THE EFFECT OF RATE OF SHEARING STRAIN ON THE SHEAR STRENGTH OF FRESHLY MIXED CONCRETE

by

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ABSTRACT

This thesis describes attempts to measure the shearing strength of freshly mixed concrete and relate it to standard "Workability" tests.

The study is a continuation of investigations made by Mr. Li Yang in 1963-65 at the University of British Columbia. Yang measured the shearing strength of eight mixes at one velocity and obtained a type of "viscosity" at that speed. This thesis broadens the investigation to shear strength of eight different mixes at seven different speeds.

The shear box developed at the University of British Columbia and used by Mr. Yang was used in these further investigations and the shapes of the shear vs. rate of shearing strain or "viscosity" curves for eight different mixes was partially developed.

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INTRODUCTION

Concrete has to be strong enough to withstand the stresses to which it is subjected and durable enough to withstand the moisture and temperature changes of its environment. To meet these requirements the quality and in some cases the quantity of the ingredients has to be carefully specified along with a minimum strength requirement for standard sample cylinders formed, cured and tested in a standard manner.

The strength properties of a given concrete mix can vary widely with the actual density that is achieved in the forms. It is therefore customary to include in the specifications a standard for "consistency" or "workability" which will enable the concrete to be compacted or consolidated in the forms to a density which will produce the desired strength properties. It is vital that the "consistency" or "workability" be such that the concrete can be transported, placed, consolidated and finished economically and without segregation.

A concrete that can be transported, placed, consolidated and finished satisfactorily is said to be "workable", but to say merely that "workability" determines the ease of placing and the resistance to segregation is too loose a description of this vital property of concrete. Also, the desired "workability" depends on the means of compaction available, the size and shape of the form and the amount of reinforcing steel. For these reasons "workability" should be defined as a physical property of concrete alone without reference to the circumstances of a particular type of construction.

To obtain a satisfactory definition it is necessary to consider what happens when concrete is compacted. Whether compaction is achieved by tamping or vibration, the process consists essentially of elimination of entrapped air from the concrete until it has achieved as close a configuration as is possible for a given mix. The work done is used to overcome internal friction between individual particles and surface friction with the surfaces of the form and reinforcement. These two can be called internal friction and surface friction respectively. In addition, some of the work done is used in vibrating the form and parts of the concrete which have already been fully consolidated. Thus the work done consists of a "wasted" part and "useful" work done to overcome internal and surface friction. Glanville, Collins & Mathews of the Road Research Laboratory have defined "workability" as, <u>the amount of useful internal work necessary to produce full compaction</u>.

The other term used to describe the state of fresh concrete, "consistency" is often taken to mean the degree of wetness; within limits wet concretes are more workable than dry concretes, but concretes of the same consistency may vary in workability. To avoid confusion the term "workability" as defined above will be used throughout this thesis.

STANDARD TESTS

The desired workability of concrete can at present be specified or controlled by a number of standard tests.

a. The Slump Test

This test is used extensively on site work all over the world. It measures the "slump" of a 12 inch high frustum of a cone of concrete when the mould in which it was fully consolidated is removed. The force acting on the concrete is that due to gravity and the amount of slump depends on the ability of this force to do work against the internal friction of the concrete. Stiff mixes have zero slump, so that in the rather dry range differences in workability cannot be detected. In the 1 inch to 5 inch slump range differences in workability are quite apparent though some authorities claim the slump test is super sensitive to slight changes in water content. At very high slumps there is considerable horizontal movement of the mass though the force is vertical and the results obtained are not very satisfactory. The slump test is not very reproducible and varies a great deal with who does it and how the concrete is placed and compacted in the cone.

b. The Kelly Ball Test

The Kelly Ball is made of steel, is 6 inch in diameter and weighs 30 lbs. The amount it settles into the wet concrete when multiplied by two approximates the "slump". It is useful on the site and can be used in a concrete buggy or in forms. It is not satisfactory for very dry or very wet concrete, but is sensitive to about the same range of workability as the slump test. It can be used with larger sized aggregate. The force on the concrete is the vertical force due to gravity but for settlement into the concrete mass some horizontal movement has to take place.

c. The Flow Test

The Flow Test is made by jogging a specified pile of concrete formed in a low 10 inch diameter truncated cone mould on a metal flow table which is raised and dropped 1/2 inch 15 times. The flow percentage is the spread of the pile expressed as a percentage of the original diameter. For small maximum size of aggregate it is considered to be more accurate than slump for some ranges of workability and is used mostly in the laboratory. Again it is unsatisfactory for very dry or very wet mixes and results vary considerably with the operator's skill in compacting the concrete in the mould. Almost all movement of the concrete is horizontal though the force done by gravity and the "drops" is vertical.

d. Power's Remolding Test

Power's Remolding Test measures the amount of work (in 1/4 inch vertical drops) in addition to gravity required to change the shape of a mass of concrete from that of the standard slump cone to that of a 12 inch diameter cylindrical container. It is not widely used even in laboratories though it gives quite good results for all but very dry mixes. Its principle of measuring the amount of work necessary to change from one shape to another appears to be a reasonable approach to measuring workability. It can not be used with large aggregate and it suffers from the same weakness as the slump and flow tests regarding the non-uniformity of compaction achieved in the slump cone.

e. The Vebe Test

The Vebe Test is almost identical to Power's Remolding Test but the work is supplied by a vibrating table and the time for the change of shape to take place is measured in seconds. The "inner ring" used in Power's apparatus is also omitted. With the Vebe apparatus the possibility exists that different aggregate sizes with different natural frequencies may respond to the vibration in different ways. The apparatus works satisfactorily with very dry as well as ordinary mixes.

f. The Compacting Factor Test

The Compacting Factor apparatus was developed to detect differences in workability of low and no slump concretes and also to remove the human error of different degrees of compaction when filling a mould. With this apparatus there are two conical hoppers with trap doors and a standard 6 inch x 12 inch cylinder mould. Concrete is loaded into the top hopper and dropped a fixed distance into the middle hopper with the assumption that in this position the amount of compaction is always the same. The concrete is then allowed to fall freely into the 6 inch x 12 inch standard cylinder mould which it fills to overflowing. The excess is struck off and the cylinder with contents weighed.

The net weight divided by that of a cylinder full of the fully compacted concrete is known as the "compacting factor". The compacting factor test uses an inverse approach to workability; the degree of compaction achieved by a standard amount of work. It gives good results with the "low slump" mixes which cannot be tested by many of the other methods that have been mentioned.

If workability is related to the amount of useful internal work necessary to produce full compaction, then it surely must vary with the internal strength of the concrete. In this thesis the assumption is made that shear strength is a measure of the internal strength of concrete and an attempt is made to measure shear strength directly in a shear box.

It can be argued also that the weakness and limitations of many of the standard tests are largely due to the fact that they do not produce shearing stresses in a very efficient manner. An attempt is made to compare their results with actual shearing strength.

A limited study of shearing strength was carried out by Mr. Li Yang. This thesis attempts to varify his work and also to see if shearing strength is effected by rate of shearing strain.

CHAPTER I

SHEAR STRENGTH AND RHEOLOGICAL PROPERTIES OF FRESH CONCRETE

The shearing strength of freshly mixed concrete is probably, like soil, made up of cohesion plus an angle of internal friction. The cohesive strength is largely related to the layers of adhered water which coat and separate all surfaces of the solids contained in the mix. The angle of internal friction comes into play usually when some solid surfaces are in contact and varies with surface roughness and shape of the solid particles. It can also have an effect when surfaces not in actual contact are separated by distances less than the magnitude of their surface roughness.

In an ideal concrete mix the volume of water and cement (and filler) must be slightly greater than the voids between the aggregate so that each piece of aggregate can be suspended individually in the cement paste. A concrete mix possessing and retaining the above characteristics during the transportation, placing and compacting operation is said to be "stable". In the above definition of a stable concrete mix the requirement that the aggregate particles of the mix shall remain completely dispersed, independent of the degree of plastic deformation, implies that the shearing stresses due to gravitation must not exceed the yield stress of the cement paste. Segregation leading to particle contact will always be prevented during the plastic deformation of a stable mix. What has been said regarding the aggregate in a stable mix also applies to cement clinker (and filler) particles in the water cement mixer constituting the paste. It too must be stable and free of any segregation or bleeding.

The rheological properties of the cement paste are effected by

a. the water/cement ratio,

b. the degree of hydration,

c. the particle size and size distribution of the cement clinker,

d. the amount of filler material ($d \leq 0.15$ m.m.) its particle shape and size distribution,

e. the presence of electrolytes, dispersing agents or other admixtures affecting the properties of the absorbed water layers,

f. the temperature.

In unstable mixes which bleed and segregate or are too dry or harsh, undoubtedly some solid surfaces are in contact or are so close that the angle of internal friction adds very considerably to the strength of the mix. Such materials have strength properties approaching solids in the plastic range and probably should be studied as solids. However with stable mixes the strength properties depend largely on cohesive or viscous forces in the paste, and the rheology can be examined from the point of view that the mix is a dense viscous liquid. This is the approach used in this thesis.

If it is considered that the shearing strength of the mix is dependent on the strength of the cement paste then it is apparent that it will vary with,

1. The plastic deformability of the cement paste and the rate of deformation,

2. The average paste layer thickness,

3. The shape of the aggregate particles.

Many of the factors affecting 1, have already been mentioned and if we are dealing with viscous shearing forces they can be expected to vary with rate of deformation.

Regarding 2, if the layer thickness is halved and the rate of linear deformation is kept constant the angular rate of shearing strain will be doubled and the shearing stress will be affected.

Considering 3, in a multilayer system the shearing strain in a layer between two solid particles will be reduced if the particles tend to rotate. Their resistance to rotation depends not only on the resistance of the surrounding paste, but also the size and shape of the particles and space between them.

CHAPTER II

HOW THE PROBLEM WAS APPROACHED

The work required to deform a liquid depends on the viscous shearing stress and the rate of shearing strain. In the classical development of the theory by Newton, a plate of area A sq. ft. moves parallel to a fixed boundary at a distance h (ft). from it. A force of P lbs. gives the plate a fixed velocity V ft/sec. and viscous shearing forces are developed between the layers of liquid lying between the moving plate and fixed boundary (see Fig. 1). The unit viscous shearing stress $\tau = P/A$ lbs./sq.ft. is a function of the rate of shearing strain $\frac{V}{h}$. For most pure liquids τ varies directly with $\frac{V}{h}$ and we have $\tau = \mu \frac{V}{h}$ where μ is a co-efficient of viscosity. μ is defined as the dynamic or obsolute viscosity and can be calculated from $\mu = \frac{P/A}{V/h} = \frac{Ph}{VA}$ lbs.sec./sq.ft. This is Newton's classic theory of viscosity and liquids for which μ is a constant are known as Newtonian liquids.

From the previous research work done at U.B.C. an apparatus was available which deforms a block of concrete in a manner similar to the block of liquid lying between the plate and the boundary. The important difference between the deformation of the cube of liquid and the cube of concrete is, as shown in Fig. 1, in how the forces are applied. In the case of the liquid the external force is applied at the top through the plate and is truly horizontal and the internal forces are all horizontal viscous shearing forces. In the case of concrete the force is applied by one end of the box, the distribution of the force is not known and the forces exerted on the concrete have small vertical components. The internal forces are therefore not all horizontal viscous shearing forces.

Although the force distribution applied to the concrete is not known the work required to cause the deformation is easy to calculate from

$$(\text{Work})_c + F'_c \; V'_c \; (\Delta t)$$

In Newton's equation for liquids the work done is (Work) = $PV(\Delta t)$ and

$$P = \frac{(\text{Work})}{V\ (\Delta t)}$$

The shearing stress $\tau_c = \frac{F_c'}{A_c} \left(\frac{10.5}{8}\right)$

where F_c' is the force measured on the dial gauge.

The viscosity of a liquid is therefore calculated from the formula:

$$\mu = \frac{(\text{Work})}{V\ (\Delta t)} \quad \frac{h}{AV}$$

and a similar quantity for the concrete can be calculated from the formula

$$\mu_c = \frac{(\text{Work})_c h_c}{V_c(\Delta t)\ A_c V_c}$$

$$= \frac{F_c'\ V_c'\ (\Delta t)\ h_c}{V_c(\Delta t)\ A_c V_c} = F_c' \left(\frac{V_c'}{V_c}\right) \quad \frac{h_c}{A_c V_c}$$

or $\mu_c = F_c' \left(\frac{10.5}{8}\right) \quad \frac{h_c}{A_c V_c}$.

CHAPTER III

DESCRIPTION OF THE APPARATUS

The apparatus used is shown in Fig. 2 and Fig. 3. The bottom and ends of the box are made of plywood and the sides are 2" x $\frac{1}{8}$" brass which were pinned individually with small clearance between strips, and teflon washers were placed on the pinned connections. A very small displacement of the box was used to keep the vertical movement of the sides to a minimum. The box was lined with two layers of teflon and the concrete itself enclosed in rubber sheeting to bridge the space between the side strips and prevent leakage of concrete. The drive was from a reversible constant speed motor through a reducing gear box and a chain drive to a rotating nut on a long threaded drive rod. The drive rod was thus moved back and forth at a constant speed. The velocity of the top of the box itself could be changed by moving the whole drive mechanism to different vertical positions and varying the linkage to the box itself.

The final linkage to the box was a proving ring with a dial gauge reading to 0.0001 inches installed in it which always remained horizontal.

The apparatus was used for all the seven speeds. For the fastest speed, the sprocket wheel attached to the drive rod was exchanged for one with a much smaller diameter, so that the force to deform the concrete was measured at a much higher speed.

Dial gauge readings were taken only when the box was passing through the dead center position and the force exerted by the end of the box on the concrete had no vertical component. It was assumed that at that instant the proving ring was measuring the shearing strength of the concrete over the horizontal area of the box.

CHAPTER IV

CALIBRATION OF APPARATUS AND SCOPE OF EXPERIMENTAL WORK TO BE UNDERTAKEN

Since the ultimate aim was to find the forces involved in the deformation of the concrete the dial gauge reading pounds force relationship had to be found and the tare force of the box accurately established.

To do this the box was filled to a depth of 8 inches with balloons full of water and dial gauge readings taken at all speeds under two different conditions; once with a head of water on the balloons sufficient to produce a pressure on the sides of the box equal to that produced by the concrete and once with a weight on top of the balloons to produce a total weight equal to that of a box full of concrete.

Fortunately the "tare" readings by both methods were almost identical and these dial gauge readings were later subtracted from those obtained with concrete in order to arrive at the shearing strength of the concrete itself.

The proving ring was calibrated in both tension and compression by loading it with dead weights and noting the dial gauge readings.

The scope of the present investigation then became studying the shear strength of eight batches of freshly mixed concrete and comparing it with the following standard workability or consistency tests:

1) The standard slump test,

2) The standard flow test,

3) Power's remolding apparatus,

4) Compacting factor apparatus.

Only one starting position and a full box of concrete was to be used, but tests would be run at seven different velocities.

CHAPTER V

DESCRIPTION OF THE FINAL EXPERIMENTAL WORK AND THE DATA OBTAINED

Concrete Mix Design

Eight different concrete mixes were designed to give slumps from 0 to 8 inches. The A.C.I. mix design method was used and the water cement ratio was kept constant at 0.6. Type 1. cement was used and the complete mix designs are given in Table 1. Sugar and bentonite were added to retard the setting time.

