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RELATION BETWEEN MOISTURE CONTENT AND FLOW-POINT PRESSURE OF PLASTIC CLAY

By Ray T. Stull and Paul V. Johnson

ABSTRACT

A study was made to determine the relation between moisture content and "flow-point pressure" of a Maryland clay, a Georgia kaolin, and a Kentucky ball clay. Their moisture contents ranged from 17 to 34, 24 to 40, and 26 to 52 percent, respectively, and the flow-point pressures ranged from 8 to 400 lb/in². The clays were extruded from a knife-edged die by means of a cylinder and a mechanically driven piston. The flow-point pressures were determined on the average of 18 load readings for each test, and the percentages of moisture determined on a composite sample of 18 portions of the clay column. Tests were also made with two extrusion cylinders of different sizes and three dies of different diameters in a study of the effect of different cylinder and die sizes upon the flow-point load.

CONTENTS

I. INTRODUCTION

When pressure is applied to plastic clay in the mold or die to form a product of uniform structure, the moisture content and the applied pressure must be adjusted so that the transmitted pressures within the clay will cause it to flow and fill the mold or die completely.

Considerable work has been done concerning the application of pressure to clays of different moisture contents in connection with studies of plasticity, and on the effect of molding pressure upon the physical properties of the dry and kiln-fired products. However, very little work has been done and information is meager concerning the relation between moisture content of clay and the corresponding pressure required to produce flow.

Bleininger and Ross [1] investigated a number of clays to determine the flow pressures required for different moisture contents. The clays

[1] *The flow of clay under pressure*, Trans. Am. Ceram. Soc. **16**, 392 (1914).

were extruded from a cylinder through a circular knife-edged orifice by means of a hand-operated testing machine and the load readings noted when movement of the clay at the orifice was observed. Moisture contents of the clay were plotted against corresponding flow pressures and their conclusion was that "The curves themselves are hyperbolic in character, as is to be expected." However, no equation was given to express the relation between moisture content and flow pressure.

MacGee, White, and Klinefelter [2] determined the flow pressures of a number of clays and shales with different moisture contents in a study of the effect of fine grinding on the flow pressure. Although no mention was made of the nature of the curves they obtained by plotting flow pressures against moisture contents, they are apparently hyperbolic in character.

In a previous investigation [3] over 300 determinations were made of the moisture contents and corresponding flow pressures of a Maryland clay. After the data had served their purpose, they were plotted, and the curve obtained indicated that the relation was hyperbolic in character, which is in agreement with the conclusion of Bleininger and Ross.[4] Inasmuch as the moisture content of the clay ranged only from 24 to 26 percent by weight of the dry clay, the data lacked sufficient spread for development of the equation for the curve and a new investigation was, therefore, undertaken in which the water content of the clay was varied over a range such that the clay was too soft at one extreme and too stiff at the other for practical molding purposes. Data were also obtained with different sizes of extrusion cylinders and dies to obtain an indication of their effect upon the nature and magnitude of "flow-point load." [5]

II. CLAYS INCLUDED AND SCOPE OF THE INVESTIGATION

Three clays representing a wide range in plasticity were included in the investigation. These were a Maryland clay, a Georgia kaolin, and a Kentucky ball clay. The moisture content of the Maryland clay was varied from 17 to 34 percent by weight of the dry clay. For the kaolin the range was from 24 to 40 percent and for the ball clay from 26 to 52 percent. The flow-point pressures ranged from approximately 8 to 400 lb/in.^{2}

III. EQUIPMENT AND TEST METHODS

1. EXTRUSION APPARATUS

The clay in the moist condition was placed in a cylinder provided with a die and piston, and pressure to produce extrusion of the clay was applied by means of a motor-driven screw-power beam-and-poise testing machine of 2,000-pounds capacity, the assembly for a test being shown in figure 1.

The extrusion cylinder (shown in fig. 2) used in obtaining the flow-point pressures was fitted with a piston having an area of 4 in.^{2} attached to a push rod. The exit end of the cylinder was provided

[2] *Properties of some Ohio red-firing clays*, J. Am. Ceram. Soc. **18**, No. 5, 158 (1935).
[3] Paul V. Johnson and R. T. Stull, *Performance of a hollow-ware extrusion machine with different combinations of augers, spacers, and dies*, J. Research NBS **14**, 711 (1935) RP798.
[4] See footnote 1, p. 329.
[5] See p. 332 for definitions of "flow-point load" and "flow-point pressure."

