UNIVERSITY OF LONDON

THE RHEOLOGY OF CEMENT PASTES

AND FRESH MORTARS

BY

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ABSTRACT

In the work presented in this thesis, the rheology of cement pastes and fresh mortars was studied as a step towards understanding the rheological principles underlying the vibration and the compaction of concrete.

For this purpose, an accurately machined double-gap rotational viscometer, having a thermocouple junction embedded in the wall of its middle cylinder, was especially constructed. The thermocouple was used to measure the rise in the temperature of the material under test.

Neat cement pastes and cement-sand mortars of various consistencies were tested in the viscometer under either constant or variable rates of shear, and their flow characteristics investigated. The effect of shear on their yield value was also studied. From the results of a number of such tests, it was established that the shear stress induced in the viscometer gaps produces a significant reduction in the plastic viscosity of the cement paste matrix. It is suggested that, subject to a certain assumption being made, this breakdown can be classified as thixotropic.

The effect of various factors on the energy input to the paste was also investigated and a method for measuring the workability of cement pastes and mortars suggested.

A theoretical approach to the breakdown of the paste is

presented.

In the light of the conclusions drawn concerning the behaviour of the cement paste, some doubts are expressed regarding the current method of measuring the concrete workability by the Vebe apparatus, and an attempt is made to explain the rheological aspects of concrete vibration.

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CHAPTER 1

THE FLOW CHARACTERISTICS OF FLUIDS

In order to study the flow characteristics of cement pastes and fresh mortars, it is necessary to consider the behaviour of some basic types of fluid when subjected to specified flow conditions.

A. Newtonian fluids

The Newtonian fluid is the simplest type of fluid and forms the basis of the rheological studies of liquids and pastes. When such a fluid is contained between two parallel planes and one of the planes is slowly moved in its own plane relative to the other, laminar flow is induced. The shearing force F per unit area acting on any plane moving with a velocity v , at a distance r from the stationary plane, is given by

$$F = \eta \frac{dv}{dr} \quad (1)$$

where $\frac{dv}{dr}$ is the rate of shear (or the velocity gradient) and η is a constant known as the coefficient of viscosity.

In practice, equation (1) is only applicable to the laminar flow of those fluids whose molecules are not hampered in their motion by molecular alignment under high rates of shear. For such a fluid, the flow characteristics can be completely defined by a single measurement of the shearing stress and the corresponding rate of

shear, because the graph representing the relationship between these two quantities is a straight line passing through the origin (Figure 1a).

Poiseuille, while investigating the flow of liquids through capillary tubes, established experimentally that the volume of liquid flowing through a capillary tube per unit time is directly proportional to the activating stress. By applying Newton's equation to the capillary tube, the following flow equation was derived

$$\frac{V}{t} = \frac{\pi R^4 P}{8 L \eta} \quad (2)$$

where V is the volume of liquid flowing in a time t , P is the net pressure difference causing the flow, while R and L are the radius and the length of the tube, respectively.

B. Bingham plastics

Bingham conducted similar experiments to those carried out by Poiseuille using clay suspensions in water and found that unless the applied stress exceeded a certain value, no flow of the suspension took place. He therefore modified Newton's equation to

$$\mu (F - f) = \frac{dv}{dr} \quad (3)$$

where μ is the mobility of the fluid and f is the yield value. The relationship between the shearing stress and the rate of shear in this case, is still linear but the straight line has an intercept

(a) A NEWTONIAN FLUID

(b) A BINGHAM PLASTIC

RELATIONSHIP BETWEEN SHEARING STRESS
AND RATE OF SHEAR

FIG. 1

on the shearing stress axis equal to the yield value (Figure 1b).

A modification of Poiseuille's equation of flow took the form

$$\frac{V}{t} = \frac{\pi R^4 (P - p)}{8 L \eta} \quad (4)$$

where p is the smallest applied pressure that will just cause the flow to start.

In practice, however, a plot of the flow against the pressure difference P , for a Bingham plastic, does not give a single straight line with an intercept p on the pressure axis as predicted from equation (4). In fact, the plot exhibits a non-linear relationship, especially at low pressures, due to the presence of plug flow. If the equilibrium of a central cylinder of the fluid having a radius r and a length L , in the capillary tube, is considered, the following equation is obtained:

$$2 \pi r L F = \pi r^2 P \quad (5)$$

On re-arranging the variables in equation (5), the shearing stress acting at a radius r is given by

$$F = \frac{r P}{2 L} \quad (6)$$

From equation (6) it is obvious that the stress is directly proportional to the radius r , and therefore no shearing of the material takes place except where r is of such a magnitude that the shearing stress associated with it is equal to, or greater than, the

yield value. Hence, the radius r_o of the unsheared plug of fluid is given by

$$r_o = \frac{2 L f}{P} \quad (7)$$

It can be seen from this expression that, irrespective of the applied pressure, r_o cannot be zero as long as the yield value itself is greater than zero. In other words, the plug flow can never be eliminated in the case of a Bingham plastic, flowing through a capillary tube.

Buckingham (1)⁺ derived a theoretical equation for the flow of plastic materials through a capillary tube. He substituted for the shearing stress F from equation (6) in Bingham's equation to get

$$-\frac{dv}{dr} = \mu \left[\frac{P r}{2 L} - f \right] \quad (8)$$

Using the above basic equation and assuming that a very thin Newtonian lubricating layer, having a constant viscosity η , exists next to the capillary tube wall, he deduced the following equation for the flow

$$\frac{V}{t} = \frac{\pi R^4 \mu}{8 L} \left[P - \frac{4}{3} f + \frac{f^4}{3\mu^3} \right] + \frac{\pi R^3 \epsilon P}{2 \eta L} \quad (9)$$

where ϵ is the thickness of the boundary layer, and R is the radius of the capillary tube.

⁺ see the list of references on page 350.

The above expression is composed of two parts and shows that the flow curve cannot be linear. The first part OA of the flow curve (Figure 2) is a straight line representing the condition in which the entire flow is the result of slippage. The second part AF is a hyperbola which becomes asymptotic to a straight line as the pressure increases and represents a mixed regime consisting of both laminar and plug flow in changing proportions. Equation (9) contains four unknown quantities which may be reduced to three by considering ϵ/η as one variable. The evaluation of these quantities can be done by solving the appropriate number of simultaneous equations; but although the plastic viscosity may be obtained with a fair degree of accuracy from such equations, the yield value determination will be far from correct.

To overcome the above difficulties, Reiner and Rivlin (2) derived the equation governing the flow of a Bingham plastic in a rotational viscometer.⁺ Bingham's equation was modified to

$$r \frac{dw}{dr} = \mu (F - f) \quad (10)$$

where w is the angular velocity, at any radius r , of the material being sheared. The shearing stress F is given by

⁺ A history of the use of rotational viscometers is given in reference (16).

THE BUCKINGHAM CURVE

FIG. 2

$$F = \frac{T}{2 \pi r^2 h} \quad (11)$$

where T is the torque transmitted to the stationary cylinder,
 r is the radius at which the shear stress is considered, and h is
the common height of fluid between the cylinders.

From equation (11) it may be deduced that the maximum and the
minimum values of the shearing stress are given by

$$F_{(\max)} = \frac{T}{2 \pi R_i^2 h} \quad (12)$$

and
$$F_{(\min)} = \frac{T}{2 \pi R_e^2 h} \quad (13)$$

where R_i and R_e are the minimum and the maximum values of the
radius, respectively. Therefore, no flow will take place as long as

$$\frac{T}{2 \pi R_i^2 h} < f \quad \text{or} \quad T < 2 \pi R_i^2 h f = T_o \quad (14)$$

But, when T exceeds T_o the material starts to flow where the
stress is greatest (i.e., at the smaller of the two radii), while no
laminar shearing takes place in the part of the material where the
shearing stress is still less than the yield value f .

When the value of the torque satisfies the following condition,

$$\frac{T}{2 \pi R_e^2 h} \geq f \quad \text{or} \quad T \geq 2 \pi R_e^2 h f = T_1 \quad (15)$$

the plug flow will be completely eliminated and all the material in

the gap will flow laminafly. From equations (14) and (15), it may be deduced that the narrower the gap the smaller is the difference between T_0 and T_1 , i.e., the smaller the torque range where plug flow occurs.

Using equations (10) and (11), Reiner and Rivlin obtained the following equation for the flow of plastic materials in the gap when no plug flow occurs:

$$\omega = \frac{\mu T}{4 \pi h} \left[\frac{1}{R_i^2} - \frac{1}{R_e^2} \right] - \mu f \log_e \frac{R_e}{R_i} \quad (16)$$

where ω is the angular velocity of the rotating cylinder. This equation is only valid for the linear part of the flow curve (Figure 3), i.e., for values of the torque from T_1 upwards. It is not necessary to know the equation of the curved part of the flow curve because the rheological constants can be derived from the linear part alone. The three torque values T_0 , T_1 , and T_2 in Figure 3 are all functions of the yield value f which can easily be evaluated from the torque intercept T_2 . The value of T_2 is obtained by putting $\omega = 0$ in equation (16), i.e., from

$$\frac{T_2}{4 \pi h} \left[\frac{1}{R_i^2} - \frac{1}{R_e^2} \right] = f \log_e \frac{R_e}{R_i} \quad (17)$$

If two instrument constants S and C are defined (3) as

$$S = \frac{1}{4 \pi h} \left[\frac{1}{R_i^2} - \frac{1}{R_e^2} \right] \quad (18)$$

CONSISTENCY CURVE OF A BINGHAM PLASTIC MADE WITH A
ROTATIONAL VISCOMETER

FIG. 3

$$\text{and } C = \frac{S}{\log_e (R_e/R_i)} \quad (19)$$

the plastic viscosity U and the yield value f are then given by

$$U = \text{Slope of linear part of flow curve} \times S \quad (20)$$

$$\text{or } U = \frac{(T - T_2)}{\Omega} \cdot S \quad (21)$$

$$\text{and } f = C T_2 \quad (22)$$

When a Newtonian fluid is used in a rotational viscometer the equation governing the flow becomes

$$\Omega = \frac{\mu T}{4 \pi h} \left[\frac{1}{R_i^2} - \frac{1}{R_e^2} \right] \quad (23)$$

and the graph showing the variation of the torque with the angular speed is a straight line passing through the origin.

C. Pseudoplastics

This group includes those materials whose consistency curve as determined with either a capillary tube or a rotational viscometer, is not linear but convex towards the shearing stress axis (Figure 4a). The up-curve and the down-curve for such a material are coincident and therefore the relaxation time is a function of the rate of shear. The decrease in the apparent viscosity (i.e., the viscosity determined on the assumption that the material is Newtonian) as the rate of shear is increased may be attributed to a shear alignment of the molecules or to a change in the shape of the suspended elastic

(a) PSEUDOPLASTIC MATERIAL

(b) THIXOTROPIC MATERIAL

CONSISTENCY CURVES OBTAINED WITH A
ROTATIONAL VISCOMETER

particles produced by the directional shearing action.

Some investigators use an empirical expression of the form given below, to define the pseudoplastic flow curve:

$$\text{the rate of shear} = \frac{dv}{dr} = \frac{F^n}{\eta_1} \quad (24)$$

where n and η_1 are constants for the material. The number n , which is always greater than unity, provides a measure of the degree of pseudoplasticity and is called the "structure number" (5). But the use of a power function of this type is often considered objectionable because the dimensions of the rate of shear $\frac{dv}{dr}$ depend on n and therefore vary from material to material.

D. Thixotropic materials

The term "thixotropy" means "change by touch" and was introduced by Peterfi (6) to describe an isothermal reversible sol-gel-sol transformation. When such a material is subjected to a shearing action, a decrease in viscosity is achieved but a rebuilding takes place on leaving the material to rest. More recently, the definition of thixotropy was broadened (8 and 9) to include materials which exhibit an isothermal reversible transformation from a higher to a lower viscosity gel. This transformation can be brought about either by an increase in the rate of shear followed by a rest period or by the application of a constant rate of shear over a period of time again followed by a rest period. When a thixotropic material is

used in a rotational viscometer to obtain an up-curve and a down-curve, the former will be curved while the latter will be straight (except for the lower part) and consequently the two curves will not coincide but form a loop (Figure 4b). This hysteresis loop is the criterion of thixotropy. On the other hand, when a thixotropic material is tested in a capillary tube viscometer, the material is sheared under an applied pressure and then discharged, and therefore no further measurements can be made on the sample in its broken-down state. In fact, the up-curve and the down-curve are made at the same thixotropic level and consequently the two curves will coincide. Hence such a viscometer is not capable of producing the characteristic hysteresis loop.

However, there has been a tendency to depart from the above concept of thixotropy and the term was sometimes loosely applied to non-Newtonian substances which did not display a hysteresis effect.

Goodeve and Whitfield (7) used the term "thixotropy" to describe the isothermal reversible decrease of viscosity with shear. In an attempt to obtain a measure of thixotropy, they define a variable x in terms of the apparent viscosity η and a residual viscosity η_0 so that

$$\eta - \eta_0 = k' x \quad (25)$$

where k' is a constant having the dimensions of viscosity. The

physical significance of x depends on the type of structure ascribed to the material used. It may be assumed to represent the concentration of links or cells in the material, and is, therefore, a measure of the internal structure present.

The spontaneous build-up is given by

$$\frac{dx}{dt} = k'' (x_m - x)^a \quad (26)$$

where k'' is a constant of proportionality, x_m is the maximum possible value of x , and a is the "order of reaction".

Assuming that "the rate of breakdown is proportional to the shear" and that the number of links disappearing per unit time is proportional to the number present (i.e., to x), the following equation may be written

$$-\frac{dx}{dt} = K S x \quad (27)$$

where S is the rate of shear and K is a dimensionless quantity representing the probability of a link breaking up in unit time under unit shear.

An equilibrium condition will be reached when the rate of build-up is equal to the rate of breakdown, and this occurs when the R.H.S. of equations (26) and (27) are equal, that is when

$$x = \frac{k'' (x_m - x)^a}{K S} \quad (28)$$

At high rates of shear or for weak structures, the equilibrium

value of x will be small compared with x_m and hence equation (28) can be simplified to

$$x = \frac{k'' x_m^a}{K S} \quad (29)$$

Substituting for x from equation (29) in equation (25), we get

$$\eta - \eta_0 = \frac{k' k'' x_m^a}{K} \cdot \frac{1}{S} = \frac{\theta}{S} \quad (30)$$

where θ is a constant for any particular system and is called the "coefficient of thixotropy". It has the dimensions of a force per unit area and represents the growth of structural viscosity with time divided by the probability of the viscosity being broken down in unit time by unit shear.

The apparent viscosity of a system conforming to the above conditions will, at high rates of shear, bear a linear relationship to the reciprocal of the shear (Figure 5). The coefficient of thixotropy is therefore the limiting slope of the viscosity versus the reciprocal shear curve as the shear approaches a high value. η_0 is the intercept of this curve on the η -axis and represents the theoretical viscosity when the structure is completely broken down.

The above theory is based on the assumption that all the links, forming the structure of the material, have the same strength. The validity of this assumption is very doubtful and the originators of the theory recognise this short-coming. In addition to this, the theory does not deal with the hysteresis effect observed in

VARIATION OF APPARENT VISCOSITY WITH RECIPROCAL SHEAR
FOR 11 % SUSPENSION OF CARBON BLACK
IN MINERAL OIL

FIG. 5

GOODEYE & WHITFIELD'S RESULTS

thixotropic materials and seems, therefore, to be only applicable to single consistency curves. Another weakness lies in the fact that only equilibrium conditions are considered, and no information is given regarding the viscosity variation during the breakdown.

Green and Weltman (10, 11, 12 and 13) take the area of the hysteresis loop obtained from a rotational viscometer as a measure of the thixotropic breakdown. They divide the breakdown into two parts: (a) breakdown with time, and (b) breakdown with rate of shear.

(a) Breakdown with time

This is the breakdown occurring at a constant rate of shear. Weltmann (10) gives the relationship between the rate of decrease in the plastic viscosity and the time of application of the shearing section, as

$$B = - \frac{dU}{dt} t \quad (31)$$

where U is the plastic viscosity, t is the time, and B is the "coefficient of thixotropic breakdown with time".

On integrating equation (31) the following expression is obtained

$$- B \log_e t = U + C \quad (32)$$

where C is the constant of integration. Hence, a plot of U against $\log_e t$ will give a straight line whose slope is the coefficient B which may be determined experimentally from the co-ordinates of any

two points, (U_1, t_1) and (U_2, t_2) , on the line by using the expression

$$B = \frac{U_1 - U_2}{\log_e t_2/t_1} \quad (33)$$

Weltmann arrived at three conclusions as a result of her work on the time coefficient:

- i) The yield value is independent of the time of application of the shearing stress, provided the top angular speed remains constant.
- ii) The rate of breakdown is independent of the top angular speed.
- iii) The time necessary for running an up-curve is the same as the time t in equation (31), i.e., the time required to reach a certain point A_t in Figure 6 is the same whether the measurement commences at T_2 on the torque axis and proceeds to A_t or starts at the point of maximum torque (when the top angular speed is applied suddenly) and proceeds to A_t by a horizontal path.

(b) Breakdown with rate of shear

This is the breakdown which occurs due to a change in the rate of shear. In Figure 6, the straight line T_2A represents the theoretical up-curve that would be obtained if no breakdown took place. If it is assumed that an up-curve could be run in zero time, there would still be a breakdown on account of the increasing rate of shear and this hypothetical curve is $T_2 A_{to}$ in Figure 6. Each top angular

THIXOTROPIC BREAKDOWN UNDER SHEAR

FIG. 6

speed is associated with an equilibrium torque A_{tE} and no further breakdown takes place unless the top speed is increased.

The two investigators have shown experimentally (11 and 12) that the area of the hysteresis loop is proportional to the square of the top angular speed w . Making the assumption that "the loss of torque due to breakdown is proportional to the rate of shear", they derive an expression for the area of the loop, as

$$A = \frac{w^2}{2 m S} \quad (34)$$

where A is the area of the loop, m is a constant for the paste, and S is an instrument constant.

Two further coefficients for the thixotropic breakdown, namely M and V , are introduced to describe the structural changes with increasing rates of shear

$$M = \frac{2(U_1 - U_2)}{\log_e (w_2/w_1)^2} \quad (35)$$

$$\text{and } V = \frac{(f_2 - f_1)}{(U_1 - U_2)} \quad (36)$$

The coefficient M is defined as the loss in shearing stress per unit increase in rate of shear, while V is the increase in the yield value per unit decrease in plastic viscosity. Shapiro (24) has shown that V is actually the value of the rate of shear corresponding to the point of intersection of the down-curves.

This theory seems to give satisfactory results for printing inks and is more generally accepted than that attributed to Goodeve and Whitfield. But the nature of the mechanism of thixotropy still remains unknown. It would appear (3), however, that the thixotropic structure is likely to be an oriented one with each particle acting like a magnet possessing a north-pole and a south-pole. Such a structure would explain the time lag which varies from particle to particle because some of the particles will always be nearer to the magnetic north-south alignment than others. Perhaps it ought to be mentioned at this stage that the mathematical evaluation of the flow for pseudo-plastic materials is considered (4) difficult and it seems to be even more so in the case of thixotropic materials.

CHAPTER II

FLOW OF CEMENT PASTES, MORTARS AND CONCRETE

A. Roller's theory

Roller (13 and 14) proposed a theory for the plastic deformation of "dispersions" and among these he includes neat cement pastes and mortars. His theory is particularly applicable to the compression of cylinders. In developing it he measured the deformation of a cylinder of the material under compression while the compression load was uniformly increased. Roller recognises that in addition to the plastic resistance, there is a viscous resistance to be overcome but he considers the influence of viscosity to be negligible at slow rates of deformation.

The apparatus used is shown in Figure 7. It mainly consists of two plates containing the specimen, a cup, and a stem. Lead shots are allowed to flow into the cup at a pre-determined rate and the load is transmitted through the stem, which moves in guides, to the top plate resting on the specimen. A recording pen is attached to the stem to record the change in the height of the specimen on a drum rotating at a constant speed. A typical experimental curve for the variation of the specimen height h with the load g is shown in Figure 8. The vertical distance OA on the graph represents the initial decrease in the height of the specimen due to its self-weight and the weight of

LOAD g

A NORMAL FLOW CURVE

FIG. 8

LOG g

PLOT FOR DETERMINING CONSTANTS
OF PLASTIC FLOW

FIG. 9

DIAGRAMATIC SKETCH OF
ROLLER'S APPARATUS

FIG. 7

LOAD g

ABNORMAL TYPES OF FLOW CURVE

FIG. 10

ROLLER'S RESULTS

the transmission system.