Typical Test Procedure

All eight tests were carried out in the concrete laboratory in two batches measured identically for each mix, according to the following procedure.

a) Mix $\frac{1}{2}$ cubic feet of concrete thoroughly according to the quantities listed in Table 1.

b) Measure the temperature of the concrete mix.

c) Perform the standard slump test and obtain the slump.

d) Perform the standard flow test and obtain the percentage flow.

e) Perform Power's remoulding test and obtain the remoulding effort.

f) Fill the shear deformation box full of concrete and carry out tests at seven different velocities, repeating each three times. (The box was set at + 3/4 in. from centre before starting).

g) Remove the concrete from the box and once more perform the Power's test to see if the consistency has changed appreciably.

h) Mix the other $\frac{1}{2}$ cubic foot of the same mix and repeat (b) to (g) but in (f) do the seven speeds in reverse order.

The concrete was vibrated externally before each reading was taken in the shear box tests. A previous complete set of readings was taken using hand rodding but the results produced such a wide scatter that they were of little value.

Another batch of the eight mixes was tested to find the relationship between the compacting factor and Power's remold effort. The comparative results are shown in Table 21.

Data

A typical data sheet showing the dial gauge readings obtained for seven different speeds and two batches of mix are shown in Table 5, which also shows reduction of the readings to lbs. force.

The results of slump, flow, remolding tests and compacting factor are given in Table 18.

NOTE: A complete set of data was obtained using hand rodding to compact the concrete in the shear box. The results however showed such a large scatter that they were discarded. They did agree in general with the results obtained later using vibration.

CHAPTER VI

CALCULATIONS

An examination of the test readings showed a satisfactory relationship between shear strength and changes in rate of shearing strain for each mix, but a very significant change in workability while each mix was being tested. In spite of the addition of bentonite and sugar as a retarder the remolding tests showed that each mix stiffened appreciably during the time it was being tested.

A correction for change of workability with time was therefore necessary and some adjustment of the F_c values measured at the proving ring was anticipated.

Previous experimental work by Yang had shown a very good relationship between F_c and Power's remolding test and an even better relationship between F_c and the "total work" in inch pounds done in the Power's apparatus including not only the 1/4 in drops but also the work done by gravity and the effect of the 4.3 lb. rider plate.

To establish the change of workability with time four different mixes identical to those used in the shear box were tested in the Power's apparatus every fifteen minutes for a three hour period. The change in drops and "total work" (done in the Power's apparatus) with time appeared to be linear for all practical purposes. Since the times since mixing had been recorded for each test it was possible to calculate the workability in terms of drops and "total work" in Power's apparatus at the times each shear force measurement was taken.

The average forces 'F_c' were taken from the batch 1 and batch 2 readings (Tables 2 & 3) and plotted against the total work done, which are shown in Figs. 7 & 8. The methods of the "Theory of Least Squares" were used to fit a curve to the observations. Neither a straight line nor a log-log graph appeared satisfactory, but a parabola was found to fit quite well.

The parabola $y = a + bx + cx^2$ ...(1), was tried; The method of least squares then leads to the condition: a, b and c must satisfy,

$$Q = \sum_i \left[y_i - (a+bx_i+cx_i^2)\right]^2 = \text{min.} \quad \ldots(2)$$

It is impossible to obtain the minimum of "Q" by satisfying the equations: $\frac{\partial Q}{\partial a} = 0$; $\frac{\partial Q}{\partial b} = 0$; $\frac{\partial Q}{\partial c} = 0$ ...(3)

and hence the notations are introduced:

$$x_i^2 = Z_i \; ; \quad S_1 = \sum x_i y_i \; ; \quad S_2 = \sum x_i^2 \; ; \quad T_1 = \sum x_i Z_i \; ;$$

$$T_2 = \sum Z_i^2 \; ; \quad V_1 = \sum y_i Z_i \; ; \quad \bar{x} = \frac{1}{N}\sum x_i \; ;$$

$$y = \frac{1}{N}\sum y_i \; ; \quad Z = \frac{1}{N}\sum Z_i \quad (i=1,2....8) \text{ and } N = 8$$

then we can write, $y_i = a+bx_i + CZ_i$ ...(4)

From condition (3) it is easy to get the following equations for b, c & a :

$$S_2 b + T_1 C = S_1 \; ;$$

$$T_1 b + T_2 C = V_1 \; ; \qquad \ldots. (5)$$

and $a = \bar{y} - b\bar{x} - C\bar{Z}$.

where $\bar{x} = 711$; $\bar{y} = 6.3$ & $\bar{Z} = 624{,}000$.

These are called "normal equations" and for our particular problem, these constants were solved and the new values were calculated. This procedure was followed for all the seven speeds.

The new force values were plotted against the work done, and proved quite satisfactory. A sample calculation is given below for speed 1. For the observations and other details see Table 8(a).

Solving for constants a, b & c from equation (5) for the observed readings i.e., "y_i" values as given in Table 8(a):

$$a = 0.07; \quad b = 0.0167 \ \& \ C = -0.88 \times 10^{5}$$

$$\therefore y = 0.07 + 0.0167\,x - 0.88 \times 10^{5}\,X^2$$

substituting the "X_i" values, the corrected "y" values are obtained, as given in Table 8(b).

The corrected "y" values for speeds 2 to 7 are given in Tables 9 to 14. The corrected F_c values and the calculated values of shear stress & absolute viscosity are given in Tables 15, 16 & 17. The calculations were made as follows:

$$\text{Shearing stress } \tau_c = \frac{F_c}{A_c}\left(\frac{10.5}{8}\right) = \frac{F_c}{64}\ (1.31)$$

$$= 0.021\ F_c \text{ lbs/sq.in.}$$

$$= 2.95\ F_c \text{ lbs/sq.ft.}$$

$$\text{Viscosity} \quad \mu_c = F_c\left(\frac{10.5}{8}\right)\frac{h_c}{A_c V_c} = F_c\ (1.31)\ \frac{8}{(64)V_c}$$

$$= 0.164\ \frac{F_c}{V_c} \text{ lbs.sec./sq.in}$$

$$= 23.6\ \frac{F_c}{V_c} \text{ lbs.sec./sq.ft.}$$

The curves plotted were:

a) The shearing stress τ against shearing strain V/h, which is shown in Fig. 9;

b) The slump, flow percentage, Power's remolding effort and compacting factor against shearing stress τ and absolute viscosity, which are shown in Figures 12 to 19.

Referring to a diagram of the apparatus in Fig. 4, it is seen that work is done by lifting and dropping concrete and the rider plate each revolution and also by gravity in lowering the centers of gravity of the concrete and the rider plate.

$$\text{Total work} = (W_c)\frac{n}{4} + W_c\,(Y_1 - Y_2) + W_R\left(\frac{n}{4} + 8.8 - S\right)$$

$$= (30.2)\frac{n}{4} + 30.2\,(3.16) + 4.3\,\frac{n}{4} + 4.3\,(8.8) - 4.3\,S$$

Total work $= 8.6\,n + 133 - 4.3\,S$ (in.lbs.) where n = number of $\frac{1}{4}$ in. drops and S = slump (in.). Table 20 shows the calculations and the "total work" done on each mix during Power's remolding test.

CHAPTER VII

RESULTS

The shearing strength was measured at seven different strain rates for eight different mixes and the results after adjustment for changes in workability during the test are plotted in Fig. 9. Evaluations of standard workability tests relative to shear strength appear on Figs. 12 to 15 and to "total work" in Fig. 10.

Similar results and comparisons relative to a calculated absolute viscosity are given in Fig. 11 and Figs. 16 to 19, but they give little, if any, additional information. Shear strength appears to be closely related to the total work necessary to remold a mass of concrete from the slump cone shape to that of a cylinder as performed in Power's Remolding Test. The correlation is so strong that it was used to adjust some of the experimental readings. Therefore both shear strength and total work in the remolding test appear to be good absolute measures of workability and suitable for the comparison of standard workability tests.

CHAPTER VIII

DISCUSSION OF RESULTS

Figure 9 really contains most of the pertinent information gathered from the experimental work. The relationships between unit shearing stress and rate of shearing strain seems to be very definite at all seven degrees of workability. From the curves it appears that all the mixes have the same basic properties but with relatively different shear strengths for different degrees of workability.

Considerable experimental results were obtained for a mix with less than 1 inch slump, or with workability greater than 900 in. lbs., but the points were so close to the 1 inch slump curve that they were not plotted. This indicates that like most other workability tests shear strength or total in. lbs. of remolding effort are not accurate measures of workability for low slump concrete.

Fig. 10 shows Power's Remolding Test, Slump and Flow plotted against workability (measured in in. lbs. of total work) and Figs. 12, 13, 14 & 15 show standard tests plotted against the shear strengths at four different speeds. In general it appears that;

a) slump is most sensitive to changes in workability and shear strength corresponding to 4 inch slump and loses sensitivity at both high and low slumps.

b) Flow gave rather erratic values and was more accurate in the drier mixes.

c) Power's Remolding Test has less change in slope than the other tests and is therefore sensitive over a wider range. It is more accurate for drier mixes.

b) The Compacting Factor Test is good for dry mixes but has little sensitivity for wet mixes.

The curves in Fig. 11 are an attempt to show changes in "viscosity" with changing rates of strain. Viscosity should be indicated by the ratio of ordinate to abscissa of figure 9, but clearly the material did not behave as a Newtonian fluid.

The assumption that the shear strength of freshly mixed concrete is dependent on the shear strength of the cement paste appears to be justified. If it were otherwise, a decrease of shear strength with rate of strain would be difficult to explain unless it was accompanied by an appreciable dilation which was not observed.

Regarding the decrease in shear strength with rate of shearing strain two explanations are:

a) There is a change in pore pressure, which affects the shear strength. This would suggest some tendency to change in volume in a paste which is not free draining.

b) The water cement paste has a flocculated structure and has thixotropic characteristics. In such materials a bond develops between particles which produces a "gel", the strength of which increases with time. With increased rate of shearing strain this bond would have less time to develop.

From the results of the investigations described in this thesis it is not possible to conclude which of the above explanations is valid and it may well be that both have an affect. It is the opinion of some authorities however that a paste with a water cement ratio of 0.6 is free draining which would favour the thixotropic explanation. Whether or not the small amounts of sugar and bentonite in the mixes contributed to the thixotropic behaviour will have to await further study.

CHAPTER IX

CONCLUSIONS

The treating of freshly mixed concrete as a liquid and the plot of unit shearing stress against rate of shearing strain appears to give some pertinent information regarding its rheology. Due to its non-Newtonian characteristics, however, any calculated value of viscosity as an absolute quantity appears to have little, if any, value.

The results of the experimental work described seem to indicate that the assumption that workability is dependent on the shear strength of the paste is valid. Concrete in the mixes used appears to have some thixotropic characteristic.

CHAPTER X

RECOMMENDATION FOR FURTHER RESEARCH

The shear box appears to work well and some further investigations of shear strength with it seem warranted.

a) Shear strengths at different deformation angles or different strains.

b) Shear strengths at very low speeds or very low rates of strain.

c) Changes in shear strength with changes in grading of aggregate.

d) Measurement of shear strength while vibrating at different frequencies.

e) Investigation of whether or not there is any dilation of concrete while it is being sheared.

f) Measurement of shear strength with different confining pressures.

g) Changes in shear strength with various admixtures.

h) Investigations of shear strength vs. total strain.

i) Shear strengths of drier mixes than were used in the present study.

CONCRETE MIX PROPORTION (1 CUBIC YARD)
A.C.I. MIX DESIGN METHOD
W/C is Constant = 0.60 by Weight

MIX #	WATER (lbs)	CEMENT (lbs)	COARSE AGGREGATE (lbs)			SAND (lbs)		RETARDING AGENTS (lbs)		TOTAL (lbs)
			$\frac{3}{4}$ in. $\frac{1}{2}$ in. & Pea size	gap	$\frac{3}{8}$"	F.S.	C.S.	BENTONITE	SUGAR	
1	277.00	460.00	850.00	425.00	425.00	710.00	867.00	9.20	0.96	4024.16
2	280.50	468.00	850.00	425.00	425.00	696.00	855.00	9.30	0.96	4009.76
3	285.00	475.00	850.00	425.00	425.00	686.00	844.00	9.50	0.96	4000.46
4	292.00	486.00	850.00	425.00	425.00	665.00	820.00	9.80	0.96	3973.76
5	297.50	495.00	850.00	425.00	425.00	658.00	810.00	9.90	0.98	3971.38
6	302.00	504.00	850.00	425.00	425.00	654.00	801.00	10.10	1.01	3972.11
7	310.00	516.00	850.00	425.00	425.00	650.00	793.00	10.20	1.07	3980.27
8	317.00	528.00	850.00	425.00	425.00	642.00	785.00	10.40	1.10	3983.50

Specific gravities of cement, C.A. & F.A. are 3.15, 2.68 & 2.64 respectively

TABLE 1

MEASURED "F_c" VALUES; 1st BATCH

SPEED	Force, F_c lbs							
	MIX #1	MIX #2	MIX #3	MIX #4	MIX #5	MIX #6	MIX #7	MIX #8
1	4.8	7.3	8.0	7.5	8.5	5.0	3.5	5.0
2	5.0	7.0	8.0	7.0	8.1	4.6	3.8	4.2
3	5.0	6.3	7.9	6.8	7.8	4.0	3.7	3.8
4	5.5	6.2	7.6	6.8	7.4	4.0	3.3	3.4
5	4.7	6.1	7.3	6.5	7.4	4.0	3.1	3.1
6	4.5	6.3	6.6	6.4	7.2	3.8	3.3	2.9
7	4.6	6.4	5.8	6.3	7.1	4.0	3.8	2.5

TABLE 2

MEASURED "F_c" VALUES; 2nd BATCH

SPEED	Force, F_c lbs							
	MIX #1	MIX #2	MIX #3	MIX #4	MIX #5	MIX #6	MIX #7	MIX #8
1	6.8	6.4	7.7	6.5	7.7	7.0	4.5	4.6
2	6.4	6.3	8.7	7.2	7.2	5.8	4.3	4.2
3	6.8	6.6	8.8	7.3	7.1	6.1	4.1	4.0
4	6.6	6.5	8.8	7.1	6.8	5.8	4.2	4.0
5	6.3	6.5	8.6	6.3	6.8	6.1	4.0	3.6
6	6.3	6.3	8.8	6.3	6.3	6.1	3.9	3.5
7	6.4	6.2	8.5	5.5	6.4	6.6	4.4	3.8

TABLE 3

TARE FORCE, lbs

SPEED	STANDARD SPROCKET WHEEL						SMALLER SPROCKET WHEEL					
	WATER			WEIGHT			WATER			WEIGHT		
	1/4"	1/2"	3/4"	1/4"	1/2"	3/4"	1/4"	1/2"	3/4"	1/4"	1/2"	3/4"
1	1.60	1.76	1.88	1.55	1.76	1.88	1.64	1.72	1.84	1.55	1.76	1.88
2	1.52	1.84	1.96	1.64	1.80	2.00	1.60	1.76	1.96	1.68	1.80	2.00
3	1.55	1.84	2.00	1.60	1.84	2.08	1.64	1.84	1.96	1.60	1.84	2.08
4	1.60	1.92	1.96	1.68	1.96	2.04	1.60	1.96	2.00	1.64	1.92	2.04
5	1.55	1.88	2.04	1.76	1.92	2.00	1.55	1.84	2.04	1.68	1.92	2.04
6	1.68	2.04	2.08	1.76	1.92	2.12	1.68	1.96	2.04	1.76	2.00	2.08
7	1.72	2.04	2.12	1.68	2.04	2.12	1.68	2.04	2.12	1.68	2.08	2.08