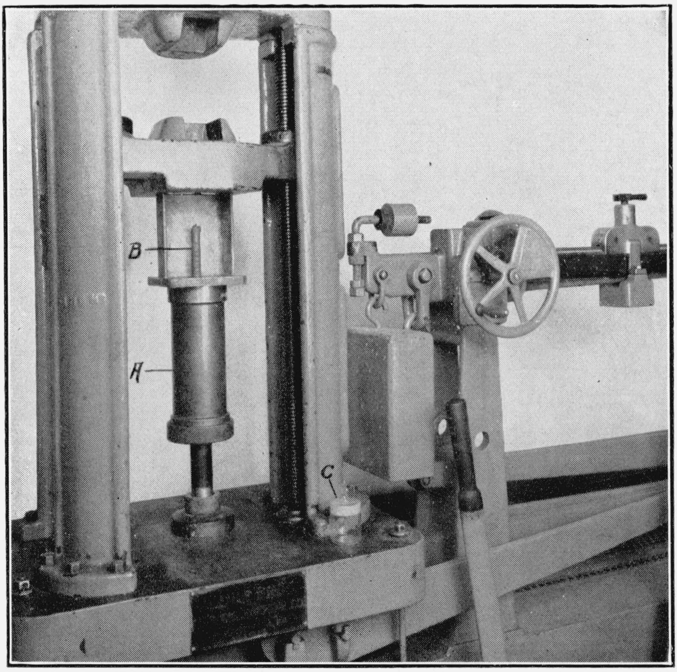

FIGURE 1.—*Machine used for determining flow-point pressures.*

A, Extrusion cylinder; *B*, clay column; and *C*, weighing bottle.

with a removable head containing the die, which consisted of a hardened tool-steel knife-edged orifice of ½-in. diameter.

Two extrusion cylinders and three dies, all of different dimensions, were used for determination of the effects of their variable sizes upon the flow-point load. The cylinders were 1½- and 2⁹⁄₃₂-in. inside diameter, respectively, and the dies were ¼, ⅜, and ½ in. in diameter. Thus, six different combinations of cylinder and die were available.

2. PREPARATION OF THE CLAY

In preparing clay specimens of varying water content, a batch of 20 pounds of clay with sufficient water added to form a soft mass was kneaded for 2 hours in a closed pug mill and allowed to stand in the mill overnight. The following morning the cover was removed and the pug mill operated slowly and continuously while evaporation of moisture proceeded at room temperature.

Before the first clay sample was taken, the mill was allowed to operate for about 10 minutes to redistribute any moisture which may have evaporated and recondensed in the mill during the night, and also to overcome the "thixotropic" stiffening of the clay.

A portion of the clay was removed for each successive test at regular intervals as evaporation progressed, so that data were obtained for small differences in moisture content over the range from a very soft to a very stiff condition of the clay.

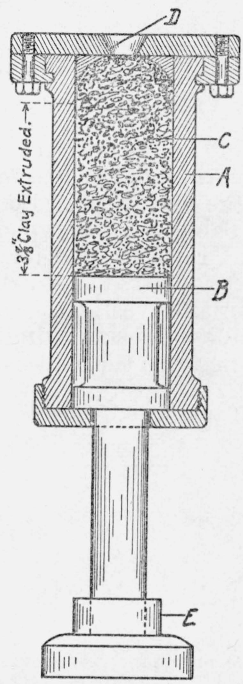

FIGURE 2.—*Sectional view of extrusion cylinder.*

A, barrel; *B*, piston, 4-in.² head; *C*, charge of moist clay; *D*, knife-edged die, ½-in. diameter, and *E*, rubber ring-pad.

3. TEST PROCEDURE

The clay was transferred from the pug mill to the extrusion cylinder in small portions, each being thoroughly tamped until the cylinder was full. The clay was then made level with the top of the cylinder, and the die attached. The cylinder with its charge of clay was immediately placed in the testing machine with the die exit upward. The push rod and piston remained stationary and the movable head of the testing machine carried the cylinder downward at a rate of 0.7 in./min.

In starting the extrusion mechanism from rest, the load would build up until movement of the clay through the die began. As the constant rate of piston displacement continued, the rate of extrusion of the clay increased with the load until both became fairly stable.

When about 4 to 5 in. of the clay column had issued, the testing machine was stopped and in approximately 3 to 5 seconds the clay column had virtually ceased flowing, and the load reading was immediately taken. The load required to start or to maintain extrusion is higher and less consistent than the load observed as the rate of extrusion approaches zero after stopping the testing machine. Therefore, the load obtained under the latter condition was adopted in this investigation and is called "flow-point load," and the pressure in pounds per square inch of piston head is called "flow-point pressure."