A plot of $\log h$ against $\log g$ gives a straight line relationship (Figure 9) and the slope of this line is used to calculate the constants for the plastic flow. Some of the materials tested gave a discontinuous curve (Figure 10a). Cement pastes gave a curve characterised by a "suspension of flow" (Figure 10b). Cement mortars, on the other hand, displayed a "failure during flow" (Figure 10c).

For an incompressible cylinder having a cross-sectional area a and a height h , the change in volume dv is given by

$$dv = a dh + h da = 2 a dh \quad (37)$$

The total plastic flow is

$$2 \int_{h_0}^h a dh = 4.605 v_0 \log h_0/h \quad (38)$$

where v_0 is the volume and h_0 is the original height of the cylinder. Roller states that the law underlying the observed linearity in the plot of $\log h$ against $\log g$ may be expressed as

$$k = \frac{dp / p}{dv / v_0} \quad (39)$$

where p is the applied compressive stress, v_0 is the volume of the specimen, and dv is the differential volume of plastic flow corresponding to an increment of pressure dp . The quantity k is called the "coefficient of renitence".

$$\text{Since } dv = -2 v_o \frac{dh}{h} \quad (40)$$

equation (39) may be rewritten as

$$k = \frac{dp/p}{dh/h} \quad (41)$$

if the factor 2 is neglected.

Integration leads to the relation

$$k = \frac{\log (p/p_o)}{\log (h_o/h)} \quad (42)$$

where p_o is the "yield value".

Since $g = p \cdot a$ and $a \cdot h = a_o \cdot h_o$,

$$\log (p/p_o) = \log (g/g_o) + \log (h/h_o) \quad (43)$$

Substituting from equation (43) in equation (42)

$$k + 1 = \frac{\log (g/g_o)}{\log (h_o/h)} \quad (44)$$

Therefore, the negative slope of the straight line obtained in the plot of $\log h$ against $\log g$ is equal to $(k + 1)$ and g_o is obtained by extrapolating the straight line back to its intersection with the line representing $\log h = \log h_o$. The "yield value" p_o is given by the ratio g_o/a_o where a_o is the initial mean area of the specimen. Roller found that the "yield value" decreases as the liquid content is increased.

In this theory, equation (42) should actually take the form

$$k = \frac{\log (p/p_o)}{\log (h/h_o)} \quad (45)$$

if the integration is performed correctly.

It is to be noted that the above theory is only applicable to slow rates of deformation and the complex behaviour of cement pastes and mortars limits its applicability to a great extent. Mason (15), however, found that the compression test provides a fairly good means of assessing the effects of additives.

B. L'Hermite's work

L'Hermite (17 and 18) tried to find a mathematical expression for the flow of fresh concrete. He used a ring-shaped metal box (Figure 11) cut at a plane normal to the axis of rotation and loaded by a piston of the same shape. The upper half of the box was rotated relative to the lower half at a given angular speed $v = \frac{d\theta}{dt}$, and the torque T and the deflection θ were measured.

The results of tests carried out under different normal pressures p are shown in Figure 12. When the values of the maximum shearing stress are plotted against the corresponding normal pressures, a straight line relationship is obtained (Figure 13). This behaviour led L'Hermite to state that fresh concrete obeys Coulomb's law. A coefficient of friction is accordingly defined by

$$k = \frac{R}{p} \quad (46)$$

L'HERMITE'S APPARATUS

FIG. 11

VARIATION OF SHEARING
STRESS WITH DEFLECTION

FIG. 12

RELATION BETWEEN MAXIMUM SHEARING STRESS AND
NORMAL PRESSURE FOR CONCRETE

FIG. 13

L'HERMITE'S RESULTS

where R is the "rigidity" of the mix and is equal to the maximum shearing stress obtained from the shearing stress-deflection graph (Figure 12). The intercept on the shearing stress axis in Figure 13 is considered as a proof that concrete possesses cohesion but is ignored in equation (46) for no apparent reason.

The work U , necessary to cause failure of the internal equilibrium is given by the area under the shearing stress-deflection curve between $\theta = 0$ and $\theta = \theta_m$, where θ_m is the value of θ at failure. Hence

$$U = \frac{k p \theta_m}{2} \quad (47)$$

L'Hermite takes the workability μ to be equal to the inverse of the work U and the expression he gives for it is

$$\mu = \frac{1}{k \theta_m} \quad (48)$$

The quantity p is left out in this expression presumably because different concrete mixes should be compared at the same normal pressure. Working on this principle, he developed a "rigidimeter" by means of which he "detected" the thixotropy of cement pastes.

When the "shear box" is vibrated on a vibrating table, the curve relating the maximum shear stress R to the normal pressure p changes from $O'I$ (Figure 14) to $O'V$ and finally to $O''A$. The intercept II in Figure 14 is called the "agitation pressure". The conclusions drawn from this investigation of the effects of vibration

CONCRETE W/C RATIO = 0.55 RATE OF DEFORMATION = 0.04 cm/sec.

RELATION BETWEEN SHEARING STRENGTH AND
APPLIED COMPRESSION FOR TESTS MADE DURING,
BEFORE, AND AFTER VIBRATION

FIG. 14

L'HERMITE'S RESULTS

on concrete, are that the vibration increases the coefficient of internal friction and that, during the vibration, the mix behaves as a Newtonian liquid obeying Stoke's law.

L'Hermite then proceeds to evaluate the "agitation pressure" II from the following expression:

$$II = A \frac{n}{3} V \frac{e}{1-e} D \quad (49)$$

where A is a constant allowing for energy absorption during impact, n is the frequency of vibration, V is the average speed of the moving particles, e is the volume of voids present, and D is the density of the mix.

In deriving the above expression, he is apparently (20) drawing an analogy between the movement of particles in the concrete mix and the movement of gas molecules in an enclosed space. In the latter case, the assumptions are made that no attraction between the molecules exists, and that the molecules occupy no volume and collide in a perfectly elastic manner. Such conditions are unobtainable in concrete, and therefore the validity of the above expression remains in doubt.

An equation for the movement of particles is then proposed

$$m \frac{d^2 x}{dt^2} + a \frac{dx}{dt} + b x = b x_0 \sin wt \quad (50)$$

where m is the mass of the particle, $(a \frac{dx}{dt})$ is the frictional force, $(b x)$ is the elastic restoring force, and $(x_0 \sin wt)$

represents "the vibration of the whole". Tattersall (20) points to a number of basic errors in the proof of the above theory which L'Hermite seems to have admitted in private communications to Tattersall.

C. Lobanov's work

Lobanov (21) determined the flow characteristics of cement pastes, cement mortars, and lime mortars in order to estimate the pressure required for pumping these materials through a pipeline. He used the Volarovich rotational viscometer which has a revolving external cylinder and a fixed internal cylinder bounded from below by hemispheres. The internal cylinder has a knurl to eliminate slip phenomena. The relevant radii of the external and internal cylinders used were 1.22 and 0.67 cms., respectively, giving a gap width of 0.55 cm.

When the flow in the gap is entirely laminar, he uses the Reiner and Rivlin equation but he gives an additional equation, to deal with the case in which the plug flow is not completely eliminated, in the form

$$\eta = \frac{f}{4 \pi n} \left[\frac{T}{T_o} - 1 - \log_e \frac{T}{T_o} \right] = \frac{f}{4 \pi n} F \left[\frac{T}{T_o} \right] \quad (51)$$

where n is the angular speed and T_o is the minimum torque at which shearing begins. The value of the function $F \left[\frac{T}{T_o} \right]$ is given in Volarovich's tables.

The results of this work pertaining to cement pastes and mortars are given in the table below and the consistency curves are shown in

Figure 15. The curvature of these curves away from the speed axis at a higher speed range is considered by Lobanov to indicate turbulence. He classifies the pastes as "visco-plastic bodies".

It is to be noted, however, that the water content in the pastes used was generally on the high side and sedimentation had apparently taken place in some of the tests described. In fact, the cement pastes that contained 30% and 33% water would be better described as cement slurries.

Lobanov's Results

Material	Water content % by weight	Yield value f in dynes/sq.cm.	Plastic viscosity in poises
Cement pastes	24 1:3	480	24.0
	30 1:1	107	14.5
	33	32	3.9
Cement mortars	18.5	950	34.4
	22.0	600	33.0

LOBANOV'S RESULTS FOR CEMENT PASTES
TESTED IN A ROTATIONAL VISCOMETER

FIG. 15

D. Papadakis' approach

Papadakis (25) used a rotational viscometer to study the rheology of cement suspensions. His viscometer is similar to that described by Dellyes (26), having a bob in the form of a hollow cylinder open at the bottom, and a revolving cup. To eliminate the effects associated with the "false set" phenomenon, all the pastes were mixed for a period of 10 minutes prior to testing. Consistency curves for pastes having a water/cement ratio between 0.43 and 1.22 (by weight) were obtained immediately after the mixing operation and also 5, 15, and 30 minutes after it. All the curves thus obtained for any one paste were found to be practically coincident and the conclusion was drawn that the rheological parameters determined from a test performed immediately after mixing remain unchanged for a period of up to 30 minutes. A typical consistency curve is shown in Figure 16. The shape of the curve seems to suggest that the paste behaves as a Bingham plastic. If the plastic viscosity is plotted on a logarithmic base against the cement concentration by volume, a straight line is obtained (Figure 17). An expression for the plastic viscosity U is therefore given as

$$U = \alpha e^{\beta \cdot R} \quad (52)$$

where R is the cement concentration by volume, while α and β are constants.

Papadakis found, however, that the constant α was equal to the

CONSISTENCY CURVE FOR CEMENT PASTE

PAPADAKIS' RESULTS

FIG. 16

FIG. 17

FIG. 18

PAPADAKIS' RESULTS

water viscosity at the test temperature and therefore, Arrhenius's formula was considered to be directly applicable

$$\eta = \eta_o e^{k \cdot c} \quad (53)$$

where η is the viscosity of the paste, η_o is the viscosity of the liquid phase, c is the concentration, and k is a constant dependent on the nature of the solid phase, and the temperature. The variation of the yield value f with the cement concentration by volume (Figure 18) was found to have the same type of relationship as that obtained for the viscosity in equation (52).

Papadakis also found that the paste displayed a light thixotropic effect as the water/cement ratio approached 0.39. But apparently his main interest was in grouts and no attempt was made to study cement pastes having a consistency comparable to that obtained in normal concrete work. Nevertheless, as a result of this work serious doubts are cast on the accepted method (27) of measuring the consistency of grouts which depends on measuring the time required for a given volume of material to flow through a calibrated orifice, because the plug flow in such a case cannot be eliminated. In fact, the time of flow thus determined depends on the specific weight of the paste, its rheological constants, and its degree of thixotropy. It appears, therefore, that it is misleading to define the "injectability" of a cement grout by a single quantity except, perhaps, when such a quantity is a function of the entire flow curve (as in the method suggested by the writer in Chapter VI).

E. Tattersall's work

Tattersall (20, 22 and 23) used a rotational viscometer to investigate the rheology of cement pastes having a consistency comparable to that obtained in normal concrete work. The viscometer was of the cup-and-bob variety with the cup as the revolving part. The relevant radii were 1.3 and 1.5 cm., giving a gap of 2 mm. and maximum and minimum rates of shear of 0.84ω and 0.63ω , in reciprocal seconds, respectively, where ω is the angular speed of the cup in r.p.m. The torque was measured by means of two close-coiled helical springs which produced a couple restraining the movement of the bob.

Cement pastes having a water/cement ratio below 0.28 were found to be too thick to be used in the viscometer, while on the other hand, pronounced sedimentation occurred at water/cement ratios exceeding 0.35. The mixing time was $\frac{1}{2}$ to $\frac{3}{4}$ minute and the actual measurements were commenced $4\frac{1}{2}$ minutes after the first drop of water was added. A typical set of successive up-curves and down-curves, for the same sample, is shown in Figure 19. From a number of such graphs Tattersall arrived at three conclusions:

- i) The obtaining of hysteresis loops indicates that a structural breakdown takes place in the paste.
- ii) There is little or no tendency for the structure to build up again in a time period comparable to that taken for an experiment, namely, 5 to 10 minutes.

SPEED OF OUTER CYLINDER (R.P.M.)

DEFLECTION OF INNER CYLINDER (mm)

DEFLECTION OF INNER CYLINDER d (mm)

TIME (SEC.)

-47-

HYSTERESIS CURVES FOR 0.3 W/C PASTE

BREAKDOWN CURVE FOR 0.3 W/C PASTE AT 386 R.P.M.

FIG. 19

TIME (SEC.)

LOGARITHMIC BREAKDOWN CURVES FOR 0.3 W/C PASTE

FIG. 21

FIG. 20

B PLOTTED AGAINST $w(w-w_1)$ FOR VARIOUS W/C RATIOS

FIG. 22

- iii) All the curves when extrapolated intersect approximately at a point on the torque axis indicating that there is little or no change in the yield value during breakdown.

He then proceeded to investigate the breakdown of cement pastes under constant rates of shear for different water/cement ratios and different constant speeds, and obtained curves similar to the one shown in Figure 20. A plot of $\log (d - d_E)$ against the time t gives a straight line relationship (Figure 21), where d is the deflection of the bob at any time t after the commencement of the breakdown, while d_E is the equilibrium value of d (reached when the breakdown associated with the speed used is virtually completed). When d_0 , the extrapolated value of d at $t = 0$, is plotted against the corresponding angular speed, a straight line is again obtained and the initial values of the plastic viscosity U and the yield value f are evaluated from it. It should be stated, however, that the writer has found this method of determining the initial values of the variables to be entirely unsatisfactory due to the effect of the inertia of the bob coming into play on starting the motor. A fuller discussion of this point is given in Chapter VI where the writer's experimental work is discussed.

Tattersall proposed an empirical exponential expression to fit the curve shown in Figure 20, in the form

$$T - T_E = (T_0 - T_E) \cdot e^{-B \cdot t} \quad (54)$$

where T is the torque at any time t , T_0 and T_E are the initial and the equilibrium values of T , respectively, and B is a constant depending on the rate of shear. The actual value of B is obtained from the slope of the straight line in the graph of $\log (d - d_E)$ against time.

A theoretical derivation of this equation is then presented as follows:

The work done in a rotational viscometer in a small time dt is $2 \pi w T dt$, where w is the angular speed of the cup in r.p.m. Therefore, in a time t , the work done W is given by

$$W = \int_0^t 2 \pi w T . dt \quad (55)$$

This work is used in:

- (a) overcoming normal viscous forces;
- (b) breaking the structure;
- and (c) keeping the structure broken.

The third item listed above is considered negligible because of the absence of any significant tendency for a rebuilding of the structure to take place. The energy is therefore assumed to be distributed between items (a) and (b) only.

At a constant rate of shear, the torque decays from an initial value T_0 to a final value T_E . The torque T_E is regarded as being independent of the "breakable structure" and is taken to

represent that part of the torque used in overcoming normal viscous forces. Hence, the work W_v done against the viscous forces in a time t is

$$W_v = \int_0^t 2 \pi w T_E dt \quad (56)$$

If the structure is assumed to consist of linkages and the torque in excess of the "viscous torque" is at any time proportional to the number of linkages still existing, then

$$T - T_E = Z (n_o - n) \quad (57)$$

where n_o is the number of linkages originally existing, n is the number broken at a time t , and Z is a constant at constant rate of shear. Z will be dependent on the rate of shear and may be written as $f(w)$. Hence n may be written as

$$n = - \left[\frac{T - T_E}{f(w)} - n_o \right] \quad (58)$$

If the work done in breaking one link is ϕ , the work W_s done in breaking n links is $(n \phi)$ or

$$W_s = - \phi \left[\frac{T - T_E}{f(w)} - n_o \right] \quad (59)$$

Adding equations (56) and (59) and equating to equation (55)

$$\int_0^t 2 \pi w T dt = - \phi \left[\frac{T - T_E}{f(w)} - n_o \right] + \int_0^t 2 \pi w T_E dt \quad (60)$$

and on differentiating

$$2 \pi w T = - \frac{\phi}{f(w)} \cdot \frac{dT}{dt} + 2 \pi w T_E \quad (61)$$

The solution of this equation may be put in the form

$$(T - T_E) = (T_o - T_E) \exp \left[- 2 \pi w \cdot f(w) \cdot t / \phi \right] \quad (62)$$

where $T = T_o$ when $t = 0$.

Equation (62) will be identical with equation (54) if

$$B = \left[2 \pi w \cdot f(w) \right] / \phi \quad (63)$$

The function $f(w)$ was originally (20 and 22) supposed to be equal to kw so that

$$B = 2 \pi k w^2 / \phi \quad (64)$$

where k is a constant, but at a later stage (23) the expression for B was changed to

$$B = \frac{2 \pi k}{n_o \phi} \cdot w (w - w_1) \quad (65)$$

where w_1 is the speed obtained from the co-ordinate of the point of intersection of the two straight lines representing the variation of T_o and T_E with the speed.

The above theory seems to be quite convincing, but a plot of B against either w ($w - w_1$) (Figure 22) or w does not give the predicted straight line passing through the origin. The assumption that the same amount of energy ϕ is required to break any linkage in the structure is not in agreement with the basic requirements (3) for a satisfactory model to represent the thixotropic structure. These requirements stipulate that the bond between the particles must be different for different particles or groups of particles. Perhaps it should be pointed out in this context that the same criticism is levelled against Goodeve and Whitfield's theory.

Tattersall's conclusion that the yield value remains constant throughout the breakdown is experimentally shown by the writer to be incorrect (see Chapter VI), but this will only affect the viscosity equation since the yield value, as such, does not appear in the above theoretical approach. In spite of the above criticisms and Tattersall's reference to the "departure from linearity of a considerable number of the $\log (d - d_E)$ - time breakdown curves", this work constitutes an important step forward towards the understanding of the rheology of cement pastes and further references to it are made in this thesis.

CHAPTER III

THE WORKABILITY OF CONCRETE

From the early days of the introduction of concrete as a reliable building material, it was realised that the water content affected the strength to a certain extent even though the concrete mixes used at the time may be classified as "wet" mixes. With the advent of reinforced concrete it became increasingly evident that some reliable method of measuring the consistency of the concrete mix was essential. Too little water results in increased voids due to the difficulty in placing, while, on the other hand, too much water causes segregation and loss of strength.

The term "workability" is used to describe the consistency of mortars and concrete and is defined in A.S.T.M. Standards (29) as "that property of a body by virtue of which it resists flow". This definition is rather vague and a better one is given by Glanville, Collins and Matthews (28). They define the workability as "that property which determines the amount of useful internal work necessary to produce full compaction". A number of tests have been devised for measuring the workability of concrete and many of them are referred to in the literature (28, 30, 31 and 32), but those tests which are generally accepted or have some bearing on the rheological approach to the problem are briefly described below.

A. The slump test

This test is arbitrary in nature and bears no direct relation to the work required in compacting the concrete. In this test, a mould in the form of a frustum of a cone having an upper diameter of 4 in., a lower diameter of 8 in., and a height of 12 in., as shown in Figure 23, is used. The mould is placed on a smooth horizontal plate and filled with the concrete to be tested in four approximately equal layers; each layer being rodded 25 times by a standard rod. The top layer is then struck level with the top of the mould, the cone immediately lifted and the amount by which the concrete slumps is measured.

Although this test is widely used for wet mixes because of its simplicity, it is generally recognised that it does not give a true measure of workability.

B. The compacting factor test

The compacting factor test (28 and 33) measures the degree of compaction achieved by imparting a standard amount of work to a given mass of concrete, and is based on the following assumptions:

- (a) the ratio of useful to applied work is constant for all mixes;
- (b) all mixes with a particular compacting factor require the same amount of applied work for full compaction.

The apparatus consists of two conical hoppers A and B (Figure 24) fitted with quick-release flap doors and mounted, at different levels,

THE SLUMP CONE

FIG. 23

INTERNAL DIMENSIONS OF
COMPACTING FACTOR APPARATUS

FIG. 24

THEORATICAL RELATION BETWEEN COMPACTING FACTOR
AND APPLIED WORK

FIG. 25

vertically above a cylindrical mould C which is clamped to a base plate. With both hopper doors closed, hopper A is loosely filled with concrete and its flap door is then released to allow the concrete to overfill hopper B which is a little smaller than hopper A. This action is supposed to bring the concrete in hopper B to a standard state. The flap door of hopper B is then released to fill the cylinder to overflowing and the excess material above the top rim of the cylinder is removed. The compacting factor is defined as the ratio of the weight of concrete in the cylinder thus filled to the weight of an equal volume of fully compacted concrete. Figure 25 shows the theoretical relationship between the compacting factor and the applied work.

