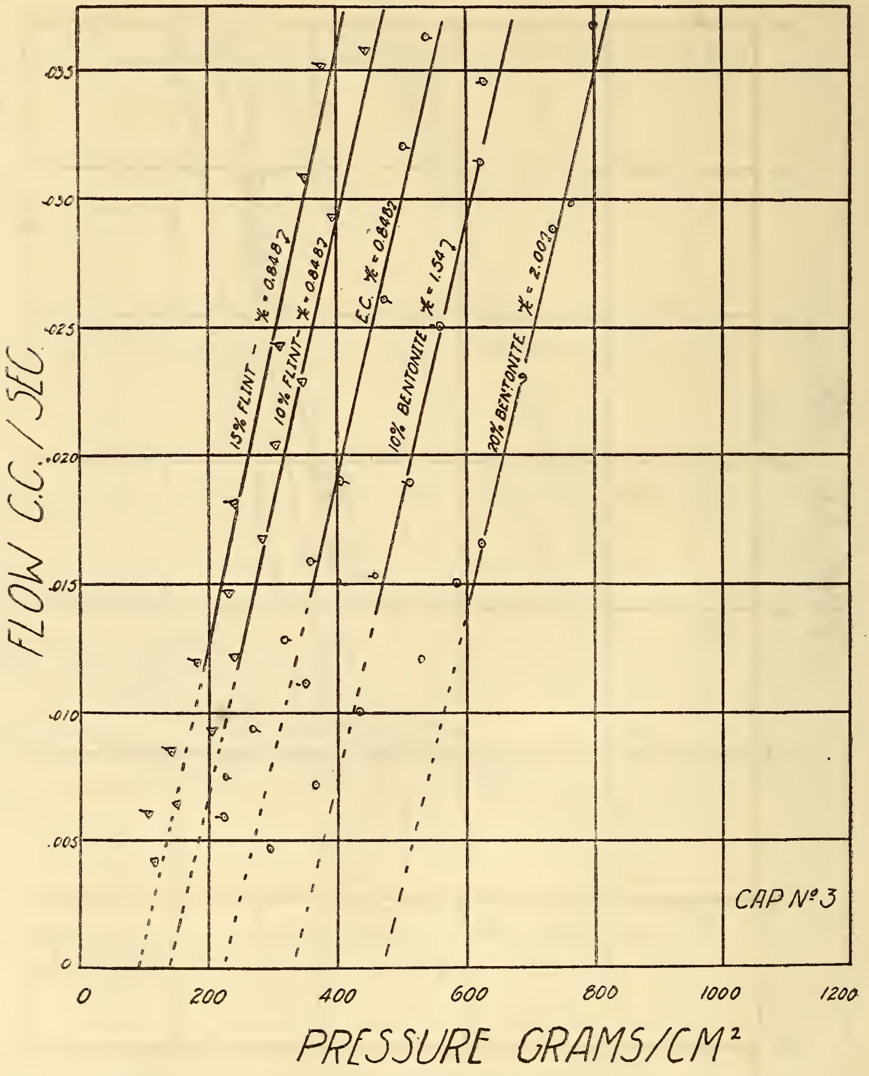

Fig. 8.—*Effect of adding plastic and nonplastic material to an English china clay slip.*

Figure 9 shows the result of adding certain reagents to clay slips. Acids are known to flocculate clays while alkalies deflocculate clays. Alum acts like an acid in this respect and we see that the addition of alum to a slip increases the intercept, or, in other words, increases the plasticity, since the slope is about the same as without the alum; alkalies have the opposite effect, as is shown by the figure. The addition of certain organic colloids, such as hot starch, gum, tannin, and gelatin to a clay slip reduces the value of the intercept and causes the slope of the pressure flow curve to be steeper. This action is shown in Figure 9.