For determination of the moisture content, a section of the freshly extruded clay column about ½ in. long was taken next to the die and placed in a weighing bottle. The procedure of taking a load reading and a corresponding portion of the clay column for the moisture determination was repeated 18 times over a piston travel of 3⅞ in., thus leaving about 1⅛ in. of clay in the cylinder. Each flow-point pressure was, therefore, obtained from the average of 18 load readings and the moisture content from a composite sample of 18 corresponding portions of the clay column.

IV. RESULTS

1. EFFECT OF VARIABLE DIE AND EXTRUSION CYLINDER SIZES AND DISTANCE OF THE PISTON HEAD FROM THE DIE ON THE FLOW-POINT LOAD

The 18 load readings observed during a test showed considerable variation, the reason for which was not at first apparent, inasmuch as the load readings could be made within an accuracy of ± 1 percent. Table 1 shows typical variations in load readings for three tests taken at random, one for each clay. The reason for this variation in the consecutive load readings became apparent when data were obtained in an investigation of the effect on the flow-point load of variable die and extrusion cylinder sizes and distance of the piston head from the die when the load reading was observed.

TABLE 1.—*Maximum, minimum, difference, and average of load readings of a test taken at random for each clay*

Load	Clays and flow-point loads		
	Maryland clay (test 23)	Georgia kaolin (test 108)	Kentucky ball clay (test 68)
	Pounds	*Pounds*	*Pounds*
Maximum	444	322	390
Minimum	360	244	318
Difference	84	78	72
Average	391	287	337

In figure 3 the flow-point loads are plotted against corresponding distances of the piston head from the die when the load readings were taken for six tests made with the Maryland clay, in which the moisture content was maintained substantially constant. The plots indicate that the loads decrease in a "wave-like" manner as the piston moves toward the die; in general, suggestive of "sine waves" with reference to sloping axes. The relation of change in the slope of the axis to change in the size of the die was not established, but it does not appear to be a simple linear relation.

The wave-like changes in load produce an oscillation frequency of slightly more than 1 cycle for the length of piston displacement between the first and eighteenth load readings. This wave-like variation in load is also observed when clays are extruded at a constant rate of flow by means of a piston, cylinder, and die, when the load readings are observed at regular time intervals.[6]

The results plotted in figure 3 indicate that the magnitude of the flow-point load is influenced by the size of extrusion cylinder, size of die, and distance of the piston head from the die when the load read-

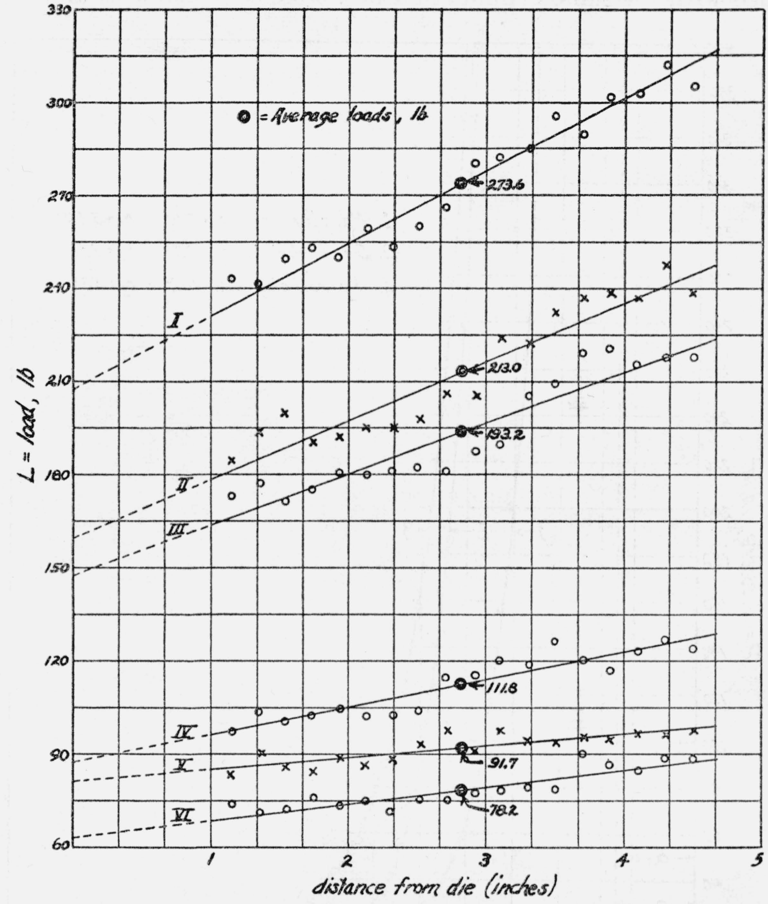

FIGURE 3.—*Effect of different extrusion cylinder and die sizes and distance of the piston head from the die upon flow-point load.*