This test enables the detection of small variations in the workability over a wide range of medium workability mixes, and has been used in the main work on mix design (34, 35 and 36). As compared with the slump test, the compacting factor test is much more reliable and covers a bigger range of consistencies, because it may be used for mixes which give no slump. A method of calculating the compacting factor in terms of the "surface index" and the "angularity index" of the aggregate, the water/cement ratio, and the aggregate/cement ratio, has been recently developed by Murdoch(45), and his calculated values are said to be in agreement with his experimental results.

C. The flow table

The flow table method of measuring workability is an empirical one and is based on the measurement of the deformation of a mass of concrete of a given shape when subjected to a "jolting" action produced by a cam movement. The concrete to be tested is cast in the form of a frustum of a cone on a metal table, by means of a mould similar to the slump cone but not so high. The casting is usually done in two layers each of which is given a standard amount of tamping with a rod. After the mould is lifted, the table is raised and dropped by turning a handle at a given rate. Under the jolting action, the diameters of the concrete cone tend to increase; and the diameter of the base after a given number of jolts, usually 15, is measured. The increase in diameter expressed as a percentage of the original value is taken as a measure of workability.

The flow table is able to measure consistencies over a similar range to that of the slump test and a standard version of it is used in American practice (38).

D. Powers' remoulding test

In this test the effort required to change a mass of concrete from one shape to another is considered as a measure of workability. The apparatus (39) is mounted on a flow table and consists of two cylinders B and C placed one inside the other as shown in Figure 26. The vertical clearance between the two cylinders can be varied. A

FIG. 26

FIG. 27

slump cone is placed inside the inner cylinder and filled with concrete in a standard manner. The slump cone is then removed, the plate A brought into contact with the concrete, and the flow table operated. The number of $\frac{1}{4}$ in. drops required to re-mould the concrete into a cylindrical form is taken as a measure of workability. A mark on the vertical rod attached to plate A indicates the completion of the transformation.

Wuerpel (40) replaced the flow table by a vibrating table and measured the time required to re-mould the concrete. Walz (48) used a similar apparatus to Wuerpel's with a frequency of 3,000 v.p.m. and an amplitude of 0.4 mm. to study the variation of the compaction time with the water content, for three different gradings. For each grading he used three different aggregate/cement ratios and found that for any one grading, the results fell on one curve irrespective of the quantity of cement used. His results are shown in Figure 27.

E. The Vebe test

The apparatus used in this test was originally developed by Bahrner (19) and consists of a metal cylinder A (Figure 28) mounted on a vibrating table B. A slump cone C is placed inside the cylinder and filled with concrete in a standard manner through a funnel D. The cone is then removed, the transparent disc E brought to rest on the concrete, and the vibrating table set in motion. Thus the concrete is re-moulded into a cylindrical shape, and the re-moulding

THE VEBE APPARATUS

FIG. 28

SLUMP ON REMOVAL

A TYPICAL VEBE TRACE

FIG. 29

is considered to be complete when the concrete is in full contact with the disc. The number of seconds required to complete the re-moulding operation is taken as a measure of the workability.

The Vebe test is capable of measuring the workability of very dry mixes for which the standard amount of work associated with the compacting factor test is too small to give a true indication of this property. There is, however, some difficulty in determining the exact instant at which the re-moulding operation ends. In an effort to overcome this drawback, Erntroy (42) incorporated a pen recorder to record the movement of the transparent disc, and a typical recorder trace (47) is shown in Figure 29. Skerl (43) improved on this by taking the time in seconds, required for the disc to reach 95% of its total movement, as a measure of the workability.

It is to be noted that in measuring the workability in time units, it is implied that the rate of energy input to the concrete is constant irrespective of the consistency of the mix. In fact, Cusens (44) considers this to be the case. But the experimental evidence presented by the writer in Chapter VI seems to cast some doubt on the validity of this assumption, which is discussed in more detail in Chapter IV.

Meyer (46) presented a modified method of measuring the workability using the standard Vebe apparatus. The cylindrical container is loosely filled with concrete and the transparent disc is allowed to rest on the mix. The vibrating table is then set in motion and a

COMPACTION OF CONCRETE

SECONDS

MEYER'S TRACE FOR CONCRETE
WITH A PLASTICIZER ($w/c=0.5$)

FIG. 30

CURVE A — PLAIN CONCRETE, 1:6 BY WEIGHT
CURVE B — CONCRETE WITH A PLASTICIZER, 1:6 BY WEIGHT

RELATION BETWEEN WORKABILITY (TAKEN AS AREA UNDER TRACE)

AND WATER/CEMENT RATIO
MEYER'S RESULTS

FIG. 31

trace of the movement of the disc (Figure 30) is recorded on a rotating drum. The area under the trace in millimetre-seconds is considered to represent the useful work done in compacting the concrete and is taken as a measure of its workability. A plot of the results is shown in Figure 31. Meyer states that the standard Vebe test result is a function of the consistency of the concrete and its workability, whereas, the area under the above trace is a measure of the workability alone.

It should be pointed out here that Meyer also assumes a constant rate of energy input into the concrete and therefore, if this assumption is valid, the work done on the concrete should be proportional to the time taken for complete compaction. Hence, the time base of the trace represents the total energy input to some scale, and the dimensions of the area under the trace are in fact those of (work x distance) and not the dimensions of work alone.

CHAPTER IV

THE VIBRATION OF CONCRETE

The realisation that a decrease in the water content of the concrete mix is accompanied by an increase in its crushing strength, led to a general reduction in the water/cement ratios used. But it was also established that if the water content is too low poor concrete is produced because of the difficulty in eliminating the air voids from the mix. To overcome this effect, tamping and vibration techniques were introduced.

Stewart (49) regards the vibration of concrete as a purely packing process. He divides the consolidation of concrete into three distinct stages, namely "initial settlement", "redistribution and de-aeration", and "stabilisation". The first stage occurs immediately after the vibration is started and consists of a general subsidence of the material without any change in the surface distribution of the particles being produced. The second stage is characterised by a sudden intense activity in the mix - the concrete flows into all corners of the mould while the air bubbles are being expelled and the surface glistens with moisture. In contrast to the first two stages, the last stage is characterised by a marked inactivity in the concrete and only occasional air bubbles break to the surface. Dutron (50) attributes the easier movement of particles under vibration to the liberation of

capillary water at the surface of the aggregates.

In this chapter, two distinct aspects of vibration are considered:

- A. The effects of amplitude, frequency, and acceleration.
- B. The energy input to the concrete.

A. The effects of amplitude, frequency, and acceleration

In order to investigate the effect of vibration on the flow of cement pastes, Auerbach (51) attached a capillary viscometer to a vibrating table. He kept the frequency of the table at a constant value of 6,000 v.p.m., and measured the flow of the paste at different amplitudes. Two fairly fluid pastes having water/cement ratios of 0.5 and 0.6 were used. The results, which are shown in Figure 32, indicate that a breakdown was taking place in the cement paste.

Walz (48) measured the rate of flow of cement pastes through a tube under vibration at different frequencies and constant amplitudes. He used two water/cement ratios of 0.4 and 0.5. The variation of the flow with the frequency is shown in Figure 33, and it can be seen that his results are similar to those obtained by Auerbach - in both cases an increase in acceleration increases the rate of flow.

Steward (49) measured the density and the strength of 4 in. cubes of concrete after vibrating them for a constant period of 8 minutes on a vibrating table at various amplitudes and frequencies. From the results thus obtained (Figures 34 and 35) he concluded that the density

AUERBACH'S RESULTS FOR
CEMENT PASTES

FIG. 32

WALZ'S RESULTS FOR
CEMENT PASTES

FIG. 33

RELATION BETWEEN DENSITY AND ACCELERATION

FIG. 34

RELATION BETWEEN STRENGTH AND ACCELERATION

FIG. 35

STEWART'S RESULTS FOR 1:2.28:3.74 (BY WT.)
CONCRETE WITH $W/C = 0.5$

and the strength of concrete increase under vibration. He also found that the best results were obtained at a frequency of 6,000 v.p.m.

The first interim report (52) of the joint sub-committee of the Institution of Civil Engineers on vibration describes tests carried out at the Building Research Station on concrete mixes having the same aggregate grading and aggregate/cement ratio, but different water/cement ratios. Cubes were cast from each of three mixes, and vibrated on a vibrating table for a constant period of 2 minutes. The influence of acceleration and frequency on the strength and the density of these samples was studied. The variation of the concrete strength with acceleration is shown in Figures 36, 37 and 38 for the various frequencies used. For the mixes having a water/cement ratio of 0.5 or 0.6, the best results were obtained at the highest frequency used, viz. 8,000 v.p.m., while, for the mix having a water/cement ratio of 0.4 a frequency of 3,000 v.p.m. gave the best results. For each of the three mixes used there is a critical acceleration below which the strength falls off rapidly, and above which little increase in strength occurs. The drier the mix, the higher is the critical acceleration. Regarding the frequency of vibration, the report states that it is not normally of such importance as the acceleration. A high frequency leads to a better surface finish so long as the vibration is sufficient to consolidate the concrete. For any given acceleration, however, :

FIG. 36

FIG. 37

FIG. 38

RELATION BETWEEN STRENGTH AND ACCELERATION

1 : 1.8 : 4.2 MIX (BY WT.)

BUILDING RESEARCH STATION'S RESULTS

the time required for full compaction increases with the frequency. This effect is more noticeable with dry mixes.

In the part of the Building Research Station work described above, the cube crushing strength of the concrete is taken as a criterion for compaction because it was established in other sections of the work (not mentioned in this thesis) that the strength ratio, defined as the ratio of the actual strength to that of the fully compacted concrete, is closely allied with the density ratio which is defined in a similar manner.

Davies (53) investigated the effects of the frequency, the amplitude, and the type of vibration on the compaction of concrete. He used two dry mixes with an aggregate/cement ratio of 4.44 by weight, and water/cement ratios of 0.32 and 0.33. Three types of vibration produced by vertical circular, horizontal circular, and vertical simple harmonic linear movements were examined. The acceleration he used ranged from 3.6 g to 25 g and the frequency range was between 2,000 and 12,000 v.p.m. Davies plotted the cube crushing strength at 28 days against the velocity and the acceleration (Figures 39 and 40) and arrived at the following conclusions:

- i) The effectiveness of vibration depends mainly on its acceleration and not on the individual values of its frequency and amplitude, but very small amplitudes of the order of 0.002 in. are comparatively ineffective.

RELATION BETWEEN STRENGTH AND VELOCITY

FIG. 39

RELATION BETWEEN STRENGTH AND ACCELERATION

FIG. 40

DAVIES RESULTS

- ii) Of the three types of vibrations used, the vertical circular vibration yields the best results.
- iii) The effectiveness of vibration increases with its acceleration, up to 20 g , but above 12 g the increase is small.

Desov (54) takes the time t necessary for a cone of concrete to change its shape to a cylindrical form (as in Wuerpel apparatus) as a criterion of the effectiveness of vibration. He gives an approximate relationship between the above time, the amplitude, and the frequency as

$$t = t_0 - \frac{\alpha}{A \cdot w} \quad (66)$$

where t_0 is a small constant, α is a thixotropy constant, A is the amplitude, and w is the frequency.

In deriving the above expression, Desov has apparently studied only one concrete mix for which he found the constant t_0 to be negligible. His results, however, are stated to be too "inexact" for judging the applicability of the above equation.

Cusens (55) uses the Vebe time and the compaction time for 6 in. cubes to compare the efficiency of vibration. He carried out tests on 6 concrete mixes at different frequencies and amplitudes to determine the Vebe time and the compaction time. When the acceleration is plotted against the reciprocal of either time, a straight line is obtained

(Figures 41 and 42). For each mix, he found that there was an optimum frequency between 3,000 and 6,000 v.p.m. giving the shortest compaction time. Frequencies at the lower end of the range are said to be preferable for very dry mixes while those at the upper end of the range are considered suitable for wetter mixes. It is also stated that there is little virtue in using high frequencies of the order of 12,000 v.p.m.

In part of his work, Cusens kept the frequency constant at 6,000 v.p.m. and studied the effect of different vibration times on the cube crushing strength of concrete, at various accelerations. Some of the results thus obtained are shown in Figures 43, 44 and 45. It can be seen from these graphs that for the wetter mixes, the curves are closely spaced, while, the the drier ones, the curves are widely separated. Cusens' results and conclusions are in agreement with those described in the first interim report of the joint sub-committee of the Institution of Civil Engineers (52). Perhaps it should be mentioned that the writer derives similar conclusions from his work with the rotational viscometer, and a further reference to this similarity is made in Chapter VI.

B. The energy input to concrete

Venkatramaiah (32 and 56) used a wattmeter to measure the energy input to a vibrating table while a known weight of concrete was being

-75-

MIX H

FIG. 44

CUSENS' RESULTS

MIX J

FIG. 45

MIXES G, H & J HAVE AGG./CEM. RATIO OF 6:1

CUSENS' RESULTS

compacted. He assumed the total power input to the table - as determined from the wattmeter curve (Figure 46) - to be expended on the following items:

- (a) hysteresis losses in the magnet;
- (b) eddy currents losses;
- (c) resistance losses in the coil;
- (d) damping losses in the table and the concrete;
- (e) compaction of concrete.

He assessed items (a), (b) and (c) by measuring the power input to the table, with its air gap jammed with an insulating material, for different frequencies and voltages. The damping losses were measured for the fully compacted concrete and assumed to have remained constant during the compaction process. Cusens (55) found that this was not the case and considered it reasonable to suppose that, at the commencement of compaction, the correct figure could have been double the value used by Venkatramaiah. Although the damping losses are usually a small percentage of the total losses, their magnitude, in a number of Venkatramaiah's results, is only a little less than the figure quoted for the work put into the concrete during compaction.

As it was not possible for Venkatramaiah to make a continuous record of the voltage, Cusens repeated the work and took readings of the voltage, the current, and the wattage throughout the compaction of the concrete. In order to estimate the electrical losses, he

VARIATION OF INPUT TO TABLE WITH TIME
DURING VIBRATION

(A TYPICAL WATTMETER CURVE OBTAINED BY VENKATRAMAIAH)

FIG. 46

determined the power input to the table for different values of voltage and current, with the table's electromagnet jammed. Cusens' results are shown in Figure 47. The difference between the curve representing the total power input and that representing the electrical losses is taken as the work done to overcome the damping effects and to compact the concrete. At first sight, the scatter of the points appears to be reasonable, but, when one considers that the amount of work put into the concrete is determined from the difference between the two curves, it becomes immediately clear that the error involved in estimating this work may be considerable. Moreover, since the work done in overcoming damping was found to be far from constant, it seems reasonable to have some doubts regarding the adequacy of this method of measuring the net energy taken by the concrete. Cusens (55) recognises this and apparently makes no attempt to evaluate the energy in question, yet he makes the assumption that the energy taken by the concrete is proportional to the time necessary for compaction, irrespective of the water/cement ratio of the mix. It appears, however, that Cusens was led into making this assumption by the fact that a plot (58) of the energy input to the concrete against the compaction time as determined from the wattmeter curve in Venkatramaiah's results, gave an approximate linear relationship. Perhaps it should be mentioned here that the determination of the compaction time from the wattmeter curve yields only approximate results because of the

ENERGY EXPENDITURE DURING VIBRATION

FIG. 47 CUSENS RESULTS

difficulty in determining the "end point". Furthermore, the results obtained by the writer from the rheological approach to the problem (see Chapter VI) do not appear to support the above assumption; although one has to bear in mind that the writer's results are obtained for cement pastes and mortars, while the results discussed above are related to concrete.

CHAPTER V

THE ROTATIONAL VISCOMETERS

In the experimental work carried out by the writer, the bulk of the tests on cement pastes and fresh mortars were performed with a "double-gap" rotational viscometer designed by him and constructed under his supervision. But it seems that such a viscometer is not very commonly used in rheological studies and therefore, the writer's derivation of the flow equations is presented in this chapter. These equations were used by the writer to evaluate the instrument constants and to determine the necessary design conditions.

A single-gap viscometer built at the Building Research Station was also used in various parts of the work to obtain corroboratory evidence regarding the behaviour of the paste.

A. Derivation of the flow equations for the double-gap viscometer

The double-gap rotational viscometer (Figure 48a) consists of three cylinders of different radii concentrically mounted so that two gaps are enclosed between the curved surfaces of the cylinders. The material to be tested is usually poured or extruded into the gaps and then sheared by rotating the middle cylinder relative to both the inner and the outer cylinders (or vice versa), and the torque transmitted through the past is measured. It is, however, generally desirable to

GENERAL DOUBLE-GAP VISCOMETER

(a)

SINGLE-GAP VISCOMETER

(b)

A PRACTICAL DOUBLE-GAP VISCOMETER

(c)

ROTATIONAL VISCOMETERS

FIG. 48

keep either the middle cylinder or the inner and the outer cylinders stationary to facilitate the torque measurement.

For a single-gap rotational viscometer (Figure 48b), Reiner (57) derived an expression for the distribution of the angular speed w across the gap. For the general case, the value of w at any radius r is given by

$$w = \frac{w_i R_i^2 \left[\frac{R_e^2}{r^2} - 1 \right] - w_e R_e^2 \left[\frac{R_i^2}{r^2} - 1 \right]}{R_e^2 - R_i^2} \quad (67)$$

where R_i and R_e are the radii of the internal and the external cylinders, respectively, while w_i and w_e are the corresponding angular speeds of the two cylinders.

Differentiating the above expression with respect to r

$$\frac{dw}{dr} = \frac{-2 w_i R_i^2 \frac{R_e^2}{r^3} + 2 w_e R_e^2 \frac{R_i^2}{r^3}}{R_e^2 - R_i^2} \quad (68)$$

$$\text{i.e.,} \quad \frac{dw}{dr} = \frac{2 R_i^2 R_e^2 (w_e - w_i)}{r^3 (R_e^2 - R_i^2)} \quad (69)$$

$$\text{Putting } a = \frac{R_i^2}{R_e^2} \text{ in equation (69)}$$

$$\frac{dw}{dr} = \frac{2 R_i^2}{r^3} \frac{(w_e - w_i)}{(1 - a)} \quad (70)$$

The rate of shear within the material in the gap, at any radius r , is given by

$$\text{rate of shear} = r \frac{dw}{dr} = \frac{2 R_i^2}{r^2} \frac{(w_e - w_i)}{(1 - a)} \quad (71)$$

From equation (71), it may be seen that the rate of shear is maximum where r has its minimum possible value, namely, R_i . The maximum rate of shear is then given by

$$\left(r \frac{dw}{dr} \right)_{\text{max.}} = \frac{2(w_e - w_i)}{(1 - a)} \quad (72)$$

The minimum rate of shear occurs where $r = R_e$ and is given by

$$\left(r \frac{dw}{dr} \right)_{\text{min.}} = \frac{2(w_e - w_i)}{(1 - a)} \frac{R_i^2}{R_e^2}$$

$$\text{i.e., } \left(r \frac{dw}{dr} \right)_{\text{min.}} = \frac{2(w_e - w_i)}{(1 - a)} \cdot a \quad (73)$$

It is clear from equations (72) and (73) that the maximum and the minimum rates of shear are solely dependent on the ratio a of the radii and the angular speeds, the actual values of the radii being immaterial.

In order to find the average rate of shear across the gap, equation (71) should be integrated with respect to r for values of r between R_i and R_e . The area A under the rate of shear curve (Figure 49) is given by

$$A = \int_{r=R_i}^{r=R_e} \frac{2(w_e - w_i)}{(1 - a)} \frac{R_i^2}{r^2} dr \quad (74)$$

Integrating equation (74) we get

$$\begin{aligned} A &= \left[-\frac{2(w_e - w_i) R_i^2}{(1 - a)} \frac{1}{r} \right]_{R_i}^{R_e} \\ &= \frac{2(w_e - w_i) R_i^2}{(1 - a)} \left[\frac{1}{R_i} - \frac{1}{R_e} \right] \\ \text{i.e., } A &= \frac{2(w_e - w_i) R_i^2}{(1 - a)} \cdot \frac{R_e - R_i}{R_i R_e} \end{aligned} \quad (75)$$

Now,

$$\text{the average rate of shear} = \frac{A}{R_e - R_i}$$

therefore,

$$\left(r \frac{dw}{dr} \right)_{\text{average}} = \frac{2(w_e - w_i) R_i}{(1 - a) R_e} \quad (76)$$

RATE OF SHEAR CURVE

FIG. 49

Equation (76) indicates that for any given ratio of the radii, the same average rate of shear is obtained at the same relative angular speed.