TABLE 4

SAMPLE DATA SHEET

SPEED	1st Batch		2nd Batch	
	Dial Gage in. $x10^{-3}$	Force lbs	Dial Gage in. $x10^{-3}$	Force lbs
1	11.90	4.80	16.90	6.80
2	12.40	5.00	15.70	6.40
3	12.40	5.00	17.00	6.80
4	13.40	5.50	16.30	6.60
5	11.70	4.70	15.70	6.30
6	11.20	4.50	15.50	6.30
7	11.30	4.60	15.90	6.40

TABLE 5

Batch 1

MIX #	Remould Drops "n"								
	order of experiment								
	End	7	6	5	4	3	2	1	Begin
	speed								
		1	2	3	4	5	6	7	
1	191	175	166	156	146	137	128	114	100
2	142	133	127	122	116	111	106	98	90
3	86	80	76	72	69	65	62	57	52
4	82	74	70	66	62	58	54	48	42
5	71	66	64	62	60	57	52	48	44
6	67	60	57	54	50	47	44	39	33
7	45	41	40	39	37	36	34	31	28
8	31	28	27	25	24	22	21	19	16

MIX #	Total Work, in. lbs.						
	speed						
	1	2	3	4	5	6	7
1	1630	1570	1480	1390	1310	1230	1110
2	1280	1220	1180	1130	1080	1030	970
3	810	770	730	710	670	645	600
4	750	720	680	645	610	580	530
5	680	660	645	630	600	560	520
6	630	600	580	540	510	480	440
7	460	450	440	420	410	400	380
8	350	340	320	310	290	280	270

TABLE 6

Batch 2

MIX #	Remould Drops "n" — Order of Experiment and Speed								
	Begin	1	2	3	4	5	6	7	End
1	102	115	124	133	142	151	161	174	190
2	82	91	97	103	109	115	121	130	140
3	55	60	63	67	70	74	77	82	88
4	40	46	50	54	58	64	68	73	80
5	41	46	48	51	54	57	59	64	70
6	35	41	44	47	50	53	56	62	70
7	25	28	29	30	31	33	34	37	41
8	14	17	18	20	21	23	24	26	29

MIX #	Total Work, in. lbs. — speed						
	1	2	3	4	5	6	7
1	1120	1190	1280	1350	1440	1520	1630
2	900	960	1010	1060	1120	1170	1250
3	630	660	690	720	750	780	820
4	510	540	580	610	660	700	740
5	510	520	550	580	600	620	660
6	460	480	510	540	570	600	640
7	350	360	370	380	390	400	420
8	250	260	280	290	300	310	330

TABLE 7

SPEED I

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or z_i x10³	$x_i \cdot y_i$ x10²	$x_i \cdot z_i$ x10⁵	z_i^2 x10⁸	$y_i \cdot z_i$ x10³
1	300	4.8	90	14.4	270	81	432
2	400	4.0	160	16.0	640	256	640
3	550	6.0	302	33.0	1660	915	1812
4	590	8.0	350	47.2	2060	1225	2800
5	640	7.0	410	44.8	2625	1680	2870
6	720	7.8	520	56.1	3750	2700	4060
7	1090	7.0	1210	76.3	13100	14400	8400
8	1400	5.8	1960	81.0	27400	38450	11380
TOTAL	5690	50.4	4992	368.8	51505	59707	32394

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	$b.x_i$	$c.x_i^2$	y "lbs" Force Corrected
1	300	4.8	0.07	5.10	-0.81	4.36
2	400	4.0	0.07	6.80	-1.44	5.43
3	550	6.0	0.07	9.35	-2.72	6.70
4	590	8.0	0.07	10.01	-3.15	6.93
5	640	7.0	0.07	10.90	-3.69	7.28
6	720	7.8	0.07	12.25	-4.67	7.65
7	1090	7.0	0.07	18.55	-10.80	7.82
8	1400	5.8	0.07	23.80	-17.65	6.22

(b)

TABLE 8

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or z_i x10^3	$x_i \cdot y_i$ x10^2	$x_i \cdot z_i$ x10^5	z_i^2 x10^8	$y_i \cdot z_i$ x10^3
1	300	4.2	90	12.6	270	81	378
2	400	4.0	160	16.0	640	256	640
3	550	5.2	302	28.6	1660	915	1570
4	600	7.5	360	45.0	2160	1300	2700
5	640	7.1	410	45.5	2625	1680	2910
6	720	8.3	520	59.7	3750	2700	4320
7	1100	7.0	1210	77.0	13310	14600	8470
8	1390	5.7	1935	79.2	26900	37500	11020
TOTAL	5700	49.0	4987	363.6	51315	59032	32008

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	$b \cdot x_i$	$c \cdot x_i^2$	y "lbs" Force Corrected
1	300	4.2	-0.03	4.89	-0.78	4.08
2	400	4.0	-0.03	6.52	-1.40	5.09
3	550	5.2	-0.03	8.96	-2.64	6.29
4	600	7.5	-0.03	9.77	-3.15	6.59
5	640	7.1	-0.03	10.42	-3.59	6.80
6	720	8.3	-0.03	11.72	-4.55	7.14
7	1100	7.0	-0.03	17.90	-10.60	7.27
8	1390	5.7	-0.03	22.65	-16.91	5.71

(b)

TABLE 9

SPEED 3

No.	x_i "in lbs" Work done	y_i " lbs" Force Measured Average	x_i^2 or z_i x10^3	$x_i \cdot y_i$ x10^2	$x_i \cdot z_i$ x10^5	z_i^2 x10^5	$y_i \cdot z_i$ x10^3
1	300	3.9	90	11.7	270	81	351
2	400	3.9	160	15.6	640	256	624
3	550	5.1	302	28.0	1660	915	1540
4	600	7.4	360	44.4	2180	1300	2665
5	640	7.0	410	44.8	2625	1680	2870
6	720	8.3	520	59.7	3750	2700	4310
7	1100	6.4	1210	70.4	13310	14600	7745
8	1380	5.9	1910	81.4	26380	36500	11280
TOTAL	5690	47.9	4962	356.1	50815	58032	31385

(a)

No.	x "in lbs" Work done	y_i " lbs" Force Measured Average	a	$b \cdot x_i$	$c \cdot x_i^2$	y " lbs" Force Corrected
1	300	3.9	0.04	4.68	-0.75	3.97
2	400	3.9	0.04	6.25	-1.33	4.96
3	550	5.1	0.04	8.59	-2.52	6.11
4	600	7.4	0.04	9.35	-2.99	6.40
5	640	7.0	0.04	9.99	-3.40	6.63
6	720	8.3	0.04	11.20	-4.32	6.92
7	1100	6.4	0.04	17.15	-10.04	7.15
8	1380	5.9	0.04	21.55	-15.85	5.74

(b)

TABLE 10

SPEED 4

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or z_i x10^3	$x_i \cdot y_i$ x10^2	$x_i \cdot z_i$ x10^5	z_i^2 x10^8	$y_i \cdot z_i$ x10^3
1	300	3.7	90	11.1	270	81	333
2	400	3.8	160	15.2	640	256	608
3	560	4.9	314	27.4	1760	988	1540
4	600	7.1	360	42.6	2160	1300	2560
5	630	7.0	397	44.1	2500	1580	2780
6	720	8.2	520	59.1	3750	2700	4265
7	1090	6.3	1210	68.7	13100	14400	7560
8	1380	6.0	1910	82.8	26380	36500	11450
TOTAL	5680	47.0	4951	351.0	50560	57805	31096

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	$b \cdot x_i$	$c \cdot x_i^2$	y "lbs" Force Corrected
1	300	3.7	0.18	4.44	-0.68	3.94
2	400	3.8	0.18	5.91	-1.21	4.88
3	560	4.9	0.18	8.28	-2.38	6.08
4	600	7.1	0.18	8.88	-2.73	6.33
5	630	7.0	0.18	9.33	-3.01	6.50
6	720	8.2	0.18	10.65	-3.94	6.89
7	1090	6.3	0.18	16.12	-9.10	7.20
8	1380	6.0	0.18	20.40	-14.48	6.10

(b)

TABLE 11

SPEED 5

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or Z_i x10^3	$x_i \cdot y_i$ x10^2	$x_i \cdot z_i$ x10^5	z_i^2 x10^8	$y_i \cdot z_i$ x10^3
1	300	3.3	90	9.9	270	81	297
2	400	3.5	160	14.0	640	256	560
3	540	5.0	292	27.0	1580	855	1460
4	600	7.0	360	42.0	2160	1300	2520
5	640	6.4	410	41.0	2625	1680	2625
6	720	7.8	520	56.2	3750	2700	4060
7	1100	6.3	1210	69.2	13310	14600	7620
8	1390	5.5	1935	76.5	26900	37500	10650
TOTAL	5690	44.8	4977	335.8	51,235	58972	29792

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	$b.x_i$	$c.x_i^2$	y "lbs" Force Corrected
1	300	3.3	-0.06	4.53	-0.74	3.74
2	400	3.5	-0.06	6.04	-1.31	4.67
3	540	5.0	-0.06	8.15	-2.39	5.70
4	600	7.0	-0.06	9.06	-2.94	6.06
5	640	6.4	-0.06	9.65	-3.34	6.25
6	720	7.8	-0.06	10.88	-4.25	6.57
7	1100	6.3	-0.06	16.60	-9.90	6.64
8	1390	5.5	-0.06	21.00	-15.80	5.14

(b)

TABLE 12

SPEED 6

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or z_i x10^3	$x_i y_i$ x10^2	$x_i z_i$ x10^5	z_i^2 x10^8	$y_i z_i$ x10^3
1	300	3.2	90	9.6	270	81	288
2	400	3.7	160	14.8	640	256	592
3	550	5.0	302	27.5	1660	915	1510
4	590	6.8	349	40.1	2060	1225	2375
5	650	6.4	423	41.6	2750	1790	2710
6	720	7.7	520	55.5	3750	2700	4050
7	1100	6.3	1210	69.3	13310	14600	7620
8	1380	5.5	1910	75.9	26380	36500	10500
TOTAL	5690	44.6	4964	334.3	50820	58067	29645

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	bx_i	$c \cdot x_i^2$	y "lbs" Force Corrected
1	300	3.2	0.02	4.44	-0.72	3.75
2	400	3.7	0.02	5.92	-1.27	4.67
3	550	5.0	0.02	8.14	-2.39	5.77
4	590	6.8	0.02	8.73	-2.72	6.03
5	650	6.4	0.02	9.62	-3.38	6.26
6	720	7.7	0.02	10.65	-4.13	6.54
7	1100	6.3	0.02	16.28	-9.60	6.70
8	1380	5.5	0.02	20.40	-15.15	5.27

(b)

TABLE 13

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	x_i^2 or z_i x10^3	$x_i \cdot y_i$ x10^2	$x_i \cdot z_i$ x10^5	z_i^2 x10^8	$y_i \cdot z_i$ x10^3
1	300	3.2	90	9.6	270	81	288
2	400	4.1	160	16.4	640	256	655
3	540	5.2	292	28.1	1580	855	1520
4	590	6.7	349	39.5	2060	1225	2340
5	610	7.0	374	42.7	2280	1400	2620
6	720	7.1	520	51.1	3750	2700	3690
7	1120	6.3	1260	70.5	14100	15900	7940
8	1400	5.5	1960	77.0	27400	38450	10780
TOTAL	5680	45.1	5005	334.9	52080	60867	29833

(a)

No.	x_i "in lbs" Work done	y_i "lbs" Force Measured Average	a	$b \cdot x_i$	$c \cdot x_i^2$	y "lbs" Force Corrected
1	300	3.2	-0.01	4.41	-0.69	3.70
2	400	4.1	-0.01	5.88	-1.24	4.63
3	540	5.2	-0.01	7.94	-2.26	5.67
4	590	6.7	-0.01	8.67	-2.70	5.96
5	610	7.0	-0.01	8.96	-2.89	6.06
6	720	7.1	-0.01	10.60	-4.03	6.56
7	1120	6.3	-0.01	16.48	-9.75	6.72
8	1400	5.5	-0.01	20.60	-15.15	5.44

(b)

TABLE 14

Consistency 300 in lbs			
SPEED	Fc 'lbs' CORRECTED	τ_c lbs/ft^2 SHEAR STRESS	μ_c lbs.sec/ft^2 ABSOLUTE VISCOSITY
1	4.36	12.85	2,240
2	4.08	12.05	1,850
3	3.97	11.70	1,360
4	3.94	11.61	1,140
5	3.74	11.04	860
6	3.75	11.05	650
7	3.70	10.91	244
Consistency 400 in lbs.			
1	5.43	16.00	2,790
2	5.09	15.00	2,310
3	4.96	14.62	1,700
4	4.88	14.40	1,400
5	4.67	13.80	1,070
6	4.67	13.80	824
7	4.63	13.65	305

TABLE 15

SPEED	Fc 'lbs' CORRECTED	τ_c lbs/ft^2 SHEAR STRESS	μ_c lbs.sec/ft^2 ABSOLUTE VISCOSITY
Consistency 500 in lbs.			
1	6.35	18.72	3,260
2	5.90	17.40	2,680
3	5.80	17.10	1,980
4	5.65	16.68	1,630
5	5.40	15.92	1,240
6	5.40	15.92	950
7	5.40	15.92	356
Consistency 600 in lbs.			
1	7.00	20.65	3,590
2	6.59	19.42	2,990
3	6.40	18.88	2,190
4	6.33	18.65	1,820
5	6.06	17.90	1,390
6	6.00	17.70	1,060
7	6.00	17.70	396

TABLE 16

SPEED	Fc 'lbs' CORRECTED	τ_c lbs/ft^2 SHEAR STRESS	μ_c lbs.sec/ft^2 ABSOLUTE VISCOSITY
Consistency 700 in lbs.			
1	7.55	22.25	3,880
2	7.20	21.21	3,260
3	6.85	20.20	2,340
4	6.80	20.00	1,960
5	6.50	19.20	1,490
6	6.50	19.20	1,140
7	6.40	18.90	420
Consistency 800 in lbs.			
1	7.8	23.00	4,000
2	7.4	21.85	3,360
3	7.1	20.98	2,430
4	7.1	20.98	2,040
5	6.8	20.00	1,560
6	6.8	20.00	1,200
7	6.8	20.00	448
Consistency 900 in lbs.			
1	7.9	23.30	4,050
2	7.4	21.85	3,360
3	7.2	21.21	2,460
4	7.2	21.21	2,070
5	6.9	20.35	1,580
6	6.9	20.35	1,220
7	6.9	20.35	455

TABLE 17

CONSISTENCY in lbs	WATER CONTENT lbs/cu.yd	SLUMP in.	FLOW %	REMOULDING EFFORT (Drops)	COMPACTING FACTOR
300	317.00	$8\frac{1}{2}$	130	23	0.990
400	310.00	$7\frac{1}{2}$	120	34	0.984
500	302.00	6	105	45	0.975
600	297.00	$3\frac{3}{4}$	90	57	0.964
700	292.00	2	80	68	0.954
800	295.0 ?	$1\frac{1}{4}$	67	79	0.945
900	283.00	1	45	90	0.935

TABLE 18

SPEED	VELOCITY 'Vc' in./sec.	HEIGHT 'hc' in.	$\frac{Vc}{hc}$ "Rate of strain" rad/sec
1	0.0368	8	0.0046
2	0.0415	8	0.0052
3	0.0548	8	0.0069
4	0.0655	8	0.0082
5	0.0818	8	0.0103
6	0.107	8	0.0134
7	0.288	8	0.0358