Curves I, II, and III, extrusion cylinder, 2⁹⁄₃₂ in. in diameter with ¼-, ⅜-, and ½-in.-diameter dies, respectively.
Curves IV, V, and VI, extrusion cylinder, 1½ in. in diameter with ¼-, ⅜-, and ½-in.-diameter dies, respectively.

ing is observed. In general, the load decreases with (a) decrease in diameter of the extrusion cylinder, (b) increase in diameter of the die, and (c) decrease in distance of the piston head from the die. Test results are, therefore, only comparable when using a definite equipment under a definite set of experimental conditions.

[6] R. T. Stull, *Wear of dies for extruding plastic clay*, BS J. Research **12**, 501 (1934) RP675. See p. 509 and fig. 5.

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2. RELATION BETWEEN FLOW-POINT PRESSURE AND MOISTURE CONTENT

In the tests for the determination of the relation between moisture content and flow-point pressure of the clays, the pressures were obtained with the same cylinder of 4-in ^{2}. cross-sectional area and die of

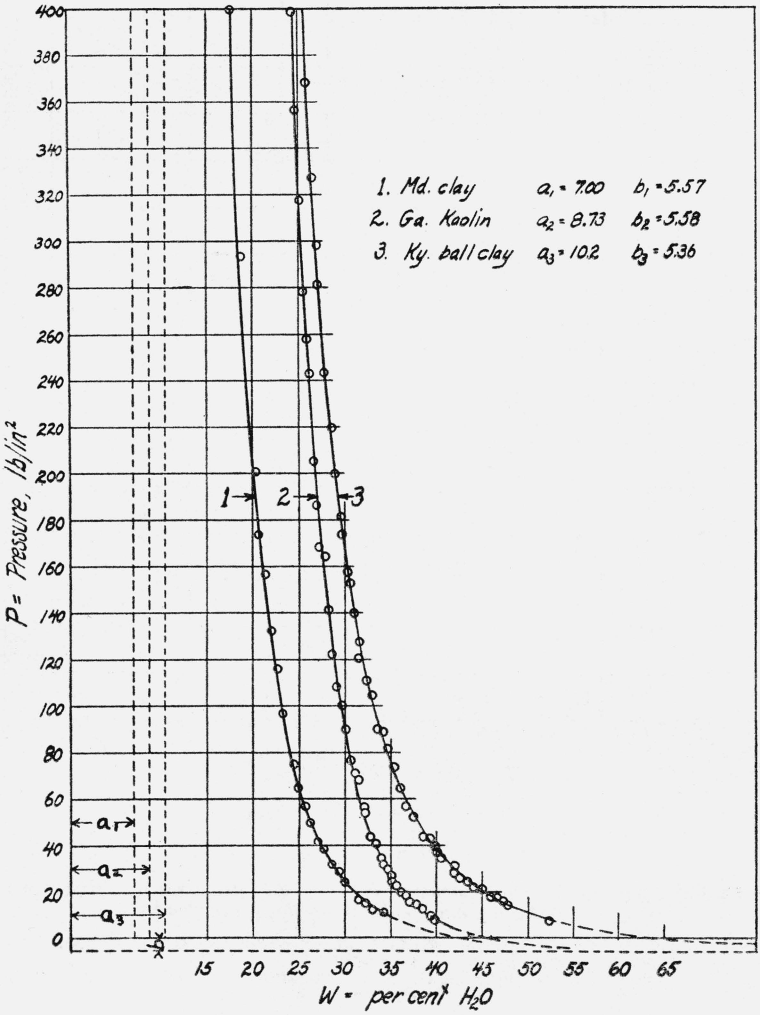

FIGURE 4.—*Relation between flow-point pressure (lb/in ^{2}.) of piston head and moisture content of the clays, in percent, of the dry weight of the clay.*

½-in. diameter operated under the same experimental conditions; hence the results are comparable among themselves.

The curves obtained by plotting the average flow-point pressures against corresponding moisture contents of the clays are shown in figure 4. They are hyperbolic in character and, according to the experimental system employed, the data indicate that the relation is of the form:

$$(p+b)(w-a)^m=K, \text{ or } p=\frac{K}{(w-a)^m}-b \tag{1}$$

in which

w = moisture content in percent of the dry weight of the clay

p = flow-point pressure in lb/in^2., of piston head, and

a, b, m, and K = constants.