If the inner cylinder remains stationary, while the outer cylinder is rotated with an angular speed Ω , as in the case of the Couette-Hatschek viscometer, the average rate of shear is given by

$$\left(r \frac{dw}{dr}\right)_{\text{average}} = \frac{2 \Omega}{(1 - a)} \cdot \frac{R_i}{R_e} \quad (77)$$

On the other hand, if, as in the Searle viscometer, the outer cylinder is kept stationary while the inner cylinder is rotated with an angular speed Ω , the average rate of shear is given by

$$\left(r \frac{dw}{dr}\right)_{\text{average}} = - \frac{2 \Omega}{(1 - a)} \cdot \frac{R_i}{R_e} \quad (78)$$

The negative sign merely indicates that the angular speed decreases as the radius increases.

The double-gap viscometer shown in Figure 48c is, in fact, a combination of the two types of the single-gap viscometer mentioned above.

Let

- R_1 = the internal radius of the outer cylinder,
- R_2 = the external radius of the middle cylinder,
- R_3 = the internal radius of the middle cylinder,

and R_4 = the external radius of the inner cylinder,
as shown in Figure 48c.

It follows from equations (72), (73) and (76), that if the paste in the two gaps is to be subjected to the same rate of shear, then the radii must be so chosen that the following relationship is satisfied:

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \quad (79)$$

It would appear that it is most important that this condition be satisfied for any double-gap viscometer which is to be used to investigate the rheology of thixotropic pastes. Otherwise, the paste in the two gaps will be subjected to different rates of shear, and therefore, the extent of the breakdown of the paste in the two gaps will not be the same. This will result in different plastic viscosities existing in the gaps at any given time.

For a single-gap rotational viscometer operating under laminar flow conditions, the relationship between the angular speed and the torque is given in terms of the plastic viscosity, the yield value, and the instrument constants, by the Reiner and Rivlin equation

$$\Omega = \frac{\mu T}{4 \pi h} \left[\frac{1}{R_i^2} - \frac{1}{R_e^2} \right] - \mu f \log_e \frac{R_e}{R_i} \quad (16)$$

where

Ω = the angular speed of the rotating cylinder in rad/sec.

μ = the mobility (or reciprocal of the plastic viscosity)
in (poise)⁻¹.

T = the torque exerted on the stationary cylinder in
dyne-cm.

h = the effective depth of immersion of the internal
cylinder in cm.

f = the yield value in dynes/sq. cm.

R_i = the radius of the internal cylinder in cm.

R_e = the radius of the external cylinder in cm.

If two instrument constants S and C are defined as

$$S = \frac{(1/R_i^2 - 1/R_e^2)}{4 \pi h} = \frac{(1 - a)}{4 \pi h} \frac{1}{R_i^2} \quad (80)$$

$$\text{and } C = \frac{S}{\log_e (R_e/R_i)} \quad (19)$$

then, the plastic viscosity U and the yield value f, can be
obtained from the following equations:

$$U = \frac{(T - T_2) S}{\Omega} \quad (21)$$

$$\text{and } f = C T_2 \quad (22)$$

where T_2 is the intercept on the torque axis of the angular speed-torque curve (Figure 3), as previously discussed in Chapter I.

The equivalent value of the constants S and C for a double-gap viscometer satisfying equation (79) can be determined as follows:

1. Constant S

For gap G_1 enclosed by R_1 and R_2 (Figure 48c) and gap G_2 , enclosed by R_3 and R_4 , the factor S is given by S_1 and S_2 , respectively so that

$$S_1 = \frac{(1 - a)}{4 \pi h} \frac{1}{R_2^2} \quad (81)$$

$$S_2 = \frac{(1 - a)}{4 \pi h} \frac{1}{R_4^2} \quad (82)$$

$$\text{where } a = \frac{R_2^2}{R_1^2} = \frac{R_4^2}{R_3^2} \quad (83)$$

Let the torque induced by the paste in gap G_1 be denoted by T' and the intercept on the torque-axis (of the angular speed-torque curve) be denoted by T_2' , and let the corresponding notations for gap G_2 be T'' and T_2'' , respectively.

Since the rate of shear induced in both gaps is the same, the plastic viscosity of the material under test in both gaps will also be the same,

$$\text{i.e., } U = \frac{T' - T_2'}{\Omega} S_1 = \frac{T'' - T_2''}{\Omega} S_2 \quad (84)$$

Therefore,

$$T' - T_2' = \frac{U\mathcal{L}}{S_1} \quad (85)$$

$$\text{and } T'' - T_2'' = \frac{U\mathcal{L}}{S_2} \quad (86)$$

Adding equations (85) and (86) we get

$$(T' + T'') - (T_2' + T_2'') = U\mathcal{L} \left[\frac{1}{S_1} + \frac{1}{S_2} \right] \quad (87)$$

But the total torque T induced by the material in both gaps is equal to $(T' + T'')$, and the total intercept T_2 on the torque-axis is equal to $(T_2' + T_2'')$, therefore equation (87) can be rewritten as

$$T - T_2 = \frac{U\mathcal{L}}{S_E} \quad (88)$$

where S_E is the equivalent constant corresponding to S for both gaps.

By comparing equations (87) and (88) we may write

$$\frac{1}{S_E} = \frac{1}{S_1} + \frac{1}{S_2} \quad (89)$$

$$\text{i.e., } S_E = \frac{S_1 S_2}{S_1 + S_2} \quad (90)$$

2. Constant C

Since the yield value f for the material in both gaps must be the same, we can write

$$f = C_1 T_2' = C_2 T_2'' \quad (91)$$

where C_1 and C_2 are the constants corresponding to C in equation (22) for gaps G_1 and G_2 , respectively.

From equation (91)

$$T_2' = \frac{f}{C_1} \quad (92)$$

$$\text{and } T_2'' = \frac{f}{C_2} \quad (93)$$

Adding equations (92) and (93), and putting $T_2 = T_2' + T_2''$, we get

$$T_2 = T_2' + T_2'' = f \left[\frac{1}{C_1} + \frac{1}{C_2} \right] \quad (94)$$

For the viscometer as a whole,

$$T_2 = \frac{f}{C_E} \quad (95)$$

where C_E is the equivalent constant corresponding to C for both gaps.

Hence, by comparing equations (94) and (95) we may write

$$\frac{1}{C_E} = \frac{1}{C_1} + \frac{1}{C_2} \quad (96)$$

$$\text{i.e., } C_E = \frac{C_1 C_2}{C_1 + C_2} \quad (97)$$

The relationships given by equations (90) and (97) were used in the calculation of the instrument constants for the double-gap rotational viscometer employed in the experimental work that follows. It is to be noted, however, that in the above analysis the inertia of the middle cylinder has been neglected and the "end effects" assumed to be the same for both gaps.

B. Design, construction, and calibration of the double-gap viscometer

1. Selection

In the early stages of the work, the original idea was to design and manufacture a single-gap viscometer of the "cup-and-bob" variety, but on further consideration of the various problems involved, it was decided that a double-gap viscometer would be much more suitable for the work contemplated. The main governing factor in making this decision was the ease of introduction of relatively thick pastes into the gap. The reason for this is that in the double-gap viscometer, the force exerted on the middle cylinder while it is being pushed into the paste, is distributed over the actual cross-sectional area of its walls only, whereas, in the case of the single-gap viscometer, this force would be distributed over the entire base area of the bob, and consequently, a much bigger force is required in the latter case to cause the flow of the paste into the gap.

Among the other advantages associated with the double-gap viscometer

in comparison with the single-gap type, the following may be mentioned;

- (a) The end effects are reduced.
- (b) The amount of paste used is considerably less than that required for a single-gap viscometer of comparable dimensions.
- (c) The fact that most of the material to be tested is contained in the gaps between the cylinders, tends to reduce any adverse effects due to sedimentation, slight non-uniformity in mixing, or segregation (as in the case of mortars).

The width of the outer gap was fixed at $\frac{1}{8}$ in. - a figure which is approximately 6 times the mean diameter of the maximum size of sand used. The figure 6 was chosen because it was considered that a lower ratio would substantially increase the interference between the sand particles and hamper the laminar flow of the material. In choosing the mean diameter of the cylinders (about $6\frac{1}{2}$ in.), consideration was given to the desirability of keeping the ratio of the gap width to the mean diameter at a low value to limit the variation in the rate of shear across the gap. In fact this variation was limited to within $\pm 3.6\%$ of the average rate of shear, so that the paste may be regarded as being truly subjected to a constant rate of shear.

2. Main features

Detailed drawings of the individual components of the viscometer

are given in Appendix I (drawing Nos. 1 - 8 inclusive). In the following description of the viscometer (Figures 50, 51 and 52), the numbers in square brackets refer to the components shown in Figure 53.

The viscometer is made entirely from mild steel. It consists of three cylinders [9, 10 and 11] assembled around a common central stepped shaft [1] which is welded to a $\frac{1}{2}$ in. thick steel base plate. The inner and the outer cylinders [9 and 11], which are the rotating cylinders, are fixed to a common stepped base [7] by means of a number of countersank screws so that the two cylinders rotate with the same angular speed. This base is bolted to a collar [2] which in turn is mounted on to the central shaft through a pair of bearings [30 and 31]. The upper of the two bearings [30] is a roller bearing and is incorporated in the design to allow small movements in the vertical direction to take place - thus improving the alignment between the main three cylinders. The lower bearing, however, is a ball bearing of the medium load and low friction variety enabling the transmission of the weight of the rotating components of the viscometer to the central shaft. Spacer tubes [3 and 4], whose inner diameter is slightly greater than the diameter of the shaft, are used to prevent any vertical movement between the inner races of the bearings.

The middle cylinder [10] is fixed to a circular shoulder ring [8] by means of countersank screws to form a single removable unit. This ring is capable of sliding very tightly along a long-stemmed collar [23]

General lay-out of the double-gap viscometer

A - cylinders B - torsion tube C - motor
D - pre-loading system E - potentiometer F - tape recorder

Figure 50

A close-up of the double-gap viscometer
with the middle cylinder in position

A - middle cylinder B - outer cylinder
C - torque scale D - pointer

Figure 51

A close-up of the double-gap viscometer
with the middle cylinder suspended clear of the gap

A - middle cylinder	B - outer cylinder
C - thermocouple junction	D - lifting rods
E - lifting screws	F - pointer

Figure 52

FIG. 53

mounted on to the central shaft through a set of two bearings - one being a roller bearing while the other is a ball bearing as in the case of the lower collar described above. The collar [23] is very finely machined and performs the dual function of acting as a guide to the middle cylinder, while this latter is being inserted into the gap, and providing a means of transmitting the weight of the cylinder to the shaft. Two small dowels, $\frac{1}{4}$ in. in diameter, and $\frac{3}{8}$ in. high,⁺ are fixed unsymmetrically on to the upper surface of the flange of the collar [23] to help position the middle cylinder. Two bolts, $\frac{5}{16}$ in. in diameter, are provided to fix the cylinder to the collar. A pair of horizontal rods $\frac{1}{2}$ in. in diameter and $5\frac{1}{2}$ in. long (Figure 52), are screwed on to the upper part of the middle cylinder unit, in order to facilitate the insertion of the middle cylinder into the paste and its subsequent removal. To help the withdrawal of the cylinder from the paste, two screws, $\frac{1}{4}$ in. in diameter and $2\frac{1}{2}$ in. long (Figure 52), are fitted to the top of the middle cylinder unit so that when they are screwed down, they abut against the flange of the collar [23] and cause the cylinder to be lifted from the paste.

A straight torsion bar [27], a little over 4 ft. in length, having one of its ends fixed to the central shaft, restrains the

⁺ These and other dimensions in the next few lines are given to facilitate the identification of the components shown on the photographs.

movement of the middle cylinder through a large tube [24], 2 in. in diameter and 4 ft. in length. In the original design, provision was made for a Beryllium Copper rod having a square cross-section to be used. But it was later decided to use a $\frac{3}{16}$ in. diameter mild steel rod because this was more readily available. The revised details for fixing the two ends of this rod are shown in Figure 54.

The torsion tube [24] has two pairs of stud-like projections protruding from its surface at different levels (Drawing No. 8, Appendix I). The upper pair is used for attaching the chord employed for pre-stressing the torsion bar (see section below), while the lower pair is used to hold the middle cylinder clear of the gap when the viscometer is being filled with paste.

3. Secondary features

(a) The middle cylinder, which is $\frac{3}{16}$ in. thick, has in its outer surface a vertical groove (Figure 52), $\frac{1}{8}$ in. wide and $\frac{3}{32}$ in. deep, in which copper-constantan thermocouple wires are accommodated. Araldite was used to embed the wires into the groove and the cylinder was machined to the correct radius, after the Araldite had hardened, to produce a smooth surface on the finished product. The thermocouple junction was embedded half-way down the common height of the three cylinders so that the temperature rise in the material under test could be measured.

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SECTIONAL ELEVATION

END FIXING OF TORSION BAR

(b) The shoulder ring [8], holding the middle cylinder, has a combination of horizontal and vertical grooves (Drawing No. 4, Appendix I) to enable it to be suspended from the torsion tube.

(c) A circular trough [21] made in two segments (Drawing No. 7, Appendix I) is fixed to the top of the inner cylinder, to collect the superfluous material extruded from the gap when the middle cylinder is inserted into the paste.

(d) Four drainage holes are provided in the stepped base [7] and in the lower collar to which it is bolted, to enable any fluid that may be forced into the space enclosed by the inner cylinder to escape (Drawings Nos. 3 and 4, Appendix I).

(e) Plugged drainage holes are also provided, at different levels, in the outer cylinder. These enable the drainage of liquids, tested in the viscometer, to be carried out (Drawings Nos. 5 and 6, Appendix I).

(f) The outer cylinder is fitted with two handles [12] to facilitate its removal for cleaning and its replacing in position.

(g) The depth of unsheared paste, which is the distance between the bottom of the middle cylinder and the bottom of the gap, is 1 in.

This can be reduced to $\frac{1}{2}$ in. by the introduction of a filler ring which completely fills the gap between the inner and the outer cylinders up to a height of $\frac{1}{2}$ in. A reduction in the volume of the paste used can thus be achieved.

(h) All bearings used are provided with seals having felt washers to

keep out dust and other impurities.

(i) The twist in the torsion bar is measured by the movement of a pointer, fixed to the upper surface of the middle cylinder unit, against a graduated circular scale bent to a radius of 15 in. (Figure 51).

(j) A second set of inner and outer cylinders (Drawing No. 6., Appendix I) is so designed that when fitted on the same stepped base [7] it gives a gap width of $\frac{1}{4}$ in., if the same middle cylinder is used. This compares with a gap of $\frac{1}{8}$ in. obtained with the first set.

4. Dimensions

(a) First set:

Inner radius of outer cylinder = $R_1 = 3.500$ in. = 8.890 cm.

Outer radius of middle cylinder = $R_2 = 3.375$ in. = 8.573 cm.

Inner radius of middle cylinder = $R_3 = 3.187$ in. = 8.095 cm.

Outer radius of inner cylinder = $R_4 = 3.074$ in. = 7.808 cm.

Gap width between outer and middle
cylinders = 0.125 in. = 0.317 cm.

Gap width between inner and middle
cylinders = 0.113 in. = 0.287 cm.

Common height of cylinders = $h' = 5.0$ in. = 12.70 cm.

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} = 0.964$$

(b) Second set:

Inner radius of outer cylinder = R_1' = 3.625 in. = 9.207 cm.

Outer radius of inner cylinder = R_4' = 2.967 in. = 7.536 cm.

Gap width between outer and middle
cylinders = 0.250 in. = 0.634 cm.

Gap width between inner and middle
cylinders = 0.220 in. = 0.559 cm.

Common height of cylinders = h' = 5.0 in. = 12.70 cm.

$$\frac{R_2}{R_1'} = \frac{R_4'}{R_3} = 0.931$$

It is to be noted that for each set of cylinders the ratios of the radii are made equal so that the same rate of shear is induced in the inner and the outer gaps.

5. Torque measurement

Although the anticipated values of the torque exerted on the middle cylinder, through the shearing of the paste, were much higher than the maximum torque that the $\frac{3}{16}$ in. diameter mild steel torsion bar could sustain without yielding, the relatively high sensitivity of such a slender rod to small variations in the torque made its use very desirable.

In order to enable the torsion bar to cope with the high torques

induced, a weights-and-pans system was incorporated in the design as shown in Figure 55. This bar pre-stressing system is shown diagrammatically in Figure 56. It consists of two pans attached to the ends of a woven nylon cord which in turn is connected by means of a small central loop to one of the upper sets of studs protruding from the surface of the torsion tube. The two parts of the cord on either side of the loop are wound round the tube and pass over two pulleys, mounted on ball bearings to reduce friction, on either side of the viscometer.

The winding of the cord round the tube is done in such a way that any weights that are placed in the pans induce a torque in the torsion bar in the opposite direction to that produced by the shearing of the paste. To guard against overstressing the bar, two $\frac{7}{8}$ in. stopper bars (A and B in Figure 56) are screwed on to the base plate of the viscometer to restrain the movement of the middle cylinder through one of its lifting rods (C in Figure 56). The maximum and the minimum values of the torque sustained by the torsion bar alone can thus be limited to $+T$ and $-T$, respectively, where T is the numerical value of the maximum torque that the bar can take without yielding. In this context, the torque is considered negative when it acts in the opposite direction to that induced by the shearing of the paste. The position of the stopper bars relative to the lifting rod of the middle cylinder is shown in Figure 57.

The double-gap viscometer with the outer
and the middle cylinders removed

A - motor B - Kapp variater C - flexible drive
D - speed control head E - reduction gear F - driving pulley

Figure 55

PLAN

DIAGRAMATIC SKETCH OF PRESTRESSING

SYSTEM FIG. 56

A view of the double-gap viscometer
showing the position of the stopper bars
relative to the lifting rod

A and B - stopper bars
C - lifting rod

Figure 57

If the torque to be measured is $+nT$, where n is any number greater than unity, then, in order to get the correct reading on the scale, enough weights must be placed in the pans to produce a negative torque $-T_w$ whose numerical value lies between $(n+1)T$ and $(n-1)T$. A feature of the above system is that if weights are placed in the pans to produce a negative torque T_w then any torque whose value lies between $(T_w + T)$ and $(T_w - T)$ can be measured. In other words, the range of the measurable torque fluctuation for any given pan load is $2T$.

6. Driving mechanism

The driving of the rotating parts of the viscometer is achieved by means of a 1-h.p., 440 volts, three-phase synchronous motor (Figure 55) running at a constant speed of 960 r.p.m. which is independent of the load. The horizontal output shaft of the motor is coupled to the input shaft of a Kopp variator whose function is to provide a reliable continuous speed variation unit operating between upper and lower limits. The actual speed variation is done through a flexible drive leading to a speed control head fixed to the viscometer frame, just below the viscometer itself. This control head incorporates a revolution counter which indicates the number of turns through which the head is turned, to the nearest tenth of a revolution.

The output shaft of the variator is attached by means of a

flexible coupling to the input shaft of a reduction gear having a vertical output shaft. On to this, a 5 in. diameter grooved aluminium pulley is keyed. A similar pulley of the same diameter is keyed to the lower collar of the viscometer, and the two pulleys are connected by three V-belts running in horizontal planes.

The driving system described above gives maximum and minimum speeds of 192 and 21 r.p.m., respectively. In order to reduce the lower speed limit still further, a $2\frac{1}{2}$ in. diameter aluminium pulley, which fits on to the output shaft of the reduction gear, is also provided. The maximum and the minimum speeds associated with this pulley are half those given above for the 5 in. diameter pulley.

7. Viscometer frame

The viscometer frame (Figure 55) consists of a number of rolled steel joists and channel sections bolted together as shown on Drawing No. 2 in Appendix I. The fact that the motor and the viscometer are mounted on a common frame, causes some of the motor vibrations to be transmitted to the paste in the viscometer. But, since the running of the motor is very smooth, any vibrations produced can only have very low amplitudes and the resultant effect on the breakdown of the paste can be considered negligible.