TABLE 19

MIX NO.	SLUMP in.	n	8.6n		(-4.3)S	(in. lbs.) WORK
1	0	146	1255	+133	-0	1388
2	$\frac{3}{4}$	112	964	+133	-3.22	1094
3	$1\frac{1}{2}$	70	602	+133	-6.50	729
4	$2\frac{1}{4}$	61	525	+133	-9.70	648
5	4	55	474	+133	-17.20	590
6	6	50	430	+133	-25.80	537
7	$7\frac{1}{2}$	35	300	+133	-32.20	401
8	8	23	198	+133	-34.4	297

TABLE 20

MIX #	POWER'S TEST DROPS	WEIGHT OF CYLINDER PARTIALLY COMPACTED "Wp" lbs	WEIGHT OF CYLINDER FULLY COMPACTED "Wf" lbs	COMPACTING FACTOR $\frac{Wp}{Wf}$
1	93	41.63	44.75	0.933
2	69	42.44	44.31	0.954
3	46	43.06	44.44	0.972
4	39	43.57	44.50	0.980
5	33	43.88	44.57	0.985
6	28	44.13	44.57	0.990
7	15	44.19	44.70	0.990
8	10	44.31	44.88	0.990

TABLE 21

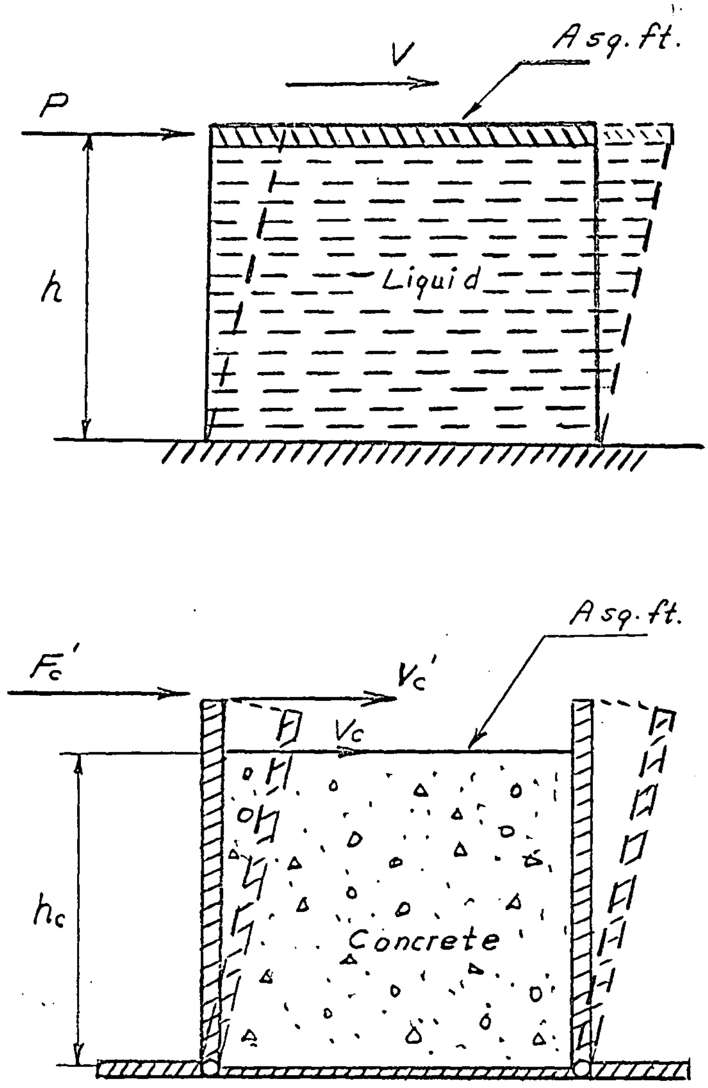


Fig.1

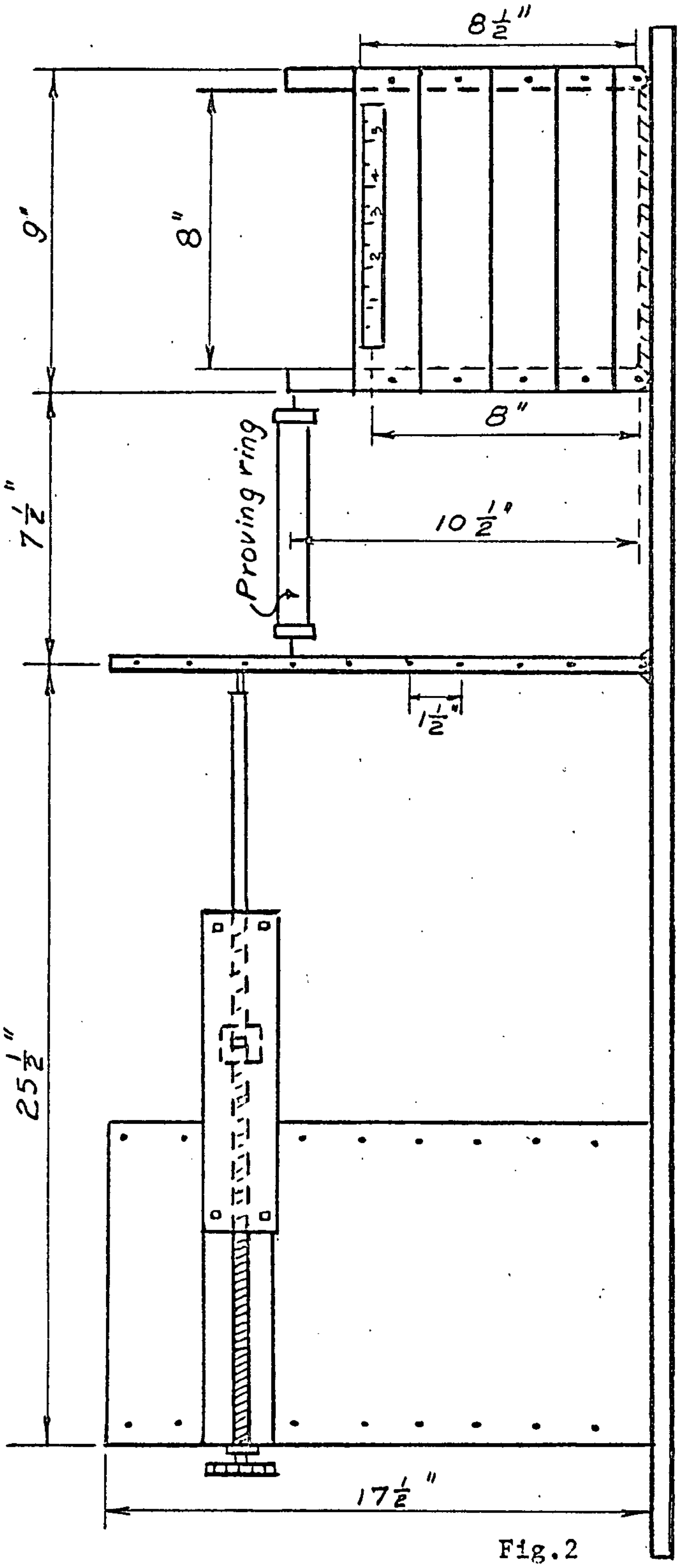


Fig.2

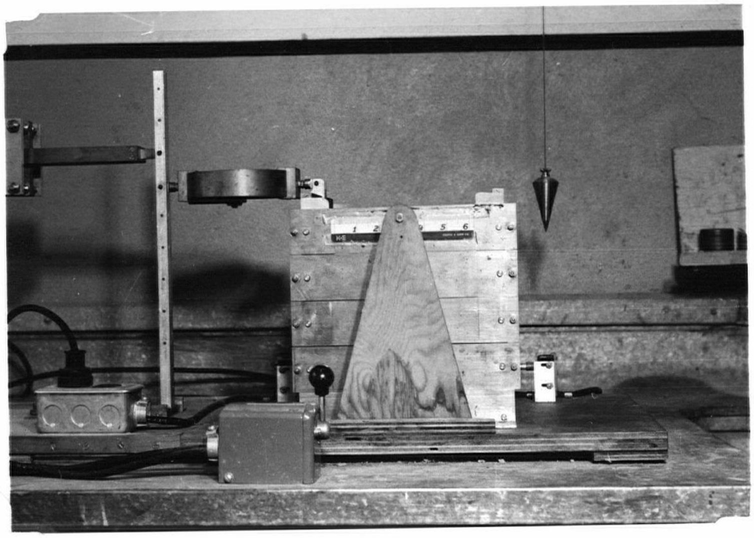


Fig. 3

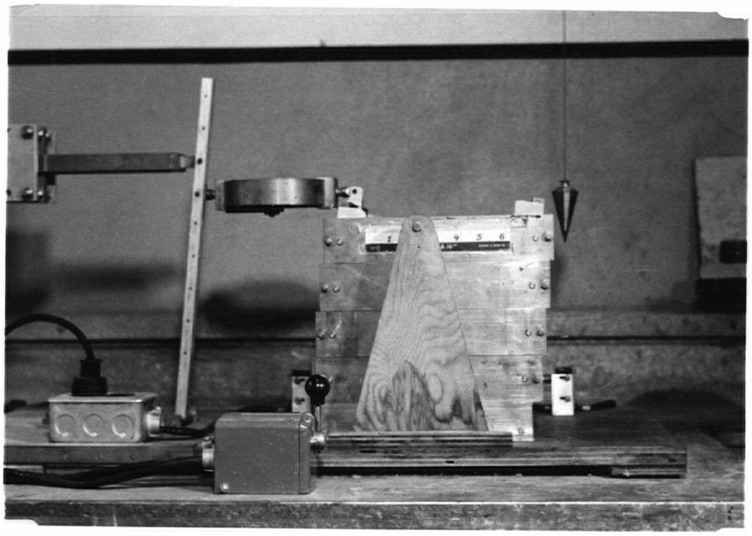


Fig. 3A

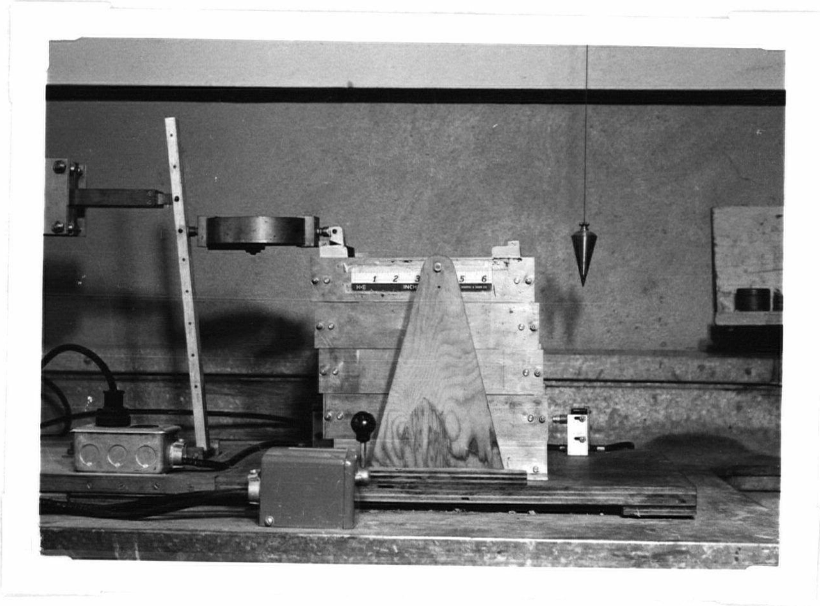


Fig. 3B

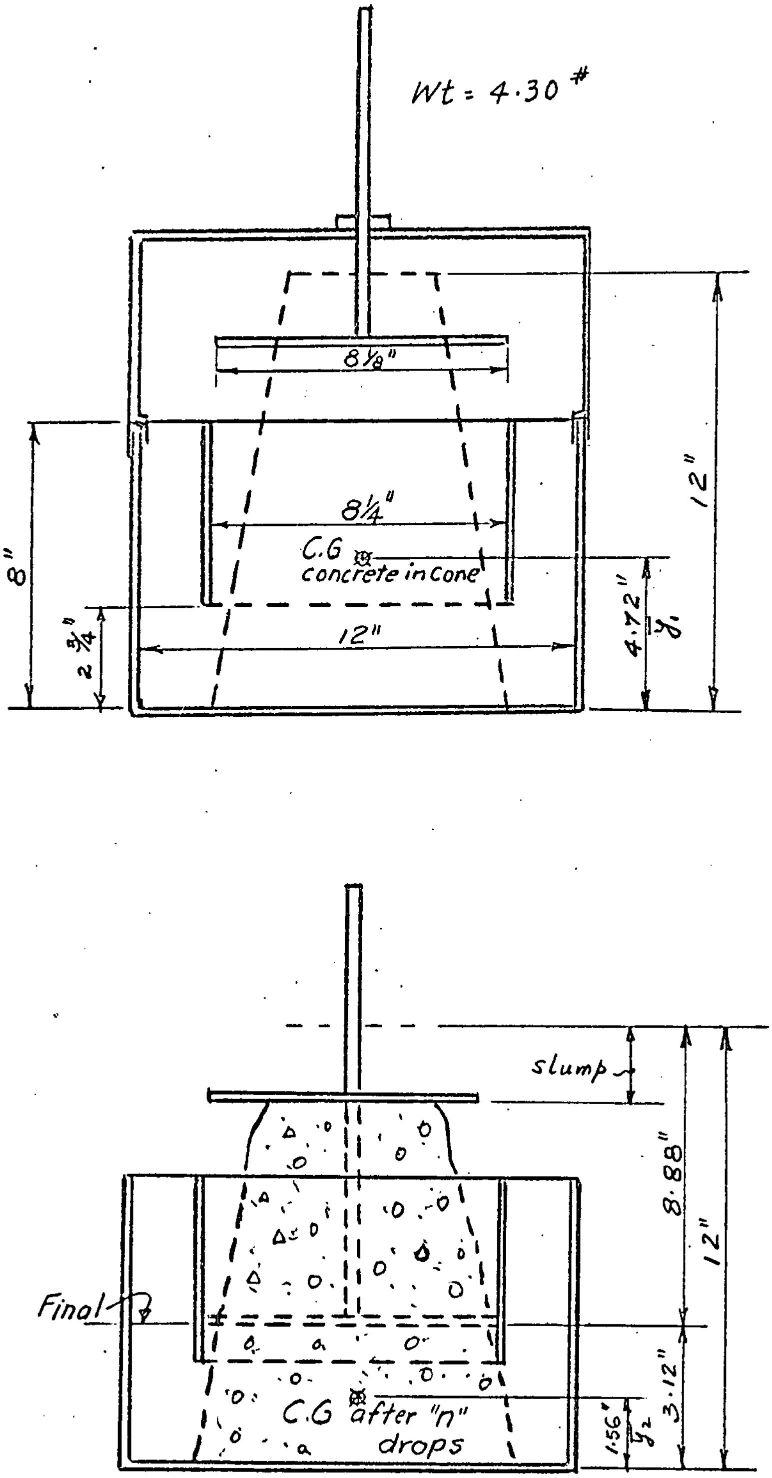

Wt = 4.30 #
8 1/8"
8 1/4"
C.G
concrete in cone
12"
8"
2 3/4"
4.72"
$\bar{y}_1$
12"
slump
8.88"
12"
Final
3.12"
C.G after "n" drops
1.56"
$\bar{y}_2$