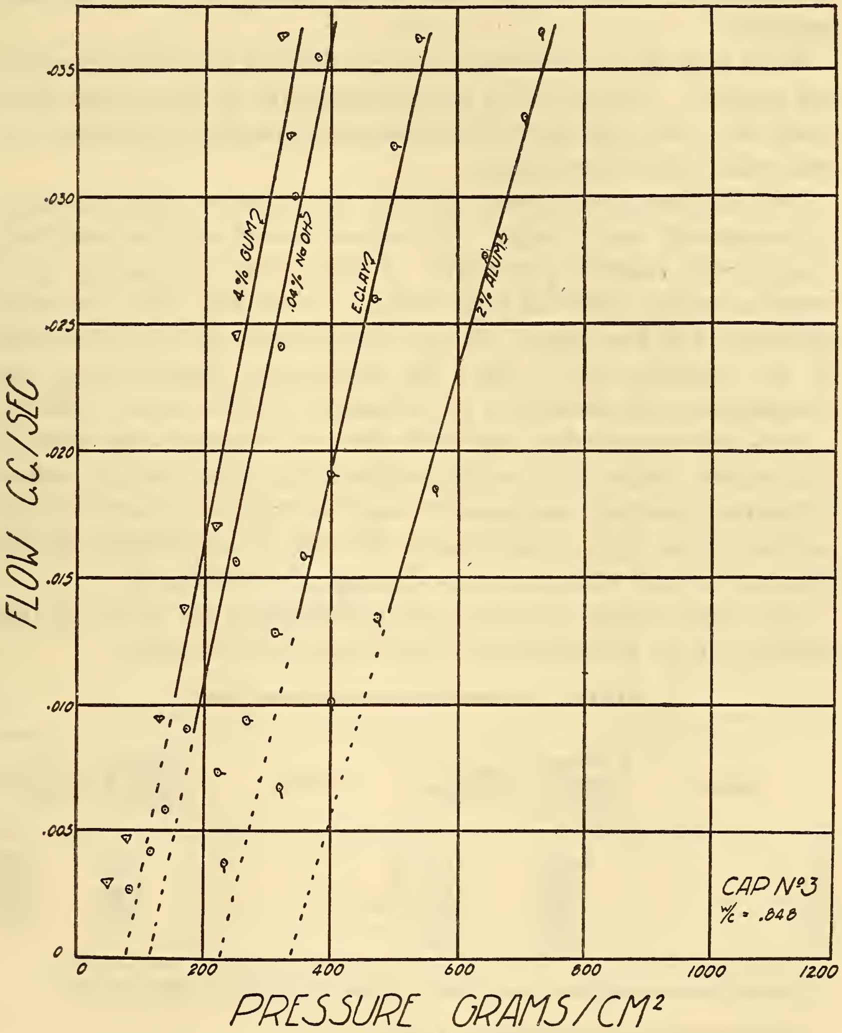

FIG. 9.—*Effect of adding flocculating and deflocculating agents to an English china clay slip.*

IV. CONCLUSIONS.

It is evident in surveying the methods brought forward for measuring this fundamental property—plasticity—that none of the methods is entirely satisfactory. It seems that plasticity is a resultant of two factors or perhaps more.

If it be true that plasticity is determined by two or more elements or components, then in comparing the relative plasticity of several clays it is necessary to have all but one of the components constant and the plasticity will vary in some manner with this one component. This was illustrated when dealing with the Bingham method.

With most of the methods it is very difficult to obtain concordant results. On account of the heterogeneity of the system clay-water it is very difficult to formulate mathematical equations that will satisfy the observations.

The Bingham plastometer enables us to detect slight changes of consistency in clay slips. We believe we are able to determine roughly the relative plasticities of clays when comparing plastometer curves over the same range of flow and with the same capillary, but the results are not independent of the dimensions of the capillary used. Thus the results are empirical and are comparable only when they are obtained with the same capillary.

It is highly probable that with the use of some other type of plastometer (other than capillary-tube type) that absolute values of the two plasticity components could be determined but with the capillary-tube type of plastometer the case is complicated by the presence of such phenomena as slippage, end effects, etc.

The writer wishes to express his indebtedness for advice in this work to Dr. E. Buckingham, of the Bureau of Standards.

TABLE 1.—Dimensions of Capillaries Used.

Number.	Average radius[1] in centimeters at 22° C.	Length in centimeters at 22° C.
1.1	0.03794	4.864
2.1	.12897	5.163
3.1	.03894	4.419
5.1	.05492	5.029
6.1	.05857	4.612
3	.06118	3.857
4	0.04547	3.856
S	.12754	16.705
Y	.10662	12.509
6.1X	.05874	9.001
L	.07563	11.620

[1] Calculated from major and minor axes of tube; cf. Zeitschr. f. physik. chem., 80, p. 683; 1912.

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