8. Calibrations

(a) Bearing friction

Although the middle cylinder did rotate quite freely when given a push in the absence of the torsion bar, it was considered desirable to have a rough idea of the magnitude of the frictional resistance induced in the bearings. To do this, the nylon cord supporting the pans was wound round the torsion tube so that the two pans opposed each other with no resultant torque being produced. Equal weights were then placed in the pans, and the pointer was moved in the positive direction to its furthestmost position on the scale and allowed to return very slowly to its original position. The reading on the scale when the pointer came to rest was noted. The pointer was then taken to its extreme position on the scale in the other direction and the process repeated. To obtain the mean equilibrium reading, the pointer was again taken to one of its extreme positions and quickly released so that it oscillated about the mean position. The scale reading was taken when the pointer came to rest, and the difference between this mean reading and each of the first two readings was calculated.

This experiment was repeated several times with different pan loads and it was found that as the pan load increased, the calculated difference between the readings also increased. The maximum value of the departure from the mean did not, in any case, exceed 0.4 of a division on the torque scale.

(b) Calibration of torsion bar

The torsion bar was calibrated as follows:

The nylon cord was connected to the torsion tube so that both pans produced a torque in the positive direction. The pans were gradually loaded with equal weights and the corresponding deflections on the scale were noted. Readings were also taken when the pans were gradually unloaded, and the whole process of loading and unloading was repeated with the nylon cord connected to produce a torque in the negative direction. The calibration graph is given in Figure 58.

In order to convert the weights to torque units, the diameter of the torsion tube was measured, near the studs, at different positions along the circumference, and the mean value calculated. The diameter of the nylon cord was also measured.

(c) Calibration of speed control

The speed control was calibrated by using a tachometer to measure the actual angular speed of the reduction gear's output shaft, corresponding to different settings of the speed control head. The calibration graph is non-linear and is shown in Figure 59.

(d) Thermocouple calibration

A Doran potentiometer, whose voltage was provided by a 2-volt dry battery, was used in the measurement of the temperature of the paste. The thermocouple was calibrated with the cold junction placed in molten ice while the middle cylinder (into which the other junction

CALIBRATION GRAPH FOR TORSION BAR

FIG. 58

CALIBRATION GRAPH FOR ANGULAR
SPEED WHEN IDENTICAL PULLEYS ARE
USED IN V-BELT DRIVE

FIG. 59

was embedded) was placed in boiling water. The calibration graph is shown in Figure 60.

(e) Determination of "end effects" ($\frac{1}{8}$ in. gaps)

In order to determine the "end effects" for the viscometer, a Newtonian liquid was needed and the commercial Lyle's Golden Syrup was originally used. On subjecting it at first to increasing and then to decreasing rates of shear, it was found that the up-curve did not coincide with the down-curve, indicating that the material was not Newtonian. At first, a rise in temperature was suspected to be the cause of the observed effect, but, on further examination of the various up-curves and down-curves obtained, it became clear that a breakdown of the structure did actually take place at the rates of shear under which the test was carried out.

As a result of the above test, it was considered essential that a Newtonian fluid, which did not break down under shear, be used for determining the "end effects". A Silicone fluid having a nominal viscosity of 10 poises ($\pm 5\%$) at 77°F , was therefore selected. This fluid had the additional advantage of having a relatively flat viscosity-temperature curve.

A known volume of this fluid was poured into the gap and allowed to settle before the middle cylinder was inserted. The fluid was then allowed to settle to a constant height and temperature (for a period of 30 minutes). Then an up-curve was run, followed by a down curve. The

THERMOCOUPLE CALIBRATION

FIG. 60

same procedure was repeated when further known volumes of the fluid were added.

The up-curve and the down-curve corresponding to any given height of fluid in the gap were found to be coincident straight lines passing through the origin (Figure 61). Figure 62 shows the variation of the deflection of the middle cylinder expressed in scale divisions, with the height of the fluid in the gap, for various constant speeds. For any one speed, the best straight line was fitted through the results by the method of least squares and the intercept on the height-axis calculated. The mean of these intercepts was taken to be the correction for the "end effects". This correction, which is independent of the height of fluid in the gaps, was found to be 0.204 in. When the viscometer gaps are completely filled with the fluid under test, this correction represents 4.08% of the depth of immersion of the middle cylinder.

As a check on the accuracy of this calibration, the viscosity of the fluid was calculated using the correction thus determined and found to be very nearly constant.

Tables 1 and 2 give the results of the above calibration which was carried out at a temperature of 65°F, with the vertical clearance, between the bottom of the middle cylinder and the bottom of the gap, reduced to $\frac{1}{2}$ in. by the introduction of the filler ring. The figure of 4.08% for the correction was considered adequate and, therefore,

HEIGHT OF FLUID IN VISCOMETER IN CM. =

VARIATION OF DEFLECTION WITH ANGULAR
SPEED FOR A SILICON FLUID
(UP-CURVES AND DOWN-CURVES ARE REPRESENTED
BY SINGLE LINES BECAUSE THEY ARE COINCIDENT)

FIG. 61

CALIBRATION FOR "END EFFECTS"
USING A SILICON FLUID

FIG. 62

Table 1

Constant speed and variable height		
Speed in r.p.m.	Slope of st. line	Intercept $\Delta h'$ on h' -axis in inches
21	0.952	- 0.217
30	0.664	- 0.172
40	0.493	- 0.198
50	0.403	- 0.212
60	0.339	- 0.215
70	0.289	- 0.178
80	0.256	- 0.209
90	0.227	- 0.229
Mean value of $\Delta h' = - 0.204$ in.		

Table 2

Constant height and variable speed			
Height of fluid in gap h' in inches	Corrected height ($h' - \Delta h'$) in inches	Slope of st. line	Viscosity of fluid U in poises
1.46	1.66	12.064	10.82
1.93	2.13	9.652	10.58
2.45	2.65	7.613	10.78
2.97	3.17	6.427	10.68
3.53	3.73	5.400	10.79
4.92	5.12	3.974	10.69
Mean value of $U = 10.72$ poises			

all the tests on cement pastes and mortars were carried out with the filler ring in position. The removal of this ring would have increased the clearance below the middle cylinder to 1 in. and reduced the "end effects", but, at the same time, it would have substantially increased the amount of paste used to fill the viscometer.

9. Viscometer constants ($\frac{1}{8}$ in. gaps)

In the following calculations, the effective height h of the gap is taken as $(h' - \Delta h')$, where h' is the common height of the cylinders and $(- \Delta h')$ is the correction for the "end effects".

Therefore h is given by

$$h = 5.00 + 0.204 = 5.204 \text{ in.} = 13.218 \text{ cm.}$$

For the inner and the outer gaps,

$$a = \frac{R_i^2}{R_e^2} = 0.931$$

Hence, from equations (72), (73), and (76)

$$\text{max. rate of shear} = 2.98 \text{ N}$$

$$\text{min. rate of shear} = 2.77 \text{ N}$$

$$\text{and average rate of shear} = 2.88 \text{ N}$$

where the rates of shear are in reciprocal seconds and the angular speed N is in r.p.m.

Substituting the dimensions of the gaps in equations (80) and (19) and using suffix 1 for the gap enclosed between the outer and the middle cylinders, and suffix 2 for the gap enclosed between the inner and the middle cylinders, we get

$$S_1 = 5.72 \times 10^{-6} \text{ cm.}^{-3}$$

$$S_2 = 6.92 \times 10^{-6} \text{ cm.}^{-3}$$

$$C_1 = 1.57 \times 10^{-4} \text{ cm.}^{-3}$$

$$\text{and } C_2 = 1.90 \times 10^{-4} \text{ cm.}^{-3}$$

From equations (90) and (97), the equivalent constants S_E and C_E are given by

$$S_E = 3.13 \times 10^{-6} \text{ cm.}^{-3}$$

$$\text{and } C_E = 0.86 \times 10^{-4} \text{ cm.}^{-3}$$

By direct measurement,

the average diameter of the torsion tube = 5.72 cm.

the average diameter of the nylon cord = 0.19 cm.

hence,

$$\text{the average value of the lever arm} = \frac{5.72 + 0.19}{2} = 2.955 \text{ cm.}$$

From Figure 58, the slope of the calibration graph for the torsion bar is 482 gm./division. Hence the stiffness k_1 of the bar is given by

$$k_1 = 482 \times 2.955 \times 981 = 1396 \times 10^3 \text{ dynes/division}$$

From equation (88), the plastic viscosity U is given by

$$U = \frac{(T - T_2) S_E}{\omega}$$

where U is in poises when T and T_2 are in dyne-cm., S_E in cm.⁻³, and ω in radians/sec.

Equation (88) can be rewritten as

$$U = \frac{(d - d_2) K}{N} \quad (98)$$

where the plastic viscosity U is in poises when the torques d and d_2 are in scale divisions and the angular speed N is in r.p.m.

The factor K is a constant corresponding to S_E .

By comparing the above two equations for U , we find that

$$K = \frac{k_1 S_E}{\pi} \cdot 30 \quad (99)$$

$$\text{i.e., } K = \frac{1396 \times 10^3 \times 3.13 \times 10^{-6} \times 30}{\pi} = 41.6$$

From equation (95), the yield value f is given by

$$f = C_E T_2 \quad (100)$$

where f is in dynes/sq. cm. when T_2 is in dyne-cm., and C_E is in cm.⁻³

Rewriting equation (100) as

$$f = K_2 d_2 \quad (101)$$

where f is in dynes/sq. cm., d_2 is the value of the torque intercept in scale divisions, and K_2 is a constant.

By comparing equations (100) and (101) we find that

$$K_2 = k_1 C_E$$

i.e.,
$$K_2 = 1396 \times 10^3 \times 0.86 \times 10^{-4} = 120$$

C. The Building Research Station viscometer

The viscometer briefly described below was designed and manufactured at the Building Research Station and was used by the writer to obtain corroboratory evidence regarding the behaviour of cement pastes under shear.

1. Construction

The viscometer (Figures 63, 64 and 65) is of the cup-and-bob single-gap type. It consists mainly of a hollow mild steel bob 5.384 cm. high having an outside diameter of 5 cm., and a rotating mild steel cup having an inside diameter of 5.207 cm. with an inside depth of 6.509 cm. The outside surface of the bob and the inside surface of the cup are vertically grooved. All exposed surfaces of the viscometer are chromium-plated to prevent corrosion.

A tapered dowel is incorporated in the design to position the bob centrally relative to the cup.

SKETCH OF B.R.S. VISCOMETER
(CROWN COPYRIGHT RESERVED)
FIG. 63

The Building Research Station viscometer

A - cup B - bob C - pick-up unit
D - mirror E - slotted belt drive F - gear lever
G - levelling screws H - motor

Figure 64

(Crown copyright reserved)

General layout of the Building Research Station viscometer
and measuring instruments

A - viscometer B - motor C - frequency modulation unit
D - speed control unit E - oscillograph
F - motor-driven camera G - transparent scale
H - light source

Figure 65

(Crown copyright reserved)

2. Driving system

The cup is connected through a slotted belt-and-pulley drive (Figure 64) and a reduction gear system, to the driving shaft of a vertically mounted 1/4 h.p. motor. Any speed, between zero and the maximum value dictated by the selected gear ratio, can be obtained by adjusting the control knob of an electrical speed control unit (Figure 66).

3. Torque measurement

The movement of the bob was originally restrained by a flat spring accommodated in a housing just above the bob itself. But, because of the difficulty involved in ensuring that adjacent turns of the spring do not touch one another when a torque is applied to the bob, a revised system of close-coiled helical springs (Figure 67) was substituted at a later date. Both systems were used by the writer in the experimental work carried out at the Building Research Station.

For the actual measurement of the torque, two methods are available:

(a) Direct method

In this method, the deflection of the bob is estimated by noting, on a transparent scale, the movement of a light spot produced by a beam of light reflected in a small mirror fixed to the top of the bob.

A close-up of the speed control unit and
the torque measuring devices for the
Building Research Station viscometer

A - speed control unit	B - speed control knob
C - oscillograph	D - motor-driven camera
E - micro-ammeter	F - transparent scale
G - light source	

Figure 66

The close-coiled helical springs system
of torque measurement

A - close-coiled helical springs
B - metal fastenings
C - weights and pans

Figure 67

(Crown copyright reserved)

(b) Electronic method

This method makes use of a variable inductance pick-up unit incorporated in a frequency-modulated pre-amplifier system, which consists of a radio frequency oscillator contained in a box located close to the point where the oscillograph and the A.C. power supply are located. The pick-up and the oscillator are connected by a comparatively short coaxial cable and the oscillator and the amplifier are connected by a cable carrying H.T. and L.T. supplies to the former and the return H.F. signal to the latter. The amplifier is supplied from a valve-stabilised power supply panel operated from A.C. mains.

The principle of operation is the frequency-modulation of the oscillator which has in its tuned circuit the variable inductance performing the measurement. The radio frequency signal is transmitted back to the amplifier, passes through an amplifying and limiting stage and is then fed through a frequency discriminator circuit.

The final output voltage is fed to the oscillograph and the movement of the bob is thus translated into the vertical movement of a light spot on the oscillograph screen. As the deflection of the bob increases, the light spot moves downwards.

A motor-driven camera can be mounted on to the oscillograph so that the light spot can be continuously photographed and its movement thus recorded. When the torque exerted on the bob is constant, a horizontal trace is obtained on the film, indicating that the

deflection of the bob is constant.

As a check on the results obtained from the oscillograph and camera system, a micro-ammeter can be included in the circuit and calibrated to measure the deflection of the bob.

4. Viscometer constants

For this viscometer the constant a is given by

$$a = \frac{R_1^2}{R_e^2} = 0.922$$

From equations (72), (73) and (76),

$$\text{max. rate of shear} = 2.70 \text{ N}$$

$$\text{min. rate of shear} = 2.49 \text{ N}$$

$$\text{and average rate of shear} = 2.59 \text{ N}$$

where the rates of shear are in reciprocal seconds and the angular speed N is in r.p.m.

The ratio between the maximum and the minimum values of the rate of shear is 1.084, and the maximum variation in the rate of shear across the gap is limited to within $\pm 4.1\%$ of the average value.

One gear ratio was used throughout the work giving:

$$\text{cup speed in r.p.m.} = 19.85 \times \text{dial reading of control knob}$$

The viscometer constants S and C were calculated from equations (80) and (19), respectively, so that

$$S = 1.95 \times 10^{-4} \text{ cm.}^{-3}$$

and $C = 48.1 \times 10^{-4} \text{ cm.}^{-3}$

For this viscometer, equation (21) may be rewritten as

$$U = \frac{(d - d_2) 4.72}{N} \quad (102)$$

where U is the plastic viscosity in poises, d and d_2 are taken for convenience to represent the torque T and T_2 , respectively, in grams acting at a lever arm of 2.59 cm. (which is the effective radius of the drum used in the calibration of the spring), while N is the angular speed in r.p.m.

Equation (22) may be represented by

$$f = 12.22 d_2 \quad (103)$$

where f is the yield value in dynes/sq. cm. and d_2 , as above, represents the torque T_2 in grams acting at a lever arm of 2.59 cm.

5. Calibration

In order to minimise the effects of drift in the electronic instruments used, the electricity supply was switched on about an hour before any tests were carried out.

The calibration of the flat spring, which was done before and after every shear test, was carried out by putting equal weights in the pans as shown in Figures 64 and 67. For each loading the readings

x LOADING BEFORE TEST
 • UNLOADING " "
 + LOADING AFTER "
 ■ UNLOADING " "

TYPICAL CALIBRATION FOR MOVEMENT OF
LIGHT SPOT ON TRANSPARENT

SCALE

FIG. 68

TYPICAL AMMETER CALIBRATION

FIG. 69

X LOADING BEFORE TEST
 • UNLOADING " "
 + LOADING AFTER "
 ■ UNLOADING " "

TYPICAL OSCILLOGRAPH CALIBRATION

FIG. 70

TYPICAL CALIBRATION FILM FOR B.R.S. VISCOMETER OBTAINED

BEFORE THE START AND AT THE END OF EACH SHEAR TEST

(FIGURES GIVEN ON FILM ARE LOADS IN PANS) FILM SPEED = 0.1 IN/SEC.

FIGURE 71

on the transparent scale and the micro-ammeter (when used) were noted. At the same time, the camera was used to photograph, at intervals, the light spot on the oscillograph screen. Readings were taken throughout the loading and the unloading cycles.

Some typical calibration curves are shown in Figures 68, 69 and 70. In Figure 71, a photostatic copy of an actual calibration film is shown.

The calibration curve, for the bob restraining system shown in Figure 67, is included with the paste results in Chapter VI.

CHAPTER VI

EXPERIMENTAL WORK ON NEAT CEMENT PASTES

A. General

In the following work on cement pastes, three different batches of unblended ordinary Portland cement were used in the double-gap viscometer. A fourth batch of ordinary Portland cement, which was blended, was used in part of the work carried out at the Building Research Station. Each batch was thoroughly mixed in a clean and dry Liner pan-mixer and then stored in polythene bags inside air-tight drums. The first batch, however, was only used for checks on the reproducibility of the results for the breakdown under constant rates of shear.

Owing to the marked effect that the specific surface and the chemical composition of the cement seemed to have on the viscosity of the paste, the experimental results for each batch were kept separate.

The upper and the lower limits of the range of water/cement ratios investigated were fixed at 0.33 and 0.28, respectively. It was considered that the net amount of water that wets the cement in fresh concrete in practice would generally fall within that range.

All the tests were carried out at a room temperature of $65 \pm 5^{\circ}\text{F}$. Actually, the mean room temperature for all the tests carried out on

cement pastes and mortars, was 66.2°F , and the standard deviation from the mean was 2.9°F . The effect of such small variations in temperature on the viscosity of the paste is considered to be negligible. Backman (59), as a result of his work on lime suspensions which were much more fluid than the pastes used in the present work, found that a temperature change of a few degrees had no significant influence on the flow curves. The reason given for this behaviour is that the temperature primarily affects the viscosity of the water, and any such variations are considered to be unimportant in relation to the total plasticity.

B. Testing procedure for the double-gap viscometer

1. Preparation of the viscometer

In view of the fact that the double-gap viscometer was made from plain mild steel, it was susceptible to oxidation. To guard against this, all exposed surfaces were oiled at the end of every day's work. Consequently, before any test could be carried out, the cylinders had to be thoroughly cleaned and all traces of oil removed with tissue paper.

2. Mixing procedure

At the beginning of every test, and before the mixing was started, the speed control head was set to the required starting speed. The middle cylinder was then suspended from the torsion tube studs (Figure 52), and a specially designed metal "funnel" (item A in

Figure 72) fitted over the gap.

At the early stages of the work, it was realised that it was important that the paste should be subjected to the same amount of breakdown during the mixing process, and a standard method of mixing was, therefore, adopted.

For every test, 1300 gm. of cement were weighed into an 8 in. diameter glass container, and the appropriate amount of tap water weighed into a beaker - both weighings being done to the nearest $\frac{1}{2}$ gm. For all the water/cement ratios investigated, this amount of cement, when mixed with water, produced a volume of paste which was in excess to that required to fill the gaps.

The mixing procedure was performed in the following sequences:

- i) The water was added gradually to the cement during the first half minute while fresh surfaces were being exposed to it.
- ii) A two-minute mixing period was then started - the mixing being done by moving a spatula having three straight edges (item B in Figure 72) diametrically across the bottom of the glass container while the latter was being slowly rotated by hand.
- iii) The paste was then allowed to rest for half a minute to enable the final checks on the speed control, the weights, etc., to be made.

Items used in connection with the double-gap viscometer

A - funnel B - spatula with three straight edges C - levelling ring
D - flex E - mixing container F - potentiometer G - battery
H - molten ice

Figure 72

- iv) The paste was then subjected to a final continuous mixing period of 3 minutes.

3. Introduction of the paste into the gap

Six minutes after the first drop of water was added to the cement, the paste was introduced into the gap using the spatula and the specially designed "funnel" (Figure 73). After all the paste was evenly distributed in the gap, a circular metal ring was introduced into the gap for levelling the paste and expelling the air bubbles. This ring was made in two halves (item C in Figure 72), which fitted into the gap just clear of the inner and the outer cylinders. One of the halves of this ring is shown in position in Figure 74.

4. Introduction of the middle cylinder

On completion of the levelling operation, the middle cylinder was slowly lowered into the gap while a piece of flex (item D in Figure 72) was held round it, just over the gap, to limit the amount of paste extruded to the outside. This procedure ensured that the inner gap was filled with paste - any excess paste being taken by the overflow trough screwed to the inner cylinder. The middle cylinder was then bolted in position, and the paste forced outside the outer gap was removed.

With the middle cylinder in position, the appropriate amount of weights was placed in the pans.