Fig.4

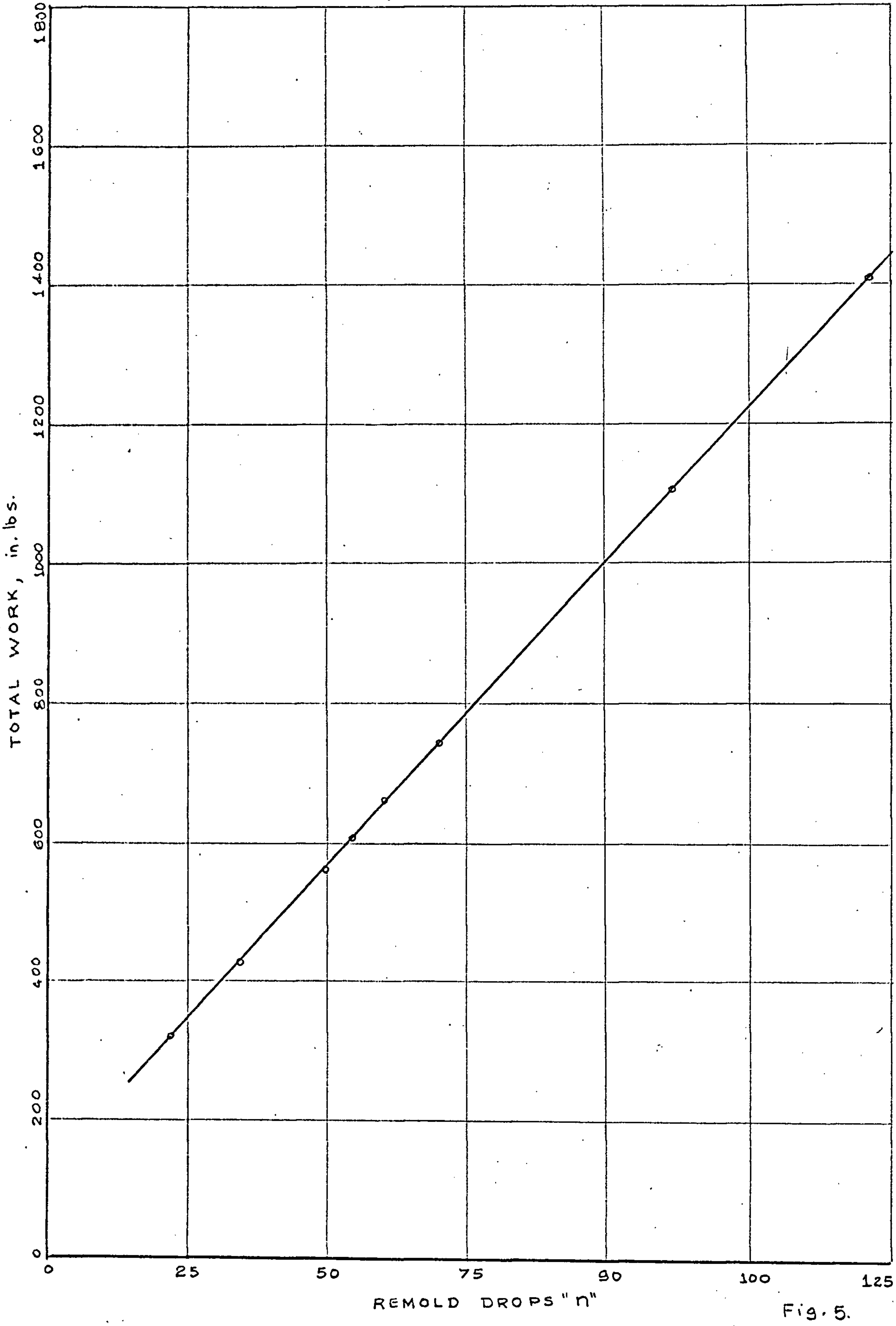
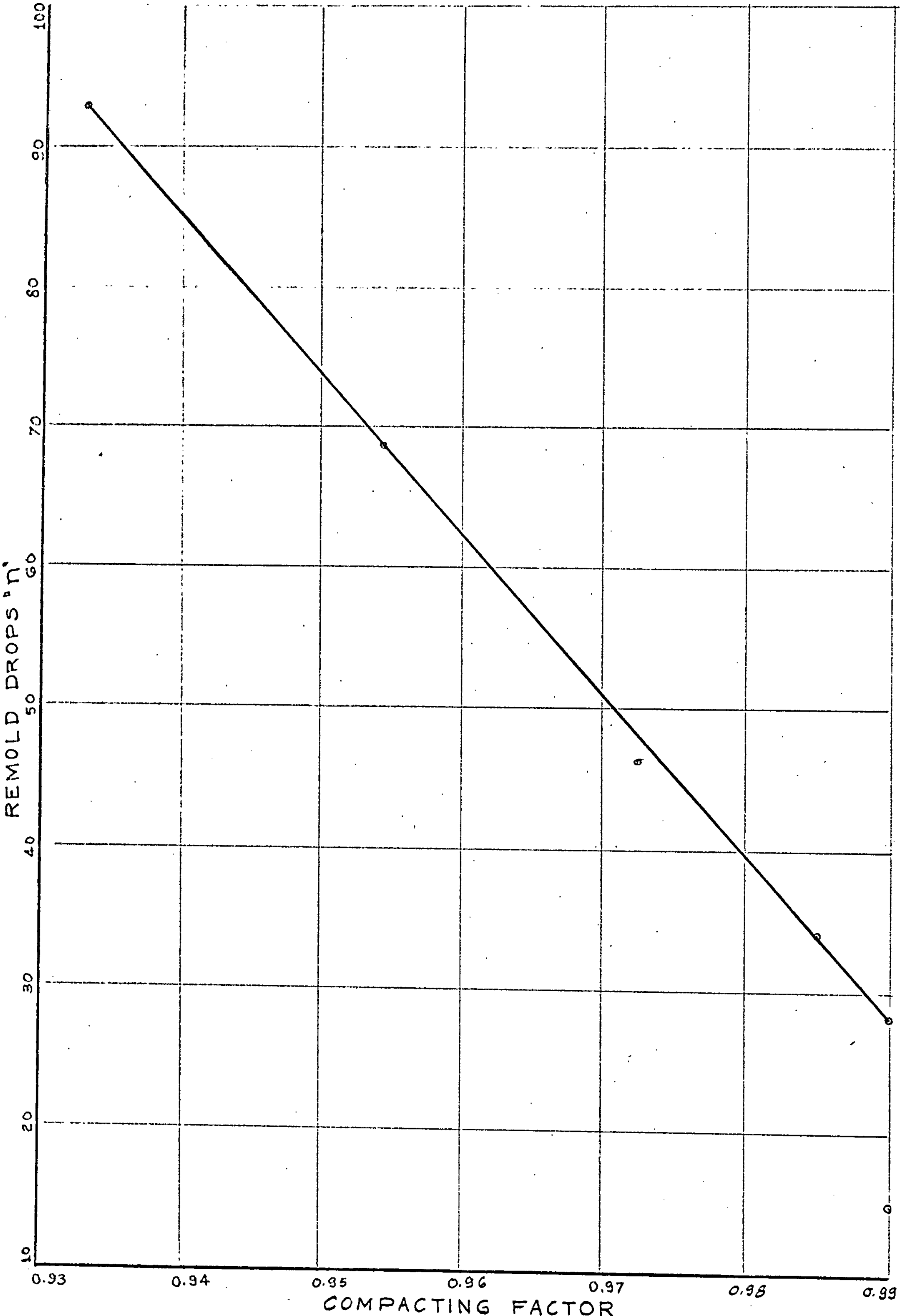

TOTAL WORK, in. lbs.
0
200
400
600
800
1000
1200
1400
1600
1800
0
25
50
75
90
100
125
REMOLD DROPS "n"

Fig. 5.



REMOLD DROPS 'n'
100
90
80
70
60
50
40
30
20
10
0.93
0.94
0.95
0.96
0.97
0.98
0.99
COMPACTING FACTOR

Fig. 6.

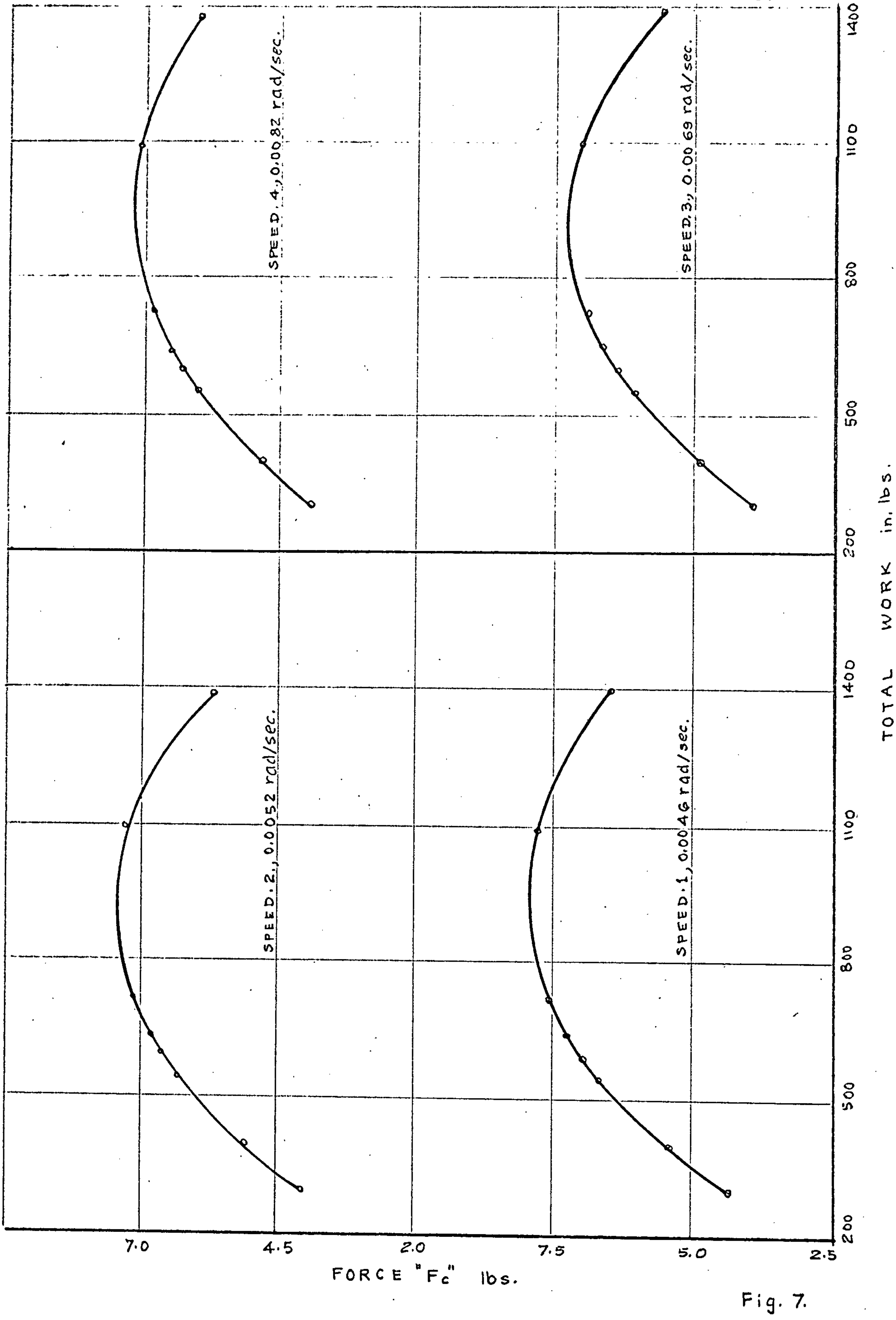
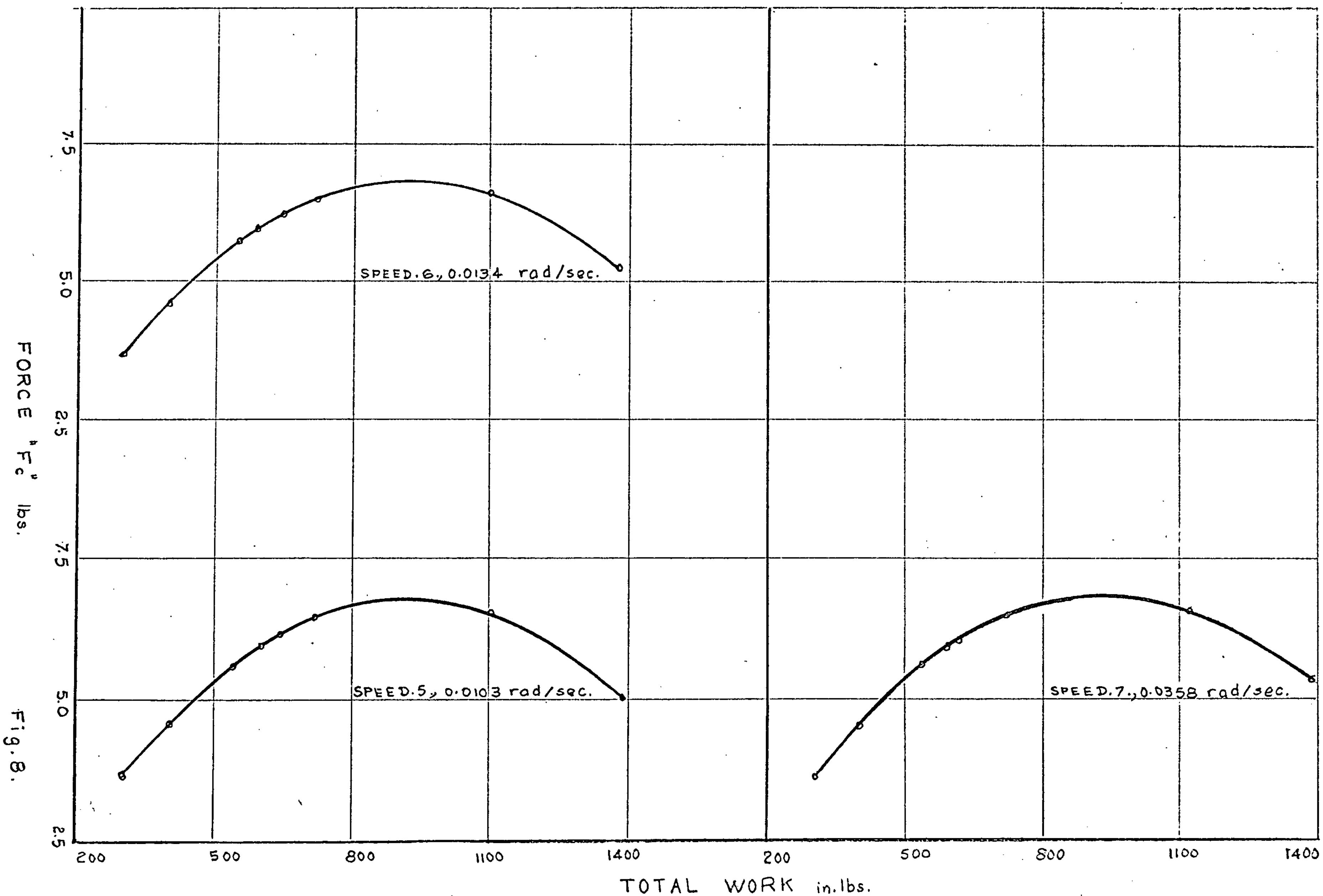

SPEED.4, 0.0082 rad/sec.
SPEED.3, 0.0069 rad/sec.
SPEED.2, 0.0052 rad/sec.
SPEED.1, 0.0046 rad/sec.
TOTAL WORK in. lbs.
FORCE "F_c" lbs.
200
500
800
1100
1400
7.0
4.5
2.0
7.5
5.0
2.5

Fig. 7.