TABLE 2.—*Values of the constants of equations 1 and 2*

Clay	a	b	m	K	Moisture content [1] when $p=0$
Maryland clay	7.00	5.57	3.50	174×10^4	44.15
Georgia kaolin	8.73	5.58	4.95	341×10^6	46.24
Kentucky ball clay	10.20	5.36	3.37	411×10^4	65.95

Average of b values=5.50, approximately

[1] In percent of dry weight of clay.

Comparison of the values of the constants determined for the clays studied may be seen in table 2.

Although the extrapolation of the curves outside of the region covered by the data may not be justifiable, it is helpful in understanding the significance of the constants obtained from the data.

The value of asymptote a indicates the content of moisture with which the hard dry clay must be imbued before it becomes amenable to flow (theoretically) at infinite pressure.

When $p=0$, then

$$w=\left(\frac{K}{b}\right)^{1/m}+a \tag{2}$$

in which w represents the percentage of moisture content of the clay at which it would flow (theoretically) under the slightest pressure.

The values for a, m, and K although constant for a definite clay, are different for different clays, and b is evidently constant for all three clays. The values of b obtained experimentally for the Maryland clay and the Georgia kaolin are substantially the same, whereas it is slightly less for the Kentucky ball clay. The average value of b, however, is approximately 5.50.

At moisture contents of the clay near the value w (eq 2), a decrease of 1 percent in moisture causes only a slight increase in the flow-point pressure, but when the moisture content approaches the value of a, a very small decrease in moisture causes an enormous increase in the flow-point pressure.

3. COMPARATIVE MOISTURE CONTENTS OF THE CLAYS AT THE SAME FLOW-POINT PRESSURES

It is well known that plastic clays highly colloidal in nature require more moisture than the less plastic clays for proper workability. This relation may be seen by comparison of the moisture contents of the three clays at the same flow-point pressures. In table 3 are given the moisture contents of the clays at flow-point pressures of 10 and 200 lb/in². The difference of 190 lb in flow-point pressure (between 10 and 200 lb) results from a difference in moisture content of 14.45 percent for the Maryland clay, 12.34 percent for the Georgia kaolin, and 21.53 percent for the Kentucky ball clay.

TABLE 3.—*Moisture contents of dry weight of the clays at two different flow-point pressures*

Clays	Moisture content at 10 lb/in²	Moisture content at 200 lb/in²
	Percent	*Percent*
Maryland clay	34.70	20.25
Georgia kaolin	39.13	26.79
Kentucky ball clay	50.71	29.18

4. FLOW-POINT PRESSURES FOR SOFT- AND STIFF-MUD CONSISTENCIES

The method most generally employed in both factory and laboratory for judging the desired consistency of a clay for molding, is by appearance, feel, and behavior in molding. Using this method for judging the proper consistencies for the equipment used, it appears that the so-called soft-mud condition of the clays was obtained at a flow-point pressure of approximately 20 lb/in². and the stiff-mud condition at about 80 lb/in².

A difference of 1 percent in moisture content at the soft-mud condition causes a difference in flow-point pressure of approximately 4 lb/in²., while the pressure difference at the stiff-mud condition is about 22 lb/in². for a difference of 1 percent of moisture.

V. CONCLUSIONS

From the data obtained under the experimental conditions herein described, the following conclusions seem justifiable:

1. The flow-point load decreased with decrease in diameter of extrusion cylinder, with increase in diameter of die, and with decrease in distance of the piston head from the die.

2. The plot of the flow-point load against corresponding distance of the piston head from the die when the load reading is observed produced a curve similar to a "sine wave" with reference to a sloping axis.

3. The relation between flow-point pressure and percentage of moisture content of the clays can be expressed by the equation $(p+b)\,(w-a)^m=K$,
where

p=flow-point pressure in lb/in². of piston head
w=moisture content of the clay in percent of the dry weight of the clay, and
a, b, m, and K=constants.

The values of a, m, and K were constant for a definite clay but different for different clays, while asymptote b was substantially constant for all three clays. The asymptote a represents the percentage of uniformly distributed moisture in the clay before it becomes amenable to flow at theoretically infinite pressure.

4. When $p=0$,

$$w=\left(\frac{K}{b}\right)^{1/m}+a,$$

in which w represents the percentage of moisture of the clay at the transition point where, theoretically, the slightest pressure would cause flow.

5. The soft-mud consistency of the clays was obtained at a flow-point pressure of about 20 lb/in^2., and the stiff-mud consistency at approximately 80 lb/in^2. A difference in moisture content of 1 percent for the soft-mud consistency caused a difference of approximately 4 lb/in^2. in flow-point pressure, and a like difference in moisture for the stiff-mud consistency caused a difference of approximately 22 lb/in^2. in flow-point pressure.

WASHINGTON, January 16, 1939.