Introduction of the paste into the gap

Figure 73

Levelling of the paste

(Only one half of the levelling ring is shown)

Figure 74

5. Recording the results

Due to the fact that the breakdown of the cement paste under shear took place very rapidly, a tape recorder was used to record the pointer readings which were shouted into the microphone together with the corresponding speed control or stop-clock readings, depending on the type of test carried out. For the constant speed tests, time readings were recorded, while for the variable speed tests, the speed readings were recorded.

In all the tests, the motor was started exactly 12 minutes after the first drop of water was added to the cement.

6. Removal of paste and cleaning

At the end of every test, the middle cylinder was unbolted, lifted a small amount by screwing down simultaneously the two lifting screws, and then completely withdrawn from the paste. The outer cylinder fixing screws were then removed and the cylinder lifted off the viscometer. The dismantling of the above two cylinders (Figure 55) exposed the cement paste in the inner gap and enabled its removal with a spatula.

The surface of the inner cylinder was then partially cleaned to allow the removal of the filler ring. This operation was followed by the removal of the overflow trough which was made in two halves for this purpose.

The cleaning of the above components, except the inner cylinder, was done very thoroughly under a jet of water and the drying up was done with tissue paper to exclude all foreign matter from the surfaces. The inner cylinder, however, had to be cleaned while still in position and any paste that accidentally entered the threaded holes in the supporting base at the bottom, was removed by means of a metal tap that fitted into the holes.

When the dried components were reassembled, care was taken to fit the outer cylinder in the same position relative to the supporting base, every time. The provision of location marks on the cylinder, corresponding to marks on the base, helped in this respect.

C. Testing procedure for the B.R.S. viscometer

Before preparing the paste for each test, the bob spring (or springs) was calibrated as previously described, and readings were taken during the loading and the unloading cycles.

As this viscometer was considerably smaller than the writer's viscometer, the amount of cement mixed for each test was only 120 gm. The appropriate amount of water, in this case, was added from a measuring cylinder. The mixing procedure adopted was the same as that already described for the double-gap viscometer. When the mixing process was completed, part of the paste was introduced into the cup to fill it to about a third of its height. The bob was then lowered

into the paste and all excess material removed.

After the appropriate starting speed was selected, the motor was started exactly 10 minutes after adding the first drop of water to the cement. When it was intended to use the camera, its motor was started just before starting the viscometer motor.

D. Work on cement pastes

The original plan of work was based on the very limited amount of available literature (20, 22 and 23) on the subject. This assumed that the yield value for the cement paste depended entirely on the water/cement ratio and remained constant throughout the breakdown process. After proceeding with the work, however, it was found that the breakdown curve, i.e., the curve for the decay of the torque with time, under a constant rate of shear could not be very accurately represented by the single exponential expression given by Tattersall, namely,

$$T - T_E = (T_0 - T_E) \cdot e^{-B \cdot t} \quad (54)$$

On examining the $\log(T - T_E)$ versus time plot, for a number of tests, it was concluded that the results would be better represented by two straight lines. In other words, the breakdown equation ought to consist of two exponential expressions - one valid between $t = 0$ and $t = t_1$ (where $30 \geq t_1 \geq 10$ sec), and the other from $t = t_1$ onwards.

The above departure from the predicted behaviour was also confirmed by tests carried out by the writer at the Building Research Station, and a fuller discussion on this point is given later on in this chapter.

A possible cause for this departure from the predicted pattern was thought to be a change in the yield value with time. Consequently, the original plan of work was revised to include an investigation of this particular aspect of the behaviour of the paste. The extra amount of work involved in doing this, resulted in the curtailment of the number of tests on mortars and the elimination of the work which was to be carried out using the second set of cylinders (associated with the $\frac{1}{4}$ in. gap).

The revised plan of work covered the following items:

1. Breakdown under variable rates of shear:

This section includes all the tests carried out to investigate the torque variation induced by the shearing action, as the rate of shear is gradually altered.

2. Breakdown under constant rates of shear:

This part of the work includes the following:

- (a) Investigation of the temperature rise in the paste.
- (b) Checks on reproducibility.
- (c) Preliminary study of the effect of the rate of shear on breakdown.
- (d) Investigation of the variation of the yield value with time.

- (e) General work on breakdown using different water/cement ratios.
- (f) Further investigation of the variation of the yield value with time.
- (g) Breakdown of the cement paste in the B.R.S. viscometer.
- (h) Effect of breakdown on strength.

In the following description of the experimental work, short summaries of the results are given in tabular forms where necessary, and the detailed results are given in Appendix III.

1. Breakdown under variable rates of shear

In each test, the viscometer was filled with paste and the motor started at its minimum speed (in the case of the B.R.S. viscometer, a starting speed of 2 r.p.m. was used). A series of up-curves and down-curves were run. The up-curves were obtained by increasing the angular speed, in steps of 5 r.p.m. every 10 seconds, and noting the torque associated with each speed. Every up-curve was followed by a down-curve obtained by the gradual reduction of the speed to its minimum value, at the same rate used for the up-curve.

Figure 75 shows the torque variation with the speed for a cement paste having a water/cement ratio of 0.31, tested in the double-gap viscometer. For convenience, the torque is represented by the deflection of the stationary cylinder. The top angular speed for the first three up-curves was fixed at 60 r.p.m., while for the remaining

TEST 43
W/C = 0.31
C.B. II

A TYPICAL SET OF UP-CURVES AND
DOWN-CURVES FOR CEMENT PASTES

FIG. 75

up-curves a top angular speed of 100 r.p.m. was used. In Figure 76, results are given of another test in which the paste was made more fluid (water/cement ratio = 0.32) and the top speeds halved, as compared with the above test. These results are very similar to those shown in Figure 75, and may be taken to be typical for a number of tests carried out at different top speeds on pastes having various water/cement ratios lying between 0.28 and 0.33.

Due to the fact that the breakdown took place very rapidly during the running of the first up-curve, it was considered desirable to carry out similar tests with the B.R.S. viscometer and to use the camera to record the breakdown. A typical set of filmed results, including the initial calibration, is shown in Figure 77. The calibration film shows that a difference in level exists between the horizontal lines representing equal torques during the loading and the unloading cycles. This hysteresis effect may be attributed partly to friction and partly to drift.

The actual traces representing the torque during the first up-curve may be seen to be fairly steep especially at the beginning of the test, indicating a fast rate of breakdown. It is also to be noted that, when the down-curve is run, the torque associated with any one speed does not remain strictly constant at the higher speeds. This is due to the fact that the time interval of 10 seconds used, was long enough to cause the effect of breakdown under a constant rate of shear

TEST 151
 $W/C = 0.32$
 C.B. III

FIG. 76

TYPICAL FILMED RESULTS FOR UP-CURVES AND DOWN-CURVES

(RINGED FIGURES ARE SPEED DIAL READINGS)

FIG. 77

to be noticeable. This phenomenon, however, does not seem to influence the magnitude of the torque to any great extent because the bulk of the breakdown occurs during the running of the first up-curve. A typical set of up-curves and down-curves obtained from such a film is shown in Figure 78. It will be seen that these curves are similar to those obtained with the double-gap viscometer.

On studying the breakdown results for a number of tests carried out with the double-gap viscometer, the following remarks can be made:

- i) The breakdown occurring during the first up-curve was so fast that the pointer was in continuous movement throughout the 10 seconds interval allotted to every speed, indicating a continuous reduction in torque. The points plotted in Figures 75, 76 and 78 are those corresponding to the torque prevailing 5 seconds after the changing of the speed.
- ii) The first up-curve, as a whole, was fairly steep, indicating that the increase in speed, at the beginning of the breakdown, was accompanied with very little change in torque. This can be attributed to the increased rate of breakdown associated with the increase in the speed - thereby leaving the torque nearly constant.
- iii) The fact that the first two or three down-curves obtained before the completion of the breakdown were straight

TEST 207
W/C = 0.30
C. B. IV

TORQUE (GMS. ACTING AT LEVER ARM OF 2.59 CMS.)

A TYPICAL SET OF UP-CURVES AND DOWN-CURVES FOR CEMENT
PASTE OBTAINED FROM FILMED RESULTS FOR B.R.S. VISCOMETER

FIG. 78

lines, indicated that no breakdown took place while the down-curves were run, i.e., the plastic viscosity remained constant.

- iv) Successive straight down-curves became progressively steeper - indicating a reduction in the plastic viscosity as the breakdown continued.
- v) The area enclosed by successive hysteresis loops became progressively smaller as the breakdown associated with the top speed used, approached the equilibrium condition.
- vi) When the equilibrium condition was reached, the up-curves and the down-curves became coincident and no further breakdown could be achieved without increasing the top speed.
- vii) For any one test, all the up-curves, except the first one, and all the down-curves displayed a tendency to meet at a common point on the torque axis when extrapolated. This tendency may have been partly responsible for leading Tattersall to assume that the yield value remained constant throughout the breakdown. The conclusion that can be correctly drawn from this tendency, however, is that the yield value tends to become constant after a substantial part of the breakdown has taken place.
- viii) The breakdown seemed to take place at all the rates of

shear investigated including the one associated with the viscometer's minimum speed.

The above remarks are in general agreement with Tattersall's deductions and seem to indicate that the cement paste behaves like a thixotropic material although no quick rebuilding of the structure takes place when the paste is allowed to rest for a period of about 10 minutes. Apart from being reversible, the thixotropic breakdown is by definition an isothermal process, and the tests described below were, therefore, carried out to establish whether this requirement is satisfied during the breakdown of cement pastes.

2. Breakdown under constant rates of shear

(a) Investigation of the temperature rise in the paste

In view of the relatively high energy input to the paste, it was considered desirable to measure the temperature rise in the paste during testing. Another reason for carrying out this measurement was to establish whether the breakdown took place under isothermal conditions, to enable a rheological classification of cement pastes to be made.

Six tests, in which the ingredients of the paste were allowed to attain room temperature before mixing, were carried out on a paste having a water/cement ratio of 0.30 to measure the temperature rise in the paste while it was being broken down at relatively high rates of shear.

In every test, before the motor was started, the cold junction of the thermocouple (whose "hot" junction was embedded in the middle cylinder) was placed in molten ice and the thermocouple wires connected to a Doran potentiometer. In each test, the viscometer speed was kept constant at 162 r.p.m., and the temperature measured by balancing the potentiometer. In three of the tests, the paste was continuously sheared for 6 minutes, while for the remaining tests, the shearing period was extended to 10 minutes. The mean value of the maximum temperature rise measured in the first set of tests was 1.1°C , and in the second set the corresponding figure was 1.6°C .

The small rise in temperature obtained indicates that the breakdown is essentially an isothermal process, since it is almost impossible (4) to maintain a constant rate of shear over an extended period of time without causing temperature increases in the sample even when an accurately controlled temperature bath is used.

(b) Checks on reproducibility

Before embarking on the investigation of the breakdown under constant rates of shear, it was considered desirable to check on the reproducibility of the results. To do this, a number of constant speed tests were carried out in duplicate.

The testing procedure adopted, was to subject the paste to a constant rate of shear and note the torque variation with time. A typical set of results thus obtained is shown in Figure 79. It can

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TYPICAL RESULTS FOR REPRODUCIBILITY

CHECKS

FIG. 79

be deduced from the rather limited scatter of points that the degree of reproducibility achieved may be regarded as being satisfactory for the type of work in hand.

Throughout the whole experimental work, a constant check on reproducibility was maintained by carrying out tests in duplicate at frequent intervals.

(c) Preliminary study of the effect of the rate of shear on breakdown

In this phase of the work, the second batch of cement and the 5 in. diameter driving pulley, giving a minimum speed of 21 r.p.m., were used. Since this investigation was of a preliminary nature, it was decided to keep the water/cement ratio at a constant value of 0.31, and study the breakdown of the paste at different constant speeds.

In every test, it was essential to set the speed control to the required value before the introduction of the paste into the viscometer, because one of the features of the Kopp variater, is that no change in the output speed can be made with the motor at rest. The actual shear tests consisted of subjecting the paste to a constant rate of shear for a period of 5 minutes, while in the mean time, the torque readings were shouted into the microphone of a tape recorder at regular intervals. These intervals were fixed at 5 seconds for the first thirty seconds of the breakdown, and then 10 seconds and longer intervals were used as the breakdown slowed down.

As the yield value was originally assumed to remain constant

throughout the breakdown, no attempt was made to run a down-curve at the end of every test to determine its magnitude, because this was considered to be easily obtainable from the graph for the variation of the initial torque (at $t = 0$) with the angular speed.

Figure 80 shows the combined torque-time curves for this series of tests. A curve obtained at a later stage for a speed of $10\frac{1}{2}$ r.p.m. is also included to give a fuller picture. In this graph, as in other graphs given throughout this thesis, the torque is represented by the deflection of the middle cylinder expressed in divisions on the viscometer scale. Typical plots of $\log(d - d_E)$ (where d_E is the final value of the deflection d) against the time t are shown in Figures 81 and 82, and it can be seen that in each case, the results lie on two distinct straight lines.

In view of this departure of the results from the single straight line predicted from Tattersall's work, a number of tests were carried out with the B.R.S. viscometer using the motor-driven camera in an effort to reduce the human error to a minimum. A typical plot of the independent results thus obtained is shown in Figure 83. It will be noted that these results are similar to those obtained with the double-gap viscometer.

On further examination of the above behaviour, the writer was led to investigate the variation of the yield value with time because it was thought that an increase in the yield value with time, could

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$w/c = 0.31$

C.B. II

ANGULAR SPEED = $10\frac{1}{2}$ R.P.M.

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(d-d_e) IN DIV. (LOG. SCALE)

TEST 33

W/C = 0.31

SPEED = 61 R.P.M.

C.B.II

RELATION BETWEEN LOG(d-d_e) AND TIME t

FIG. 81

TEST 35

W/C = 0.31

SPEED = 102 R.P.M.

C.B.II

(d-d_e) IN DIV. (LOG. SCALE)

RELATION BETWEEN LOG(d-d_e) AND TIME t

FIG. 82

account for the points not falling on a single straight line. This aspect of the work is dealt with in detail in section (d).

In an attempt to obtain a single simple expression for the breakdown curve, the results were again plotted by Weltmann's method where the deflection d is plotted against $\log t$. A typical such plot is shown in Figure 84, and it can be seen that the points again do not all lie on a single straight line - the departure being most prominent at low torques. Hence, this approach was not considered to be very satisfactory.

If it is assumed that, for any given water/cement ratio, the same amount of breakdown is imparted to the paste during the mixing and the filling operations, the initial plastic viscosity U_0 should be independent of the testing speed. A plot of the initial deflection d_0 (of the middle cylinder) against the angular speed, should, therefore, give a straight line with an intercept d_2 on the deflection axis, representing the initial yield value to some scale. For the purpose of plotting such a graph, the value of d_0 was determined by extrapolation from the $\log(d - d_E)$ -time graph. Figure 85 shows the variation of d_0 with the angular speed. It can be seen that the plotted points are rather scattered about the straight line drawn through them. Furthermore, the torque represented by the intercept on the deflection axis is very high and is actually greater than the torque prevailing towards the end of any of the tests in Figure 80.

A PLOT OF DEFLECTION AGAINST TIME BY WELTMANN'S METHOD

FIG. 84

$w/c = 0.31$
C.B. II

VARIATION OF INITIAL DEFLECTION
WITH ANGULAR SPEED

FIG. 85

In other words, the torque given by the intercept, which in theory is necessary to overcome the yield value alone, seems to be greater than the actual torque required to overcome the yield value and to keep the paste flowing. This anomaly threw considerable doubt on the feasibility of obtaining d_0 by extrapolation from the $\log(d - d_E)$ -time graph.

As a result of further work (described in section d) carried out to evaluate the yield value for this particular paste, it was established that the torque intercept was not constant but varied with time from zero to a maximum value of 4.3 scale divisions. For the purpose of evaluating the plastic viscosity of the paste, a constant intercept equal to half the maximum value, i.e., 2.15 divisions, was taken.

The variation of the plastic viscosity with time at different rates of shear is given in Figure 86, and the effect of the rate of shear on the equilibrium (or final) viscosity is shown in Figure 87. In order to compare the rates of breakdown under different rates of shear, a plastic viscosity U_{80} was defined as that viscosity associated with 80% of the total breakdown obtained at the highest rate of shear used. Figure 88 shows the effect of the angular speed on the time t_{80} necessary to reduce the initial viscosity U_0 to U_{80} , as determined from the viscosity-time graph.

It can be deduced from Figure 86 that the higher the rate of shear, the higher is the rate of breakdown in the paste and the greater

VARIATION OF PLASTIC VISCOSITY WITH TIME

FIG. 86

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EFFECT OF RATE OF SHEAR ON
EQUILIBRIUM PLASTIC VISCOSITY

FIG. 87

EFFECT OF SPEED ON TIME REQUIRED TO
REDUCE THE VISCOSITY FROM
 U_0 TO U_{80}

FIG. 88

is its magnitude. But there seems to be a limit beyond which any increase in the rate of shear would only increase the rate of breakdown, with no significant reduction in the equilibrium viscosity U_E being achieved - as illustrated in Figure 87.

The total energy input W_T to the paste at any time t_1 , was determined by estimating the area under the torque-time curve between $t = 0$ and $t = t_1$. Also, the corresponding net breakdown energy $(W_T - W_E)$, defined as the total energy input minus the energy W_E required to overcome the equilibrium torque, was determined. The above two quantities, namely W_T and $(W_T - W_E)$, are represented by the shaded areas in Figure 89.

The variations of W_T and $(W_T - W_E)$ with time, are shown in Figures 90 and 91, respectively. From these graphs, it will be seen that while the total energy input to the paste increases with time irrespective of the breakdown level, the net breakdown energy tends to become constant as the equilibrium condition is approached. The reason for this behaviour lies in the fact that W_T includes the energy required to keep the paste flowing and this energy has to be provided even when no breakdown takes place. Consequently, all the plots in Figure 90 start off as curves but tend to become straight lines as the breakdown approaches completion. Moreover, these curves seem to suggest that the rate of energy input to the paste is not constant. This appears to contradict Cusens' assumption (discussed

SHADED AREA REPRESENTS
TOTAL ENERGY INPUT W_T
AT ANY TIME t_i

SHADED AREA REPRESENTS
NET BREAKDOWN ENERGY
 $(W_T - W_E)$ AT ANY TIME t_i

DIAGRAMS SHOWING WHAT IS MEANT
BY TOTAL ENERGY INPUT W_T AND
NET BREAKDOWN ENERGY $(W_T - W_E)$

FIG. 89

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$W/C = 0.31$
C.B. II

VARIATION OF TOTAL ENERGY
INPUT WITH TIME

FIG. 90

$W/C = 0.31$
C. B. II

VARIATION OF NET BREAKDOWN
ENERGY WITH TIME

FIG. 91

in Chapter IV) that the rate of energy input to concrete during vibration is constant. Perhaps it should be pointed out here that the writer's method of determining the energy input is a direct method of measurement - unlike the method used by Venkatramaiah and Cusens which determines the energy input to the concrete as the difference between two quantities of comparable magnitudes.

In view of the important implications that this behaviour may have on workability measurements, the question of energy input is discussed in more detail in section (e) of this Chapter, where the effect of the water/cement ratio on the breakdown of the paste is studied.

The effects of the angular speed on the final values of W_T and $(W_T - W_E)$ are shown in Figures 92 and 93, respectively. These graphs indicate that the energy consumption in both cases increases with the rate of shear. This behaviour, when considered in the light of the previous conclusions reached regarding the magnitude and the rate of the breakdown, seems to indicate that, from the point of view of energy consumption, it is inefficient to subject the paste to high rates of shear which are beyond a certain limit, if the shearing of the paste is to continue for a comparatively long period of time. In this particular case this limit may be fixed at the rate of shear associated with a speed of 60 r.p.m.

At a speed of 61 r.p.m., for instance, the viscosity is reduced

EFFECT OF SPEED ON TOTAL ENERGY
INPUT 5 MINUTES AFTER START OF
BREAKDOWN

FIG. 92

VARIATION OF NET BREAKDOWN ENERGY
(5 MIN. AFTER START OF BREAKDOWN)
WITH ANGULAR SPEED

FIG. 93

from 63.5 to 10.1 poises in five minutes and the total energy consumption required to achieve this, is 5330 joules. On the other hand, a speed of 102 r.p.m. reduces the viscosity to 6.9 poises in the same period of time with a corresponding energy expenditure of 9940 joules. In other words, the energy consumption is almost doubled in order to increase the breakdown by 6%.

A summary of the results for this series of tests is given in Table 3.