FORCE "F_c" lbs.
7.5
5.0
2.5
7.5
5.0
2.5
SPEED.6, 0.0134 rad/sec.
SPEED.5, 0.0103 rad/sec.
SPEED.7., 0.0358 rad/sec.
200
500
800
1100
1400
200
500
800
1100
1400
TOTAL WORK in.lbs.

Fig. 8.

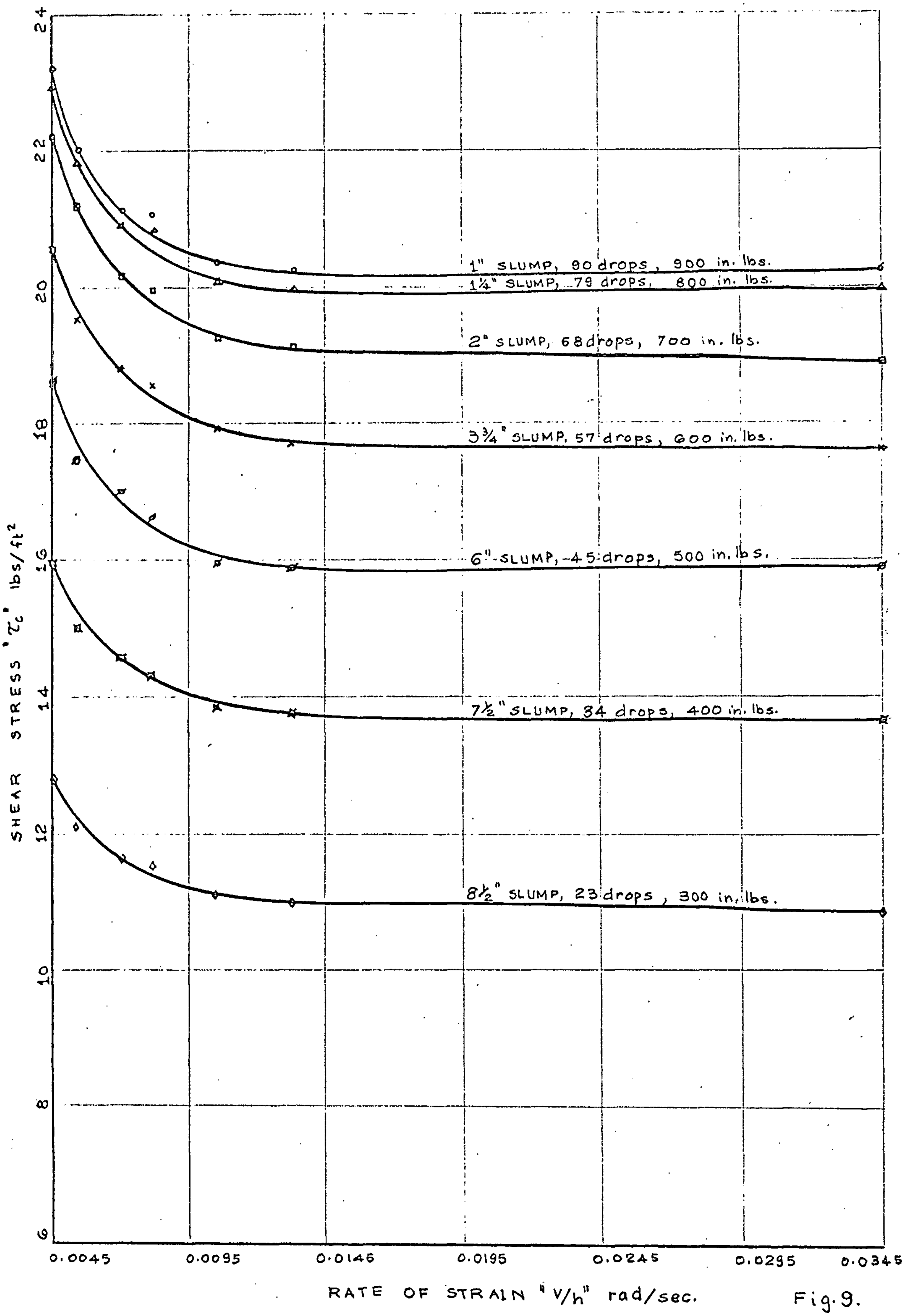

1" SLUMP, 90 drops, 900 in. lbs.
1¼" SLUMP, 79 drops, 800 in. lbs.
2" SLUMP, 68 drops, 700 in. lbs.
3¾" SLUMP, 57 drops, 600 in. lbs.
6" SLUMP, 45 drops, 500 in. lbs.
7½" SLUMP, 34 drops, 400 in. lbs.
8½" SLUMP, 23 drops, 300 in. lbs.
SHEAR STRESS "τ_c" lbs/ft^2
6
8
10
12
14
16
18
20
22
24
0.0045
0.0095
0.0146
0.0195
0.0245
0.0295
0.0345
RATE OF STRAIN "V/h" rad/sec.

Fig. 9.

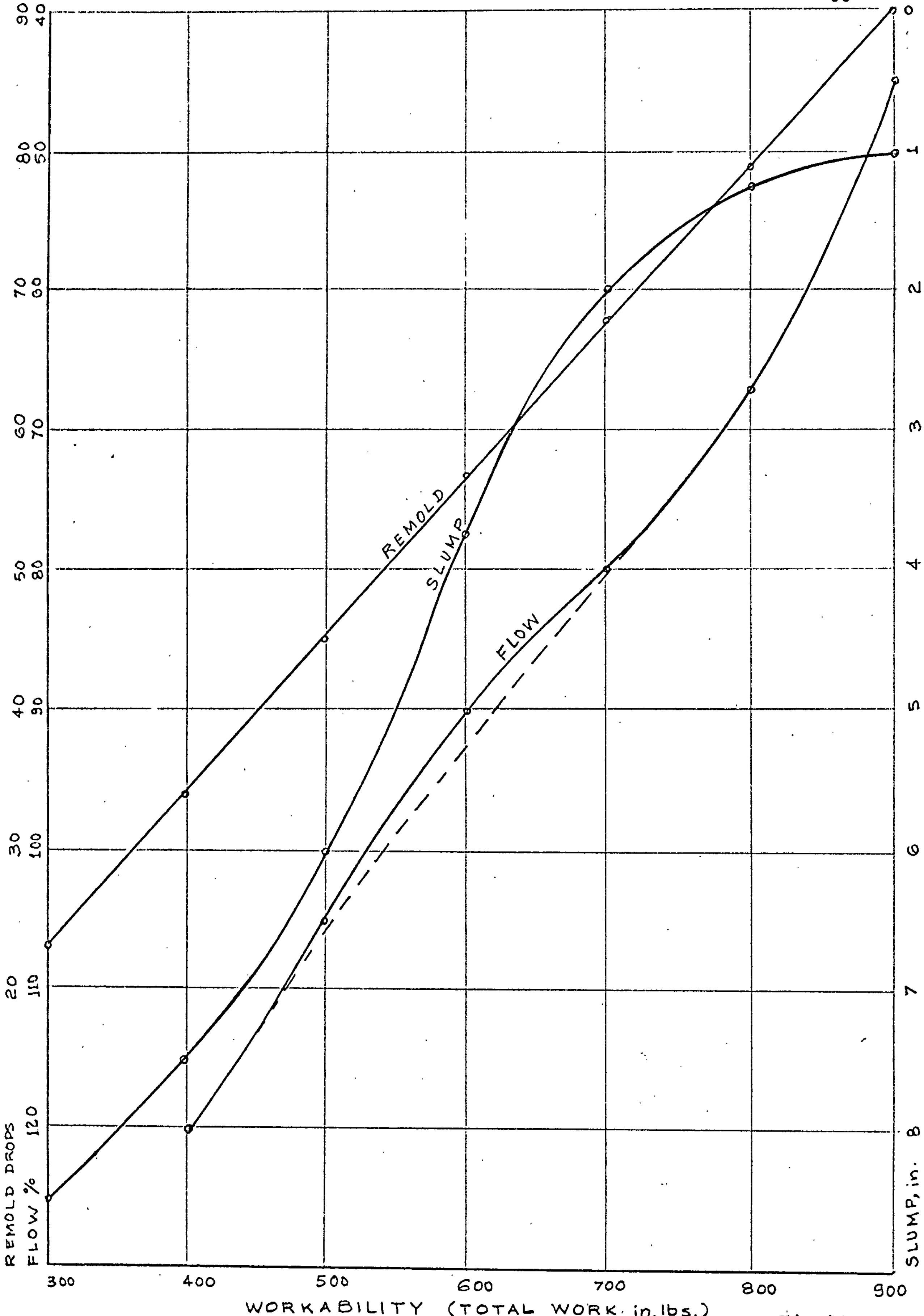
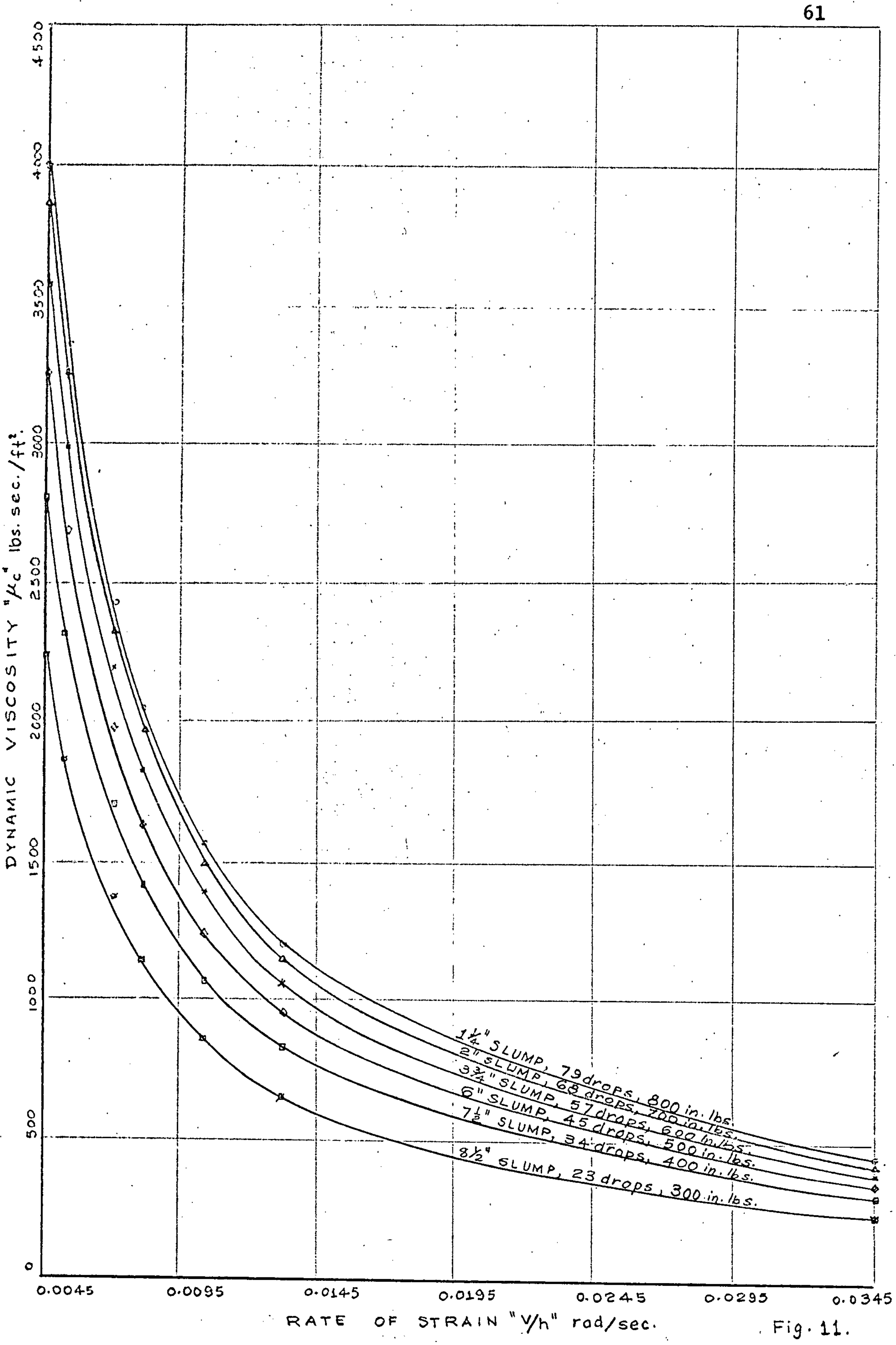

REMOLD DROPS
FLOW %
SLUMP, in.
WORKABILITY (TOTAL WORK in.lbs.)
REMOLD
SLUMP
FLOW
300
400
500
600
700
800
900
90 40
80 50
70 60
60 70
50 80
40 90
30 100
20 110
120
0
1
2
3
4
5
6
7
8

Fig. 10.



DYNAMIC VISCOSITY "μ_c" lbs. sec./ft².
RATE OF STRAIN "V/h" rad/sec.
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0.0045
0.0095
0.0145
0.0195
0.0245
0.0295
0.0345
1¼" SLUMP, 79 drops, 800 in. lbs.
2" SLUMP, 68 drops, 700 in. lbs.
3¾" SLUMP, 57 drops, 600 in. lbs.
6" SLUMP, 45 drops, 500 in. lbs.
7½" SLUMP, 34 drops, 400 in. lbs.
8½" SLUMP, 23 drops, 300 in. lbs.

Fig. 11.