(d) Investigation of the variation of the yield value with time

This investigation was undertaken in an attempt to explain the departure of the experimental results from the best straight line drawn through them in the $\log(d - d_E)$ -time graph, and to evaluate the yield value - in view of the difficulty involved in obtaining a reasonable value for it from the theoretical relationship between the initial torque and the angular speed.

The tests consisted of subjecting the paste to a constant rate of shear, i.e., a constant viscometer speed, for a predetermined period of time, at the end of which a down-curve was run with the angular speed gradually reduced to its minimum value. The speed was then increased rapidly to its original value and two more down-curves were run in the same manner. A fourth down-curve was also obtained for the paste after subjecting it to continuous shearing for a further period of 2 minutes at the top speed used in the test.

Table 3

W/C = 0.31 $d_2 = 4.3$ div. $U_{80} = 18.5$ poises C.B.II

Test No.	Speed in r.p.m.	Extra-polated d_o in div.	U_o in poises	U_E in poises	t_{80} in seconds	W_T after 300 secs. in joules	$(W_T - W_E)$ after 300 secs. in joules
84	10.5	18.2	63.5	27.5	> 300	494	76
32	21.0	21.5	63.5	20.3	> 300	1300	185
28	38.0	31.5	63.5	13.7	57.0	2846	441
45	50.0	36.2	63.5	12.3	31.0	4278	631
33	61.0	44.0	63.5	10.3	13.0	5308	773
41	70.0	43.1	63.5	9.3	8.4	6283	896
34	80.0	48.4	63.5	7.7	2.2	6824	996
35	102.0	48.5	63.5	7.0	1.0	9888	1341

Two series of tests were carried out using different top speeds and a constant water/cement ratio of 0.31.

Series I

In this series, the constant rate of shear used was that associated with a speed of 50 r.p.m. To obtain the down-curves, the speed was gradually reduced in decrements of 5 r.p.m. at 10 second intervals. A typical first down-curve is shown in Figure 94 and the subsequent down-curves for the same test are shown in Figure 95.

In all the tests in which the top speed was maintained for an initial period not exceeding 50 seconds, it was found that the first down-curve was a straight line. When this initial period exceeded 50 seconds, however, the first down-curve displayed a tendency to become curved. The method of least squares was used to fit the best straight line through the results in the cases where the down-curve was straight. The yield value intercept (i.e., the torque intercept representing the yield value) as well as the slope of the lines, which determines the plastic viscosity, were calculated. For the curved down-curve, the intercept was obtained by extrapolating the curve to the torque axis.

The results thus obtained are given in Table 4.

All the straight first down-curves for this series are shown in Figure 96, while the curved ones are shown in Figure 97. In Figure 96 the actual points are omitted to avoid confusion.

The variation of the yield value intercept with time which is

TEST 49

W/C = 0.31

ANGULAR SPEED OF 50 R.P.M.

HELD FOR 25 SECONDS BEFORE

DOWN-CURVE IS RUN

TYPICAL FIRST DOWN-CURVE
BEFORE TENDENCY TO CURVE

SETS IN

FIG. 94

TEST 49

W/C = 0.31

C.B. II

ANGULAR SPEED OF 50 R.P.M.

HELD FOR 25 SECONDS BEFORE

DOWN - CURVES ARE RUN

A TYPICAL SET OF SUCCESSIVE DOWN - CURVES
OBTAINED BEFORE THE YIELD VALUE APPROACHED
ITS MAXIMUM VALUE

FIG. 95

Table 4.

Water/cement ratio = 0.31 Cement Batch II Top Speed = 50 r.p.m.				
Test No.	Time at top speed in seconds	Yield value intercept in divisions	Yield value in dynes/sq.cm.	Plastic viscosity in poises
44	10	0	0	23.9
47	15	0.30	36	21.7
46	20	1.47	176	17.9
49	25	2.07	248	15.8
48	30	2.71	325	15.0
50	35	3.75	450	15.5
51	37	3.77	453	14.9
52	45	4.00	480	17.7
53	50 ⁺	4.15	498	14.0

Table 5.

Water/cement ratio = 0.31 Cement Batch II Top speed = 70 r.p.m.				
Test No.	Time at top speed in seconds	Yield value intercept in divisions	Yield value in dynes/sq.cm.	Plastic viscosity in poises
59	5	0.58	70	19.6
63	15	3.03	363	13.8
64	15	3.35	402	13.8
60	20	3.92	470	14.1
67	30 ⁺	4.61	553	12.1

⁺ Beyond this limit the first down-curves become curved

STRAIGHT FIRST DOWN-CURVES

FIG.96

$W/C = 0.31$

C.B. II

TOP SPEED = 50 R.P.M.

CURVED FIRST DOWN-CURVES

FIG. 97

shown in Figure 98, can be divided into three distinct stages:

- (a) A short initial period, immediately after the motor is started, characterised by the apparent disappearance of the yield value.
- (b) A period characterised by a rapid rebuilding of the yield value.
- (c) A period of relative inactivity in which the yield value remains practically constant.

Thus, it would appear that the yield value is affected by the breakdown to a great extent. However, in view of the importance of the above behaviour of the paste, especially in relation to the vibration of fresh concrete, it was felt that an independent check on the results was necessary. This was effected by comparing the variation of the plastic viscosity with time, given in Table 4, with the corresponding curve obtained independently from a single constant speed test carried out at the same top speed (Figure 99). Bearing in mind that every value for the plastic viscosity given in Table 4 is the result of a completely independent test on a variable material, the relatively narrow scatter of points in Figure 99 serves as a useful check on the work.

The above disappearance of the yield value is probably only partly responsible for the departure of the results from the straight line in the $\log(d - d_E)$ -time graph. This is due to the fact that the

EFFECT OF SHEARING TIME AT TOP ANGULAR SPEED
ON YIELD VALUE INTERCEPT

FIG. 98

COMPARISON BETWEEN PLASTIC VISCOSITIES DETERMINED
FROM A SINGLE CONSTANT SPEED TEST AND THOSE
OBTAINED FROM INDIVIDUAL DOWN-CURVES

FIG. 99

magnitude of the final yield value is rather small.

Series II

This series of tests was originally intended to be similar to Series I in all respects except for the top speed which was fixed at 70 r.p.m. At first, the rate of speed reduction adopted was the same as for Series I, but due to the relatively high rate of breakdown prevailing at speeds equal to, or near, the top speed used, it was found that a time interval of 10 seconds between successive speed reductions of 5 r.p.m. was too long a period for the down-curve to be a straight line. Leaving the paste for 10 seconds at a speed of 65 r.p.m., for instance, produced a considerable amount of breakdown under a constant rate of shear. A down-curve illustrating this effect is shown in Figure 100, where the departure of the points from the straight line drawn through them is very noticeable, particularly at the higher speeds.

A rate of speed reduction of 10 r.p.m. at 10 seconds intervals gave satisfactory results, but this rate was changed to 7 r.p.m. at 5 seconds intervals to obtain more points for the curve. To increase the number of points still further, the 5 in. diameter driving pulley was replaced by the $2\frac{1}{2}$ in. diameter one which was capable of giving a minimum speed of $10\frac{1}{2}$ r.p.m.

The results for this series are given in Table 5. A curve showing the change of the yield value intercept with time is shown in

TEST 58

$W/C = 0.31$

A CONSTANT SPEED OF 70 R.P.M. HELD

FOR 2 SECONDS BEFORE RUNNING

DOWN-CURVE

DEPARTURE OF FIRST DOWN-CURVE
FROM LINEARITY AT HIGH SPEEDS

FIG. 100

Figure 101. It will be seen that this curve is of the same general shape as that shown in Figure 98 for a speed of 50 r.p.m., and therefore, the results for Series II give support to the conclusions drawn from Series I.

It is to be noted, however, that for Series II the initial time interval during which the yield value seems to disappear, is much shorter than for Series I. Also, the tendency of the down-curve to be curved sets in earlier at the higher speed; namely, at 30 seconds as compared with 50 seconds for Series I. These two observations indicate that the rebuilding of the yield value in time may be a function of the rate of breakdown, but a more comprehensive study would be needed to determine the actual relationship between the two.

In general, it may be stated that the results obtained from Series I are more reliable than those obtained from Series II because the short time intervals associated with the latter, made it difficult to keep the viscometer at a constant speed for the required period. This tendency was aggravated by the fact that the calibration curve for the speed control was not linear, so that the time required for effecting the speed change was not constant. The maximum yield value intercept is 4.65 divisions for Series II and 4.30 divisions for Series I and this latter figure was adopted for calculating the plastic viscosity for the above reason.

In view of the fact that the curve for the variation of the yield

VARIATION OF YIELD VALUE
WITH TIME

FIG. 101

value intercept with time appeared to depend on the rate of shear, a constant yield value intercept, equal to half its maximum value, was used for the purpose of calculating the plastic viscosity in section (c) and also in section (e) below. This assumption, while introducing a small error in the evaluation of the viscosity, obviated the necessity to carry out a series of tests similar to those described above, for every one of the rates of shear investigated.

The practical significance of the disappearance of the yield value lies in the fact that, if during the vibration of concrete, a breakdown under shear takes place in the cement paste matrix (and it will be suggested that this is actually the case), then, an analogy may be drawn between the behaviour of the paste in a rotational viscometer, and its behaviour under vibration. The elimination of the yield value, increases the fluidity of the concrete mix and causes it to flow under its own weight. This may increase the efficiency of the vibrator because the material may then flow even in those parts of the mix where the reduction in the plastic viscosity is not very great.

(e) General work on breakdown using different water/cement ratios

In the following series of tests, the third batch of cement was used. These tests constituted the bulk of the work done on the breakdown of neat cement pastes at constant rates of shear, and were undertaken to study the effect of the rate of shear on the breakdown

for different water/cement ratios.

Due to the difficulty in evaluating the initial torque, encountered in the preliminary series of tests already described, it was decided to obtain a direct reading for the maximum value of the cylinder deflection in every test. A down-curve was also run at the end of every test to determine the yield value intercept. Five speeds were generally used for each of the water/cement ratios investigated (except for the water/cement ratio of 0.33 where only three speeds were used). The same five speeds were used throughout the work so that the effect of the water/cement ratio on the breakdown at equal rates of shear could also be studied. The highest speed used was fixed at 50 r.p.m. to limit the drying out of the paste in the gap towards the end of the experiment.

A typical set of down-curves run at the end of the constant speed tests, is shown in Figure 102, where it can be seen that the curves, obtained for various speeds and a constant water/cement ratio, are very close to one another and tend to meet at a common point on the deflection axis when extrapolated. This tendency indicates that the final yield value is independent of the rate of shear, and for this reason, a single yield value is given in Table 6 for each of the water/cement ratios used.

The relationship between the water content and the yield value intercept thus determined is shown in Figure 103. It can be seen that

A TYPICAL SET OF DOWN-CURVES RUN AT
END OF CONSTANT SPEED TESTS TO DETERMINE
YIELD VALUE

FIG. 102

EFFECT OF WATER CONTENT ON
EXTRAPOLATED YIELD VALUE INTERCEPT

FIG. 103

although the water content has a marked effect on the yield value, the magnitude of the latter over the range considered, remains comparatively small. A plot of the yield value f on a logarithmic base against the percentage by weight p of the water present (Figure 104) gives a straight line. The relationship between f and p may be expressed as

$$f = 871000 e^{-0.34 p} \quad (104)$$

If in Figure 104, the percentage of water is replaced by the cement concentration by volume, a straight line would still be obtained. An expression similar to Papadakis' equation (Chapter II) can therefore be derived. As it is customary in concrete technology to use the water/cement ratio or the percentage of water present, rather than the cement concentration, to describe the consistency of the mix, this alternative expression is not included in this thesis.

The yield values given in Table 6, are of the same order as those quoted by Lobanov and by Papadakis for the thicker pastes. But, in general, the writer's figures are lower than those obtained by either of these investigators. This reduction in the yield value may, however, be attributed to the breakdown of the paste. Tattersall, on the other hand, gives lower figures for the yield value than those obtained by the writer.

RELATION BETWEEN YIELD VALUE
AND WATER CONTENT

FIG. 104

Table 6.

Water/cement ratio	Yield value intercept in divisions	Yield value f in dynes/sq. cm.
0.33	1.5	180
0.32	1.8	216
0.31	2.4	288
0.30	3.1	372
0.29	3.4	408
0.28	4.4	528

Typical plots of the variation of $\log(d - d_E)$ with time, are given in Figures 105 and 106. It may be stated that in all such plots two straight lines, meeting at a point between $t = 10$ and $t = 25$ seconds, fitted the results better than a single line.

As can be seen from the summary of the results given in Tables 7 - 12, inclusive, the values of the initial deflection d_o , as obtained by extrapolation from the $\log(d - d_E)$ -time graphs, are of the same order as the corresponding observed values of the maximum deflection d_m . When the angular speed is plotted against the extrapolated d_o (Figure 107), a straight line is obtained for each of the water/cement ratios used. The method of least squares was used to calculate the slope and the intercept of each of the straight lines shown in Figure 107. From these, the initial plastic viscosity U_o

(d-d_e) IN DIV. (LOG. SCALE)

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TEST 88
W/C = 0.31
SPEED = 38 R.P.M.
C.B. III

RELATION BETWEEN LOG(d-d_e) AND TIME

FIG. 105

TEST 97
W/C = 0.29
SPEED = 30 R.P.M.
C.B. III

(d-d_e) IN DIV. (LOG. SCALE)

RELATION BETWEEN LOG(d-d_e) AND TIME

FIG. 106

Table 7

$$W/C = 0.28$$

$$\text{Yield value intercept} = 4.4 \text{ div.}$$

C.B. III

Test No.	Speed in r.p.m.	Extrapolated d_o in div.	Observed max. defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
107	10.5	19.8	19.5	19.8	0.0339	0.0083	0.0212	0.0134	17.5	0.0664
103	21.0	29.3	26.3	37.4	0.0829	0.0117	0.0436	0.0272	27.7	0.1336
104	30.0	33.8	33.9	52.4	0.0996	0.0162	0.0516	0.0397	36.2	0.1617
105	38.0	40.5	39.4	65.8	0.1577	0.0188	0.0791	0.0638	42.9	0.1832
106	50.0	49.4	48.0	85.8	0.1968	0.0179	0.0949	0.0701	54.7	0.1933

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$$U_{50} = 42.8$$

$$U_{60} = 37.4$$

$$U_{70} = 32.1$$

$$U_{80} = 26.7 \text{ (poises)}$$

Test No.	U_o in poises	U_E in poises	W_T after 300 secs in joules	$(W_T - W_E)$ after 300 secs in joules	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
107	69.6	30.7	535	99	80.65	147.60	271.10	> 300	9.8	6.2
103	69.6	18.5	1312	250	6.30	12.20	29.80	68.65	25.8	8.9
104	69.6	16.0	2184	379	1.20	3.10	14.40	38.25	38.7	13.3
105	69.6	16.0	3148	356	0.90	1.40	2.80	10.95	49.0	9.8
106	69.6	16.0	5150	461	0.80	1.10	1.75	4.10	64.4	8.7

Table 8

 $W/C = 0.29$

Yield value intercept = 3.60 div.

C.B. III

Test No.	Speed in r.p.m.	Extrapolated d_o in div.	Observed max. defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
109	10.5	16.8	16.3	16.8	0.0238	0.0160	0.0201	0.0191	15.0	0.0668
100	21.0	26.5	25.9	31.8	0.0663	0.0147	0.0428	0.0320	24.3	0.1222
97	30.0	28.7	28.0	44.6	0.1163	0.0165	0.0595	0.0465	30.7	0.1609
98	38.0	32.9	32.2	56.1	0.1645	0.0177	0.0839	0.0647	36.7	0.1813
110	50.0	43.6	41.8	73.2	0.1815	0.0158	0.0890	0.0601	45.8	0.2018

 $U_{50} = 35.8$ $U_{60} = 31.1$ $U_{70} = 26.4$ $U_{80} = 21.7$ (poises)

Test No.	U_o in poises	U_E in poises	W_T after 300 secs. in joules	$(W_T - W_E)$ after 300 secs. in joules	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
109	59.4	27.0	449	73	71.55	119.60	298.40	>300	8.2	7.0
100	59.4	17.9	1205	206	13.25	29.55	52.10	88.85	20.9	8.6
97	59.4	14.8	1911	275	1.15	3.00	15.10	42.30	32.1	9.1
98	59.4	14.1	2736	287	0.85	1.35	2.90	14.40	41.4	7.3
110	59.4	12.3	4119	489	0.90	1.30	2.25	6.50	56.6	8.2

Table 9

C.B. III

Yield value intercept = 2.9 div.

 $W/C = 0.30$

Test No.	Speed in r.p.m.	Extra-polated d_o in div.	Observed max. defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
91	10.5	14.9	15.0	14.9	0.0290	0.0106	0.0251	0.0188	13.1	0.0729
92	21.0	19.9	19.7	28.4	0.0991	0.0145	0.0481	0.0386	21.0	0.1326
99	30.0	25.6	25.0	39.9	0.1302	0.0156	0.0676	0.0516	27.8	0.1561
93	38.0	28.9	28.3	50.2	0.1732	0.0187	0.0871	0.0757	32.7	0.1827
94	50.0	37.4	36.4	65.5	0.1765	0.0136	0.0778	0.0488	40.7	0.2056

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 $U_{80} = 19.1$ (poises) $U_{70} = 23.40$ $U_{60} = 27.7$ $U_{50} = 32.0$

Test No.	U_o in poises	U_E in poises	W_T after 300 secs. in joules	$(W_T - W_E)$ after 300 secs. in joules	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
91	53.4	23.2	387	67	65.50	114.50	287.10	> 300	7.6	4.6
92	53.4	16.2	1030	142	2.70	15.10	43.70	94.15	18.7	6.4
99	53.4	14.7	1795	211	1.20	2.95	16.05	50.25	27.8	6.5
93	53.4	12.9	2433	227	0.80	1.30	2.80	15.10	36.9	6.2
94	53.4	10.5	3596	505	0.85	1.20	2.05	6.05	51.4	8.1

Table 10

 $W/C = 0.31$

Yield value intercept = 2.3 div.

C.B. III

Test No.	Speed in r.p.m.	Extra-polated d_o in div.	Observed max.defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
86	10.5	13.2	12.5	13.2	0.0218	0.0144	0.0220	0.0195	11.6	0.0711
87	21.0	17.0	16.7	25.2	0.0998	0.0178	0.0556	0.0494	18.4	0.1361
90	30.0	23.9	23.3	35.6	0.1443	0.0183	0.0714	0.0622	24.7	0.1570
88	38.0	24.6	24.2	44.8	0.1625	0.0163	0.0802	0.0634	28.7	0.1738
89	50.0	31.7	31.0	58.6	0.1873	0.0127	0.0766	0.0486	36.9	0.1968

 $U_{50} = 29.0$ $U_{60} = 25.3$ $U_{70} = 21.5$ $U_{80} = 17.8$ (poises)

Test No.	U_o in poises	U_E in poises	W_T after 300 secs. in joules	$(W_T - W_E)$ after 300 secs. in joules	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
86	47.7	21.0	337	55	64.35	100.85	275.10	> 300	6.8	5.2
87	47.7	14.5	895	114	1.85	10.75	33.10	68.40	16.7	5.6
90	47.7	13.5	1596	170	1.30	2.60	10.05	39.20	24.7	5.8
88	47.7	11.8	2216	226	0.65	1.05	2.25	12.85	32.8	5.4
89	47.7	10.4	3410	429	0.70	1.00	1.65	4.60	45.0	6.8

Table 11⁺

$W/C = 0.32$ Yield value intercept = 1.8 div. C.B. III

Test No.	Speed in r.p.m.	Extrapolated d_o in div.	Observed max. defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
119	10.5	11.4	10.8	11.4	0.0234	0.0129	0.0226	0.0204	10.1	0.0647
111	21.0	15.1	14.5	21.9	0.1184	0.0176	0.0607	0.0607	16.4	0.1243
112	30.0	21.4	20.9	30.9	0.1421	0.0166	0.0708	0.0607	22.0	0.1452
120	30.0	19.6	19.3	30.9	0.1421	0.0147	0.0727	0.0603	22.1	0.1424
113	38.0	25.7	25.1	38.9	0.1554	0.0112	0.0665	0.0432	26.6	0.1629
114	50.0	31.2	30.6	50.9	0.1587	0.0144	0.0679	0.0475	32.2	0.1975
122	50.0	29.6	29.2	50.9	0.1613	0.0151	0.0689	0.0510	32.6	0.1909

⁺ Some of the tests carried out in duplicate are included in this table to illustrate the reproducibility of the results. The table is continued on the next page.