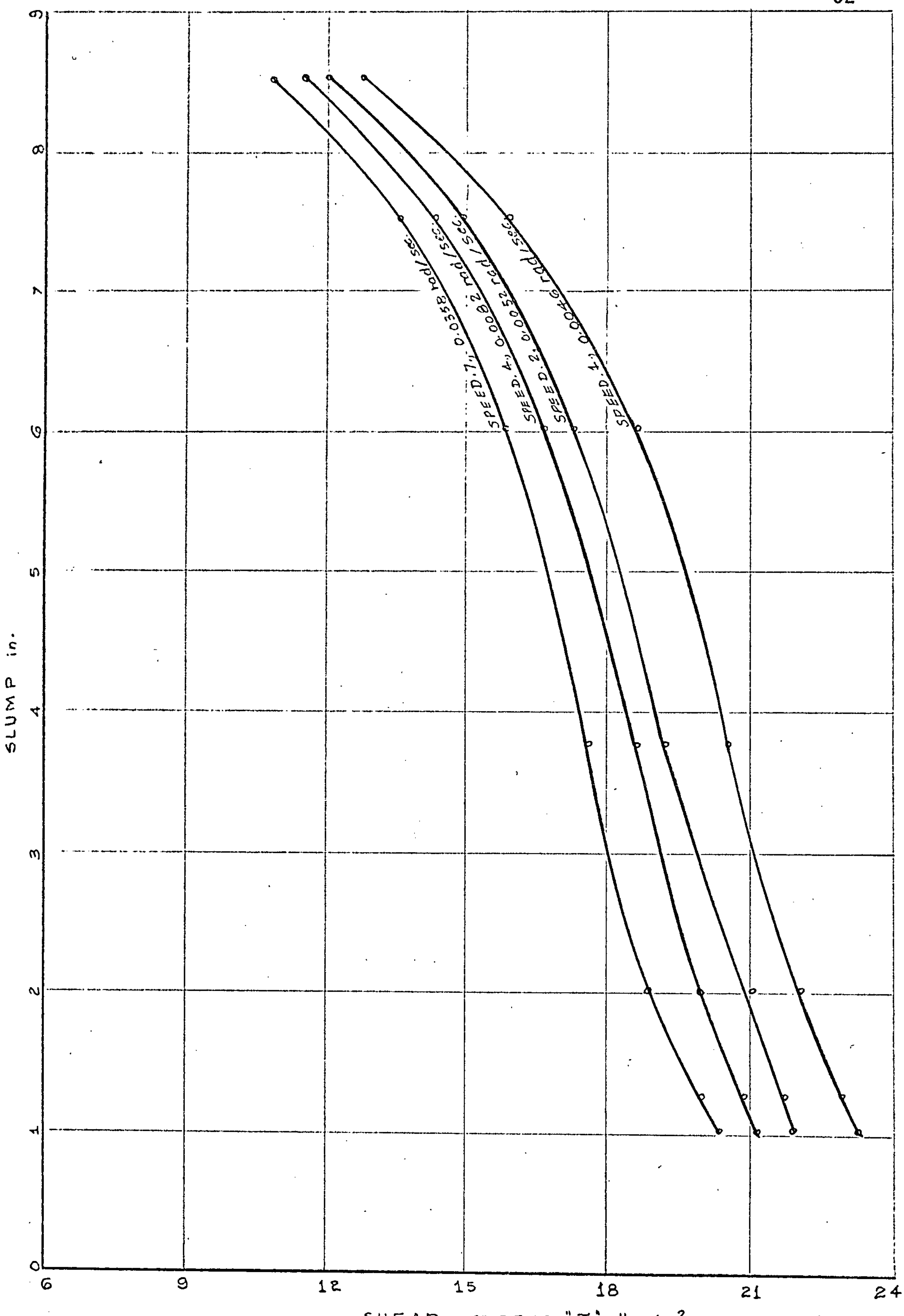
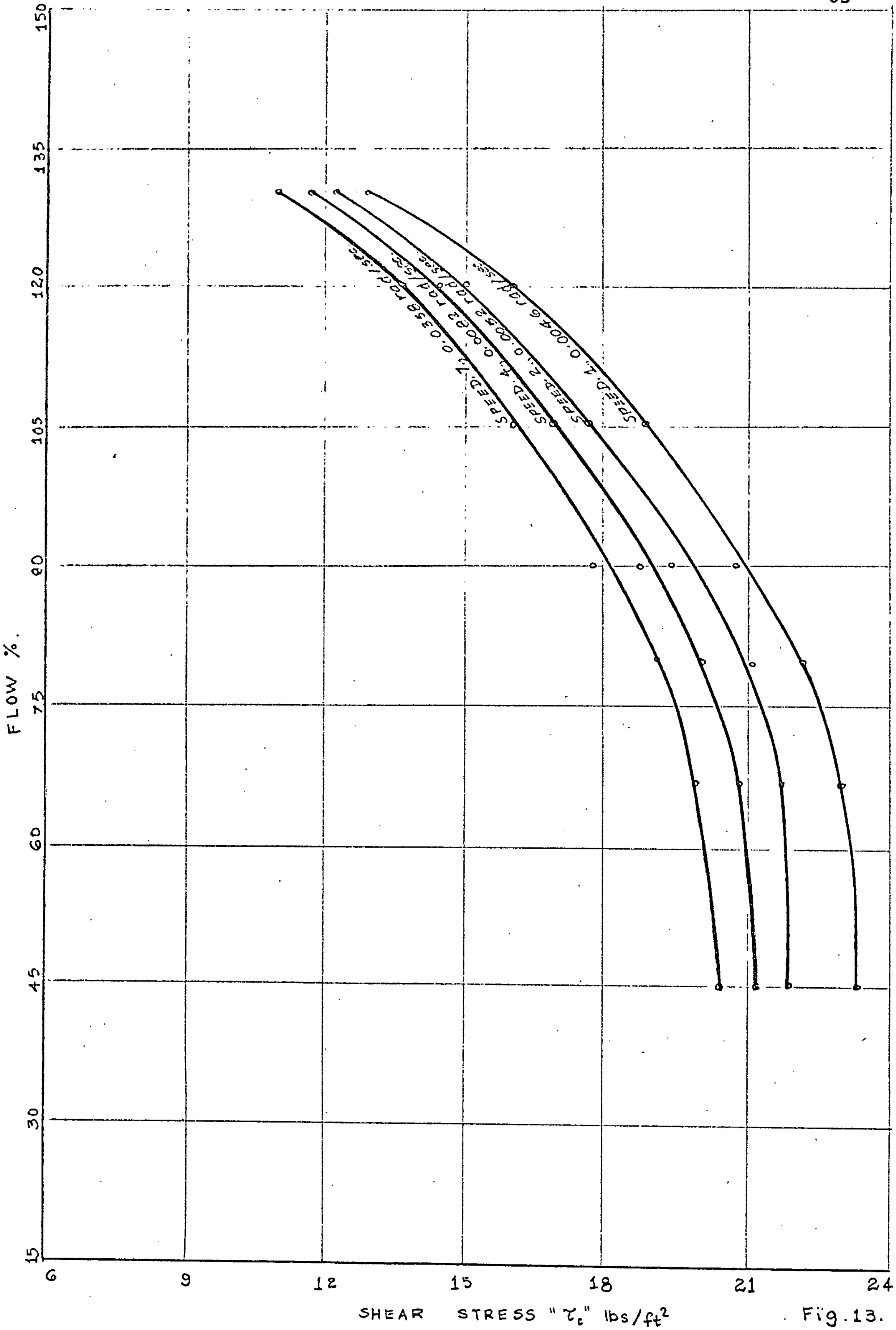

SLUMP in.
0
1
2
3
4
5
6
7
8
9
6
9
12
15
18
21
24
SHEAR STRESS "τ_c" lbs/ft^2
SPEED 7.; 0.0358 rad/sec.
SPEED. 4.; 0.0082 rad/sec.
SPEED. 2.; 0.0052 rad/sec.
SPEED. 1.; 0.0046 rad/sec.

Fig. 12.



SPEED. 1. 0.0046 rad/sec.
SPEED 2. 0.0092 rad/sec.
SPEED 4. 0.0182 rad/sec.
SPEED 1.3 0.0358 rad/sec.
FLOW %.
150
135
120
105
90
75
60
45
30
15
6
9
12
15
18
21
24
SHEAR STRESS "τ_c" lbs/ft^2

Fig.13.

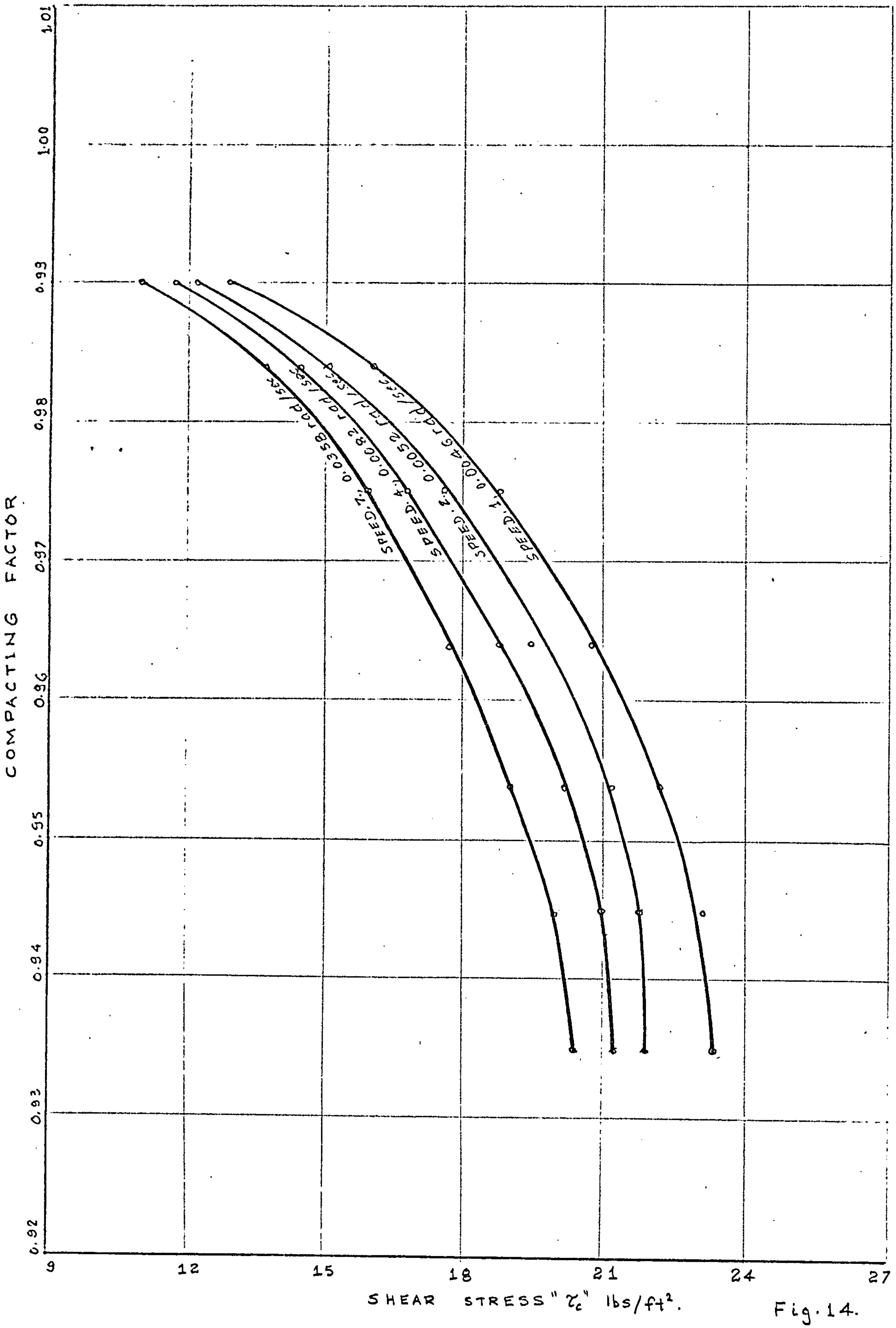
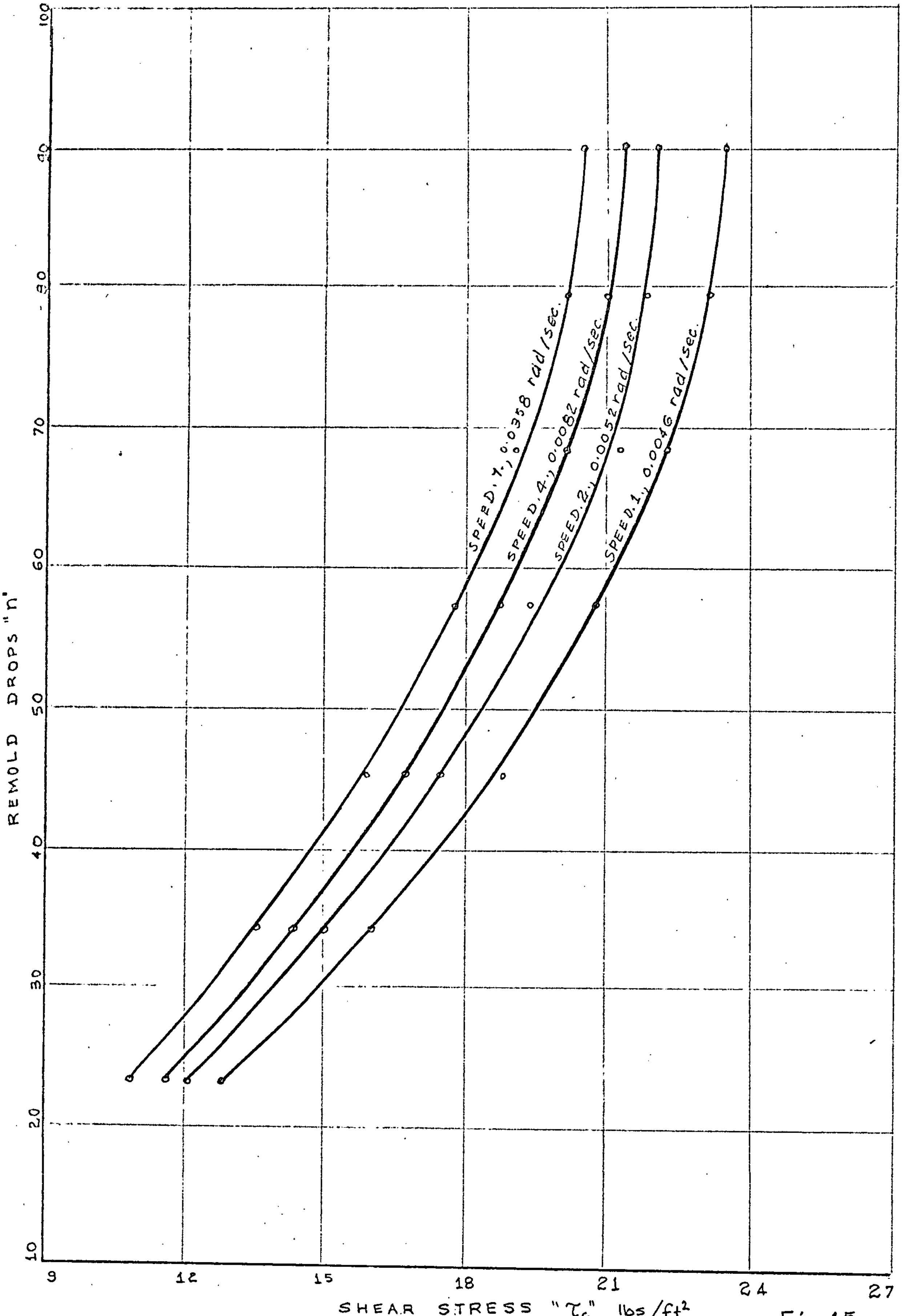

COMPACTING FACTOR
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
SPEED. 7: 0.0358 rad/sec
SPEED. 4: 0.0082 rad/sec
SPEED. 2: 0.0052 rad/sec
SPEED. 1: 0.0046 rad/sec
9
12
15
18
21
24
27
SHEAR STRESS "τ_c" lbs/ft^2.

Fig. 14.



REMOLD DROPS "n"
SHEAR STRESS "τ_c" lbs/ft^2
SPEED.7., 0.0358 rad/sec.
SPEED.4., 0.0082 rad/sec.
SPEED.2., 0.0052 rad/sec.
SPEED.1., 0.0046 rad/sec.
10
20
30
40
50
60
70
80
90
100
9
12
15
18
21
24
27

Fig. 15.

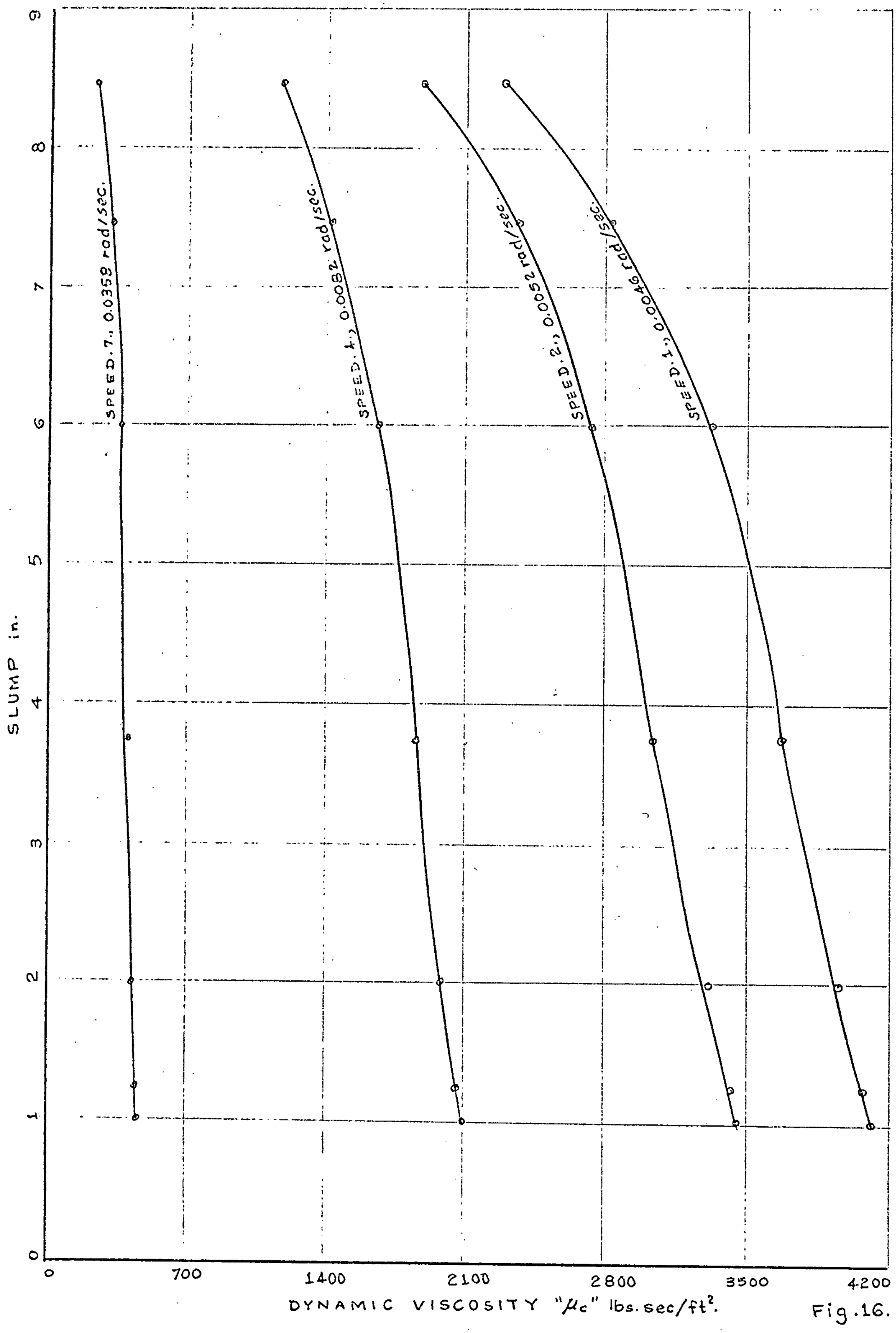

SLUMP in.
0
1
2
3
4
5
6
7
8
9
SPEED.7., 0.0359 rad/sec.
SPEED.4., 0.0032 rad/sec.
SPEED.2., 0.0052 rad/sec.
SPEED.1., 0.0046 rad/sec.
0
700
1400
2100
2800
3500
4200
DYNAMIC VISCOSITY "μ_c" lbs.sec/ft^2.

Fig.16.

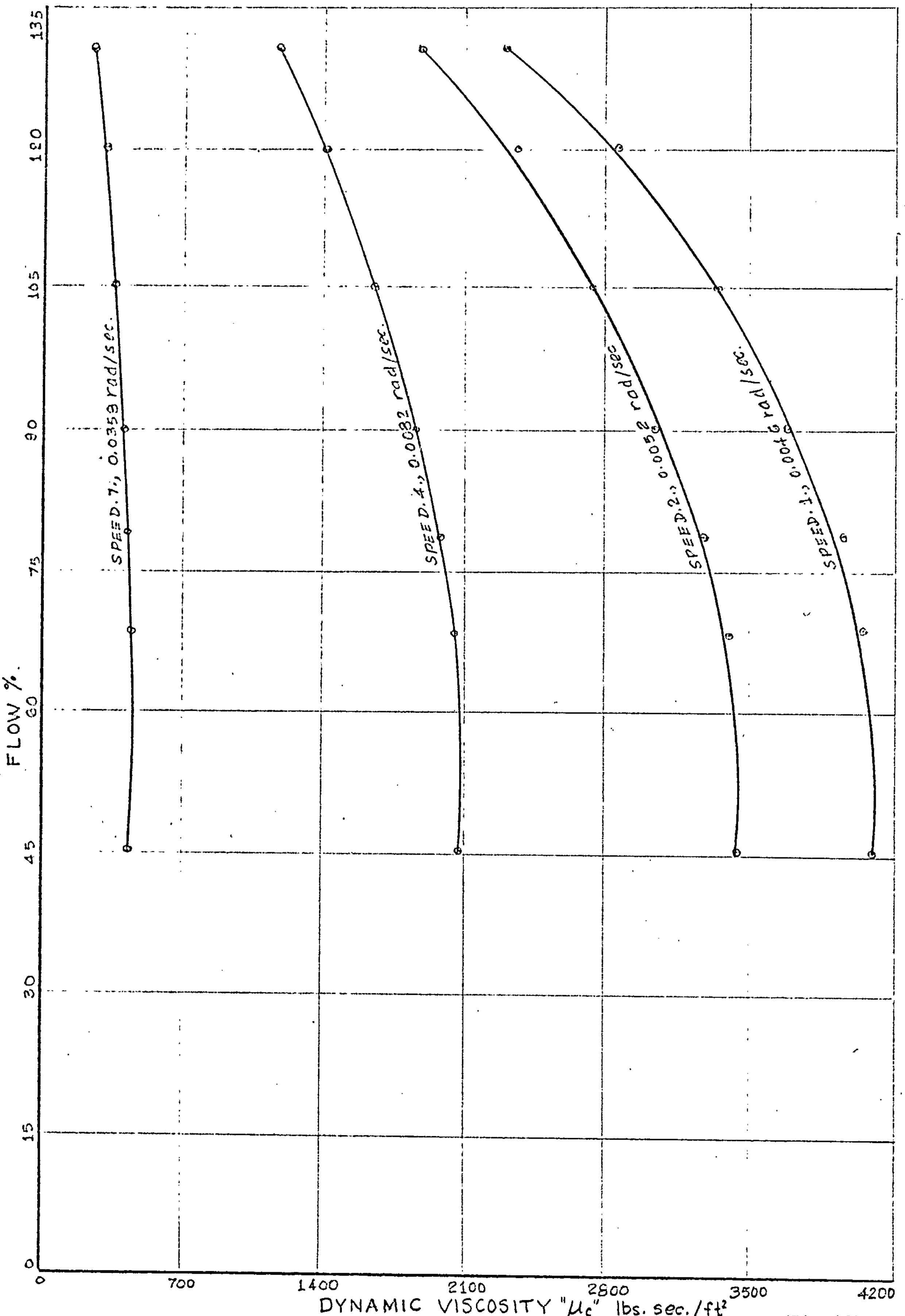

FLOW %
0
15
30
45
60
75
90
105
120
135
0
700
1400
2100
2800
3500
4200
DYNAMIC VISCOSITY "μ_c" lbs. sec./ft²
SPEED 7., 0.0359 rad/sec.
SPEED 4., 0.0032 rad/sec.
SPEED 2., 0.0052 rad/sec
SPEED 1., 0.0046 rad/sec.

Fig. 17.

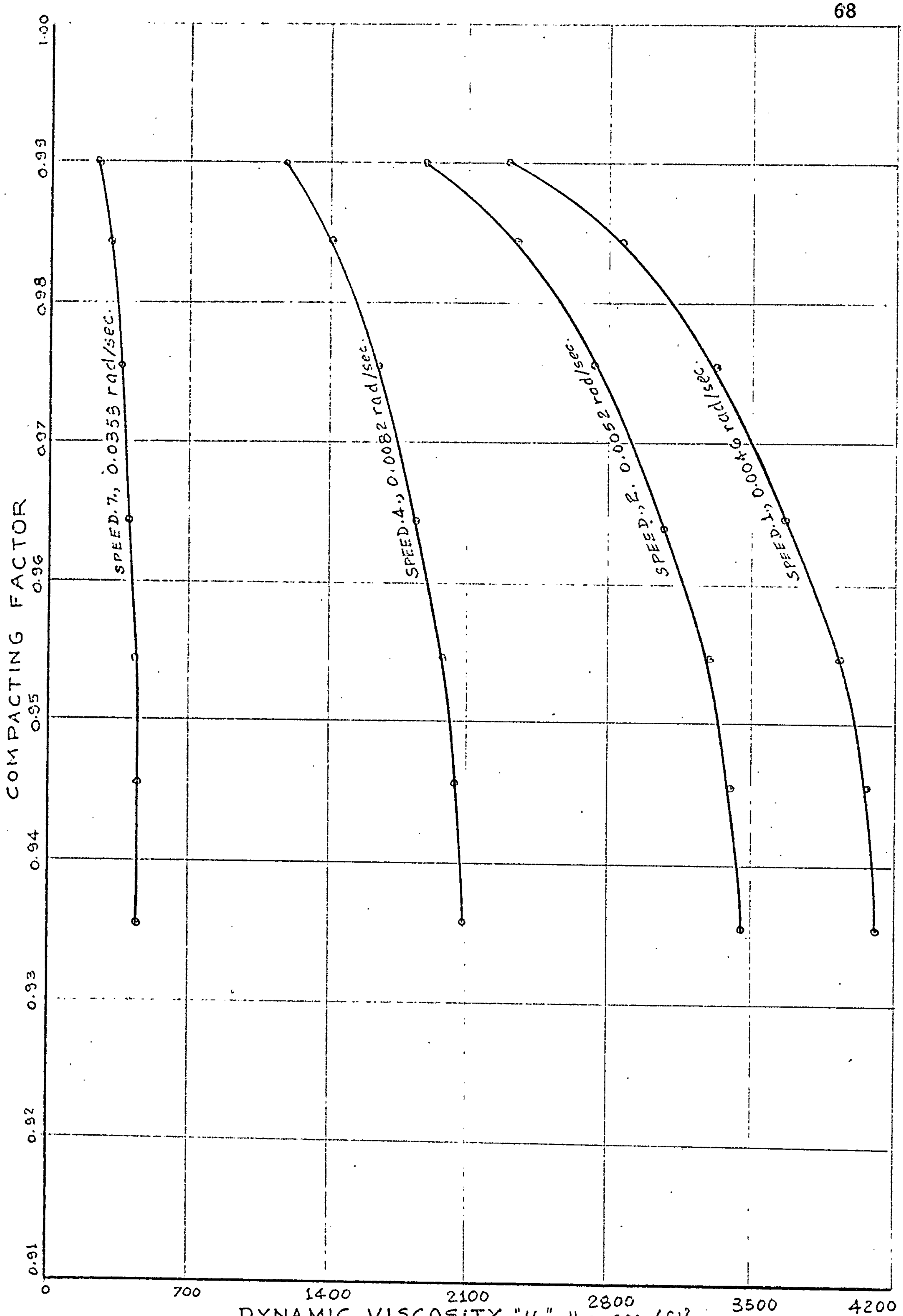

COMPACTING FACTOR
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0
700
1400
2100
2800
3500
4200
DYNAMIC VISCOSITY "μ_c" lbs. sec./ft^2
SPEED.7, 0.0353 rad/sec.
SPEED.4., 0.0082 rad/sec.
SPEED.2, 0.0052 rad/sec.
SPEED.1, 0.0046 rad/sec.

Fig. 18.

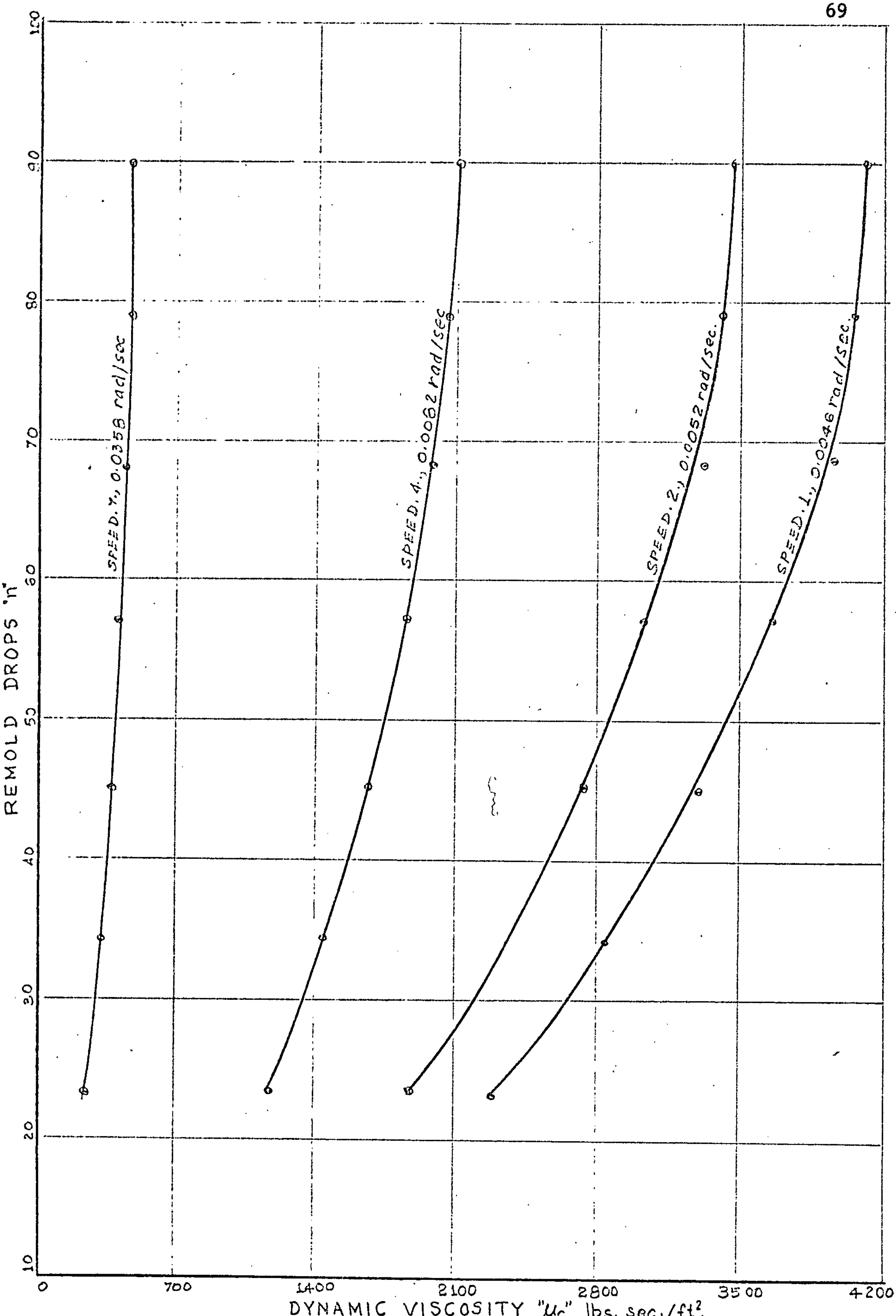

REMOLD DROPS 'n'
DYNAMIC VISCOSITY "μ_c" lbs. sec./ft^2.
0
700
1400
2100
2800
3500
4200
10
20
30
40
50
60
70
80
90
100
SPEED. 7., 0.0358 rad/sec
SPEED. 4., 0.0062 rad/sec
SPEED. 2., 0.0052 rad/sec.
SPEED. 1., 0.0046 rad/sec.

Fig. 19.

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