Table 11 (continued)

$U_{50} = 25.1$
 $U_{60} = 21.8$
 $U_{70} = 18.5$
 $U_{80} = 15.2$ (poises)

Test No.	U_o in poises	U_E in poises	W_T after 300 secs. in joules	$(W_T - W_E)$ after 300 secs. in joules	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
119	41.6	21.2	309	47	85.75	221.10	> 300	> 300	5.4	3.8
111	41.6	14.8	851	79	3.65	14.10	47.10	266.15	13.5	3.9
112	41.6	13.0	1504	152	1.60	3.75	18.75	65.10	20.6	4.6
120	41.6	13.4	1536	145	1.15	3.10	20.20	73.10	20.3	4.0
113	41.6	11.2	2130	274	1.25	2.15	6.10	36.85	27.7	5.1
114	41.6	8.6	2907	447	1.00	1.45	2.70	9.40	39.7	8.0
122	41.6	9.3	3048	413	0.85	1.35	2.65	11.85	38.9	7.9

Table 12

$W/C = 0.33$ Yield value intercept = 1.4 div. C.B. III

Test No.	Speed in r.p.m.	Extra-polated d_o in div.	Observed max. defl. d_m in div.	Calculated d_o in div.	B_1 between $t=0$ and $t=15$ sec	B_2 between $t=20$ and $t=300$ sec	B_3 between $t=0$ and $t=60$ sec	B_4 between $t=0$ and $t=300$ sec	C	m
123	10.5	9.6	8.5	9.6	0.0548	0.0142	0.0329	0.0329	8.2	0.0766
124	30.0	18.1	17.8	26.1	0.1460	0.0134	0.0677	0.0552	18.9	0.1369
125	50.0	27.3	27.1	43.0	0.1388	0.0162	0.0605	0.0469	28.5	0.1762

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$U_{50} = 21.8$ $U_{60} = 19.2$ $U_{70} = 16.5$ $U_{80} = 13.8$ (poises)

Test No.	U_o in poises	U_E in poises	W_T after 300 secs.	$(W_T - W_E)$ after 300 secs.	t_{50} in secs.	t_{60} in secs.	t_{70} in secs.	t_{80} in secs.	$(d_o - d_E)$ for B_1, B_3 and B_4 in div.	$(d_o - d_E)$ for B_2 in div.
123	35.2	16.6	242	28	45.35	103.10	> 300	> 300	4.7	2.5
124	35.2	11.8	1339	132	1.45	2.95	13.70	64.40	16.9	3.5
125	35.2	8.4	2789	413	1.10	1.70	3.85	18.30	32.1	8.4

C.B. III

VARIATION OF INITIAL DEFLECTION
WITH SPEED

FIG. 107

and the yield value f , were evaluated. The results thus obtained are given in Table 13.

Table 13.

Water/cement ratio	Initial plastic viscosity U_0 in poises	Yield value intercept in divisions	Yield value f in dynes/sq.cm.
0.33	18.6	4.8	576
0.32	21.1	5.4	647
0.31	19.9	7.7	924
0.30	23.6	8.3	996
0.29	27.1	10.2	1222
0.28	30.7	12.5	1500

The yield values given in the above table, seemed to be very high in comparison to those given in Table 6. In fact, the equilibrium torque as measured at the minimum speed used ($10\frac{1}{2}$ r.p.m.), was, in some cases, less than the corresponding extrapolated yield value intercept given above. This behaviour is similar to that previously discussed in the preliminary work in section (c).

The reason for this discrepancy, lies in the fact that when the motor was started, a substantial part of the torque was used up in accelerating the middle cylinder and its attachments - thereby

reducing the observed maximum value of the torque. The effect of this behaviour on d_o was more pronounced at the higher speeds because of the very high rates of breakdown produced. For the minimum speed, however, the rate of breakdown was considerably slower and the pointer reached its maximum position about 3 or 4 seconds after the motor was started (Figure 108). In such a case, the torque required to overcome the inertia of the middle cylinder unit, may be regarded as being comparatively small, and, therefore, the initial plastic viscosity can be obtained from the extrapolated value of the initial torque. The initial plastic viscosity thus determined was taken to be common to all pastes having the same water/cement ratio.

The plastic viscosity was calculated on the previously stated assumption that the yield value intercept remains constant at half its maximum value, as determined from the down-curves run at the end of the constant speed tests. Thus knowing the initial plastic viscosities, the corresponding initial deflections were calculated. These are given in Tables 7 - 12.

Since the available published literature (23) suggested that a single straight line would satisfactorily fit the results on the $\log(d - d_E)$ -time graph, it was considered desirable to investigate how accurately such a line would represent the writer's results. To do this, a straight line passing through the calculated d_o was fitted through the points by the method of least squares described in

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VARIATION OF DEFLECTION WITH TIME

FIG. 108

Appendix II involving a specially devised method of weighting. Three such straight lines were drawn as follows:

- i) A line fitting the results between $t = 0$ and $t = 15$ seconds.
- ii) A line fitting the results between $t = 0$ and $t = 60$ seconds.
- iii) A line through all the results, i.e. between $t = 0$ and $t = 300$ seconds.

Each of these lines represents the deflection d in the form

$$d - d_E = (d_0 - d_E) \cdot e^{-B \cdot t}$$

where d_0 and d_E are the initial and the equilibrium values of d , respectively, t is the time, and B is a constant equal to the slope of the straight line in the logarithmic plot.

A typical set of deflection curves corresponding to these alternative straight lines is shown in Figure 109 and it will be noted that the curve associated with line (ii) gives the best fit. The slopes, B_1 , B_3 and B_4 , of these lines, are given in Tables 7 - 12, inclusive.

If, however, two straight lines are drawn through the results so that the first line fits the results between $t = 0$ and $t = 15$ seconds, while the second line passes through the results from $t = 20$ seconds onwards, as shown in Figure 110, then a close representation of the observed deflection is achieved. Figure 111 shows typical

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TEST 110

$w/c = 0.29$

ANGULAR SPEED = 50
R.P.M.

TYPICAL SET OF CURVES SHOWING THE
AGREEMENT BETWEEN THE OBSERVED CURVE
AND THOSE GIVEN BY SUGGESTED EXPRESSIONS

FIG. 109

TYPICAL VARIATIONS OF COEFFICIENTS

$B_1, B_2 \text{ \& } B_3$ WITH ANGULAR SPEED

FIG. III

curves for the variation of the slopes B_1 and B_2 of these two straight lines with the speed. The corresponding variation for the straight line fitting the results between $t = 0$ and $t = 60$ seconds, is also included on the same graph.

In an effort to obtain a single expression for the deflection which would be valid for the entire curve without any significant error being involved, an equation of the following form was adopted

$$d = C \cdot t^{-m} \quad (105)$$

where d is the deflection of the middle cylinder, t is the time, while m and C are empirical constants depending on the speed and the consistency.

A typical graph of $\log(t)$ against $\log(d)$, in which a straight line was fitted by the "weighted" method of least squares (Appendix II), is shown in Figure 112. The straight line shown was so chosen that it passed through the point representing the calculated initial deflection d_0 which was assumed to occur at $t = 0.1$ seconds. This was done to overcome the difficulty involved in plotting $\log(t)$ when $t = 0$. The deflection-time curve corresponding to this line is included in Figure 109, and it can be seen to fit the results better than the single exponential curves. It has to be borne in mind, however, that, in contrast to the exponential expression used, a power function of the type given in equation (105) has no meaning

when $t = 0$ or when $t = \infty$. In addition to this, the use of the power function may be objectionable from the theoretical point of view because the dimensions of the viscosity, as determined from it, depend on m as previously mentioned in Chapter I. Despite these criticisms, it appears that such expressions are still in common use where they closely fit the observed results, and probably this particular case can be classified in this category.

The variations of m and C with the speed for the various water/cement ratios used, are shown in Figures 113 and 114, respectively. It may be concluded from these graphs that while the water content has a marked effect on C , its influence on m appears to be small. Hence m may be assumed to be a function of the speed alone, within the range of the water/cement ratios investigated. A plot of $\log(m)$ against $\log(N)$, where N is the angular speed in r.p.m. is shown in Figure 115, and the equation for m , given by the straight line drawn thereon, is

$$m = 0.0144 N^{0.68} \quad (106)$$

The empirical equation for the deflection d would therefore take the form

$$d = C \cdot t^{-0.0144} N^{0.68} \quad (107)$$

where t is the time in seconds, N is the speed in r.p.m., while

C. B. III

POINT	W/C
▲	0.28
x	0.29
•	0.30
+	0.31
o	0.32
▼	0.33

VARIATION OF COEFFICIENT m
WITH ANGULAR SPEED

FIG. 113

VARIATION OF COEFFICIENT C WITH
ANGULAR SPEED

FIG. 114

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C. 8. III

POINT	w/c
x	0.28
▲	0.29
+	0.30
•	0.31
□	0.32
▼	0.33

COEFFICIENT M (LOG. SCALE)

ANGULAR SPEED IN R.P.M. (LOG. SCALE)

RELATION BETWEEN $\log(M)$ AND $\log(N)$

FIG. 115

the constant C is a linear function of the speed. In fact C is equal to the deflection of the cylinder 1 second after the start of the breakdown. In equation (107), d may represent the torque in any convenient units provided the same units are used for C .

Figures 116 and 117 illustrate the effect of the breakdown on the plastic viscosity of cement pastes having a water/cement ratio of 0.29 and 0.31, respectively. The curves shown may be taken as typical for the other water/cement ratios used. It can be seen from these graphs that the curves associated with the wetter paste are more closely spaced than those for the drier one, and that the lower speeds are comparatively ineffective in breaking down the paste. Similar tendencies were observed by Cusens (55) while studying the effects of the vibration time and the acceleration (of the vibrator) on the cube crushing strength of concrete (Figures 43, 44 and 45). This similarity seems to suggest that for any given mix, the resulting cube crushing strength, which is a function of the compaction, depends to a certain extent on the amount of breakdown achieved in the cement paste matrix. In this context, the viscometer speed is assumed to produce the same effect on the paste as that induced by the acceleration of the vibrator. This assumption is further supported by the general agreement between Auerbach's results (51), shown in Figure 32, and the results shown in Figures 116 and 117, as the flow time plotted by Auerbach is in fact a function of the viscosity (equation 4,

VARIATION OF PLASTIC VISCOSITY WITH TIME

FIG. 116

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VARIATION OF PLASTIC VISCOSITY WITH TIME

FIG. 117

Chapter I), while the amplitude, at a constant frequency, represents the acceleration to a certain scale.

The viscosity-time graphs (Figures 116 and 117) seem to indicate that, irrespective of the water content in the paste, an increase in the rate of shear produces an increase in the rate and the magnitude of the breakdown. The increase in the magnitude of the breakdown tends, however, to become comparatively small if the rate of shear exceeds a certain limit. In Figures 116 and 117, for instance, this limit may be set at the rate of shear corresponding to 30 and 21 r.p.m., respectively. This effect is perhaps better illustrated in Figure 118 where the equilibrium (or final) viscosity is plotted against the angular speed. It may also be seen from this graph that the thicker the paste, the more pronounced is the decrease in the equilibrium viscosity as the angular speed is increased.

The above conclusions are in agreement with the results of the work on the vibration of fresh concrete carried out at the Building Research Station (52) where it was established that, for every one of the three mixes studied, a critical acceleration, which increased with the stiffness of the mix, existed (Figures 36, 37 and 38). Below this critical value, the strength and the density of the concrete cubes increased substantially with the acceleration, but when the acceleration was increased beyond this value, it produced little change in the final concrete properties. Here again, the results

EFFECT OF ANGULAR SPEED ON EQUILIBRIUM
PLASTIC VISCOSITY BASED ON FULL
YIELD VALUE

FIG. 118

seem to suggest the existence of some close relationships between the compaction and the plastic viscosity on the one hand and between the acceleration and the rate of shear on the other.

The effect of the water/cement ratio on the initial plastic viscosity U_0 is shown in Figure 119, and it will be noted that the paste is very sensitive to small changes in the water content. This is in agreement with the results of the work recently carried out by Murdock (45) using the Vicat apparatus. He found that the consistency of the neat cement paste changed quite suddenly when the water/cement ratio (by weight) was increased by 1%. In comparison to Murdock's results, the curves obtained by the writer have the added advantage that they give the actual value of the viscosity, whereas Murdock measured the depth of penetration of the Vicat plunger which gave only a rough indication of the consistency. Furthermore, the above penetration test gives no indication as to the consistency of the paste when a total penetration is obtained.

When $\log(U_0)$ is plotted against the percentage by weight p of the water content in the paste, a straight line is obtained (Figure 120) and the equation relating the two variables may be written as.

$$U_0 = 13500 e^{-0.24 p} \quad (108)$$

When the initial plastic viscosity U_0 is difficult to determine

EFFECT OF WATER/CEMENT
RATIO ON INITIAL PLASTIC
VISCOSITY

FIG. 119

INITIAL PLASTIC VISCOSITY IN POISES (LOG. SCALE)

C. 8. III

100
80
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1

20 21 22 23 24 25

PERCENTAGE OF WATER PRESENT (BY WEIGHT)

FIG. 120

RELATION BETWEEN INITIAL PLASTIC
VISCOSITY AND WATER CONTENT

(as in the case of cement mortars), a reasonably good estimate of the relative initial viscosities for various pastes, can be obtained by comparing the viscosities U_5 prevailing 5 seconds after the start of the motor. This is only valid if all the viscosities U_5 are obtained for the same rate of shear. In this context, U_5 is computed on the assumption that the yield value is zero, but very similar results can be obtained if half the maximum yield value is taken into account. The values for U_0 and U_5 are given in Table 14. In Table 15 the ratios of the viscosities in any one column, in Table 14, to the highest viscosity in the same column, are listed. It can be seen from Table 15 that a good agreement is generally obtained between the ratios for U_0 and the corresponding ones for U_5 - this agreement being particularly good when the speed is 30 r.p.m.

To examine the effect of the rate of shear on the rate of breakdown, the time t_{80} , necessary to reduce the viscosity from U_0 to a value U_{80} , was determined for various speeds, from the viscosity-time graphs - U_{80} being the viscosity achieved after 80% of the total breakdown at a constant speed of 50 r.p.m. has taken place. The variation of t_{80} with the speed is illustrated in Figure 121, and it will be noted that all the curves shown tend to become fairly flat as the speed is reduced, indicating a substantial increase in the breakdown time.

Table 14

Water/ cement ratio	Plastic viscosity U_5 in poises					Initial viscosity U_0 in poises
	speed $10\frac{1}{2}$ r.p.m.	speed 21 r.p.m.	speed 30 r.p.m.	speed 38 r.p.m.	speed 50 r.p.m.	
0.33	33.7		19.8		17.1	35.2
0.32	42.8	27.6	24.1	21.4	17.6	41.6
0.31	49.5	31.1	27.1	22.4	19.6	47.7
0.30	53.5	35.1	31.0	25.0	22.4	53.4
0.29	63.0	47.4	35.1	28.7	27.3	59.4
0.28	73.4	51.0	40.2	34.8	28.2	69.6

Table 15.

Water/ cement ratio	Viscosity ratios					
	$U_5/73.4$ ($10\frac{1}{2}$ r.p.m.)	$U_5/51.0$ (21 r.p.m.)	$U_5/40.2$ (30 r.p.m.)	$U_5/34.8$ (38 r.p.m.)	$U_5/28.2$ (50 r.p.m.)	$U_0/69.6$
0.33	0.46		0.49		0.61	0.51
0.32	0.58	0.54	0.60	0.61	0.62	0.60
0.31	0.68	0.61	0.68	0.65	0.69	0.69
0.30	0.73	0.69	0.77	0.72	0.79	0.77
0.29	0.86	0.93	0.87	0.83	0.97	0.85
0.28	1.00	1.00	1.00	1.00	1.00	1.00

C.B. III

EFFECT OF ANGULAR SPEED ON TIME REQUIRED
TO REDUCE THE PLASTIC VISCOSITY FROM U_0
TO U_{80}

FIG. 121

Three other viscosities, namely, U_{70} , U_{60} , and U_{50} , were defined in a similar manner to U_{80} to represent, respectively, the viscosity after 70%, 60%, and 50% of the total breakdown, obtained at a constant speed of 50 r.p.m., have taken place. To determine accurately the breakdown times (t_{80} , t_{70} , t_{60} , and t_{50}) associated with each of the above viscosities, use was made of an electronic computer to fit the best curve through the experimental results for the variation of viscosity with time. The curve fitting was done by the method of least squares and the expression used was of the form

$$U = A/t^2 + B/t + C + D.t + E.t^2 + F.t^3 \quad (109)$$

where U is the plastic viscosity, t is the corresponding breakdown time, and A , B , C , D , E and F are constants. Using this expression, which fitted the results to within 0.1 poise, the required breakdown times were calculated by the computer to the nearest 0.05 second.

When, for each of the water/cement ratios used, the time required to achieve a given viscosity, i.e., t_{80} , t_{70} , t_{60} , or t_{50} , is plotted against the corresponding speed on logarithmic bases, a straight line, similar to the ones shown in Figure 122, is obtained.

The line can be represented by the following equation:

$$t = G . N^q \quad (110)$$

where t is the breakdown time in seconds, N is the viscometer speed in r.p.m., while G and q are empirical constants.

Table 16 gives the values of q and G for 20 such straight lines fitted by the method of least squares. It will be noted from this table that q tends to remain constant irrespective of the viscosity and the water/cement ratio. The mean of the 20 tabulated values of q is -3.23 and the standard deviation from the mean is 0.20. The value of q was also determined for five viscosities between U_{80} and $1.5 U_{80}$ for the five water/cement ratios in question. All of the 25 values of q in this case lay between -3.01 and -3.75, with a mean value of -3.34 and a standard deviation of 0.19. It would appear therefore that equation (110) can be rewritten as

$$t = G/N^{3.3} \quad (111)$$

for all the pastes investigated.

The paste having a water/cement ratio of 0.33 was not included in the above determination of q because three tests only were performed on it.

The effect of the speed on the energy input to the paste, necessary to reduce the viscosity from U_0 to U_{80} , is shown in Figure 123. It will be seen that the energy input is comparatively small at the higher speeds. This can be explained by the fact that the time required for the viscosity to attain the value of U_{80} is

Table 16

Water/cement ratio	Viscosity attained	Actual value of viscosity in poises	q	G
0.32	U ₅₀	25.1	- 2.778	30,000
0.32	U ₆₀	21.8	- 3.249	319,000
0.32	U ₇₀	18.5	- 3.501	2,365,000
0.32	U ₈₀	15.2	- 3.733	23,374,000
0.31	U ₅₀	29.0	- 2.949	36,000
0.31	U ₆₀	25.3	- 3.160	150,000
0.31	U ₇₀	21.5	- 3.444	987,000
0.31	U ₈₀	17.8	- 3.228	1,565,000
0.30	U ₅₀	32.0	- 2.914	36,000
0.30	U ₆₀	27.7	- 3.154	180,000
0.30	U ₇₀	23.4	- 3.318	832,000
0.30	U ₈₀	19.1	- 3.276	2,428,000
0.29	U ₅₀	35.8	- 3.151	114,000
0.29	U ₆₀	31.1	- 3.237	280,000
0.29	U ₇₀	26.4	- 3.336	933,000
0.29	U ₈₀	21.7	- 3.127	1,349,000
0.28	U ₅₀	42.8	- 3.147	99,000
0.28	U ₆₀	37.4	- 3.295	288,000
0.28	U ₇₀	32.1	- 3.299	680,000
0.28	U ₈₀	26.7	- 3.353	2,278,000

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EFFECT OF ANGULAR SPEED ON THE TOTAL
ENERGY INPUT REQUIRED TO REDUCE THE
PLASTIC VISCOSITY FROM U_0 TO U_{80}

FIG. 123

reduced at these speeds and, hence, the amount of energy necessary to keep the paste flowing is reduced accordingly - thus resulting in an overall reduction in the energy consumption.

The effects of the angular speed on the total energy input to the paste and the net breakdown energy, at the end of the test, are shown in Figures 124 and 125, respectively. These graphs indicate that, in contrast to the tendency observed in Figure 123, the energy consumption increases as the speed increases. The same effect is observed from the typical curves for the variation of the energy with time, shown in Figures 126 and 127.

The conclusion to be drawn from the above is, that it is more economical (as far as the energy input to the paste is concerned) to use the higher range of speeds provided the shearing of the paste is stopped immediately after the required viscosity is attained. If, however, the shearing action is to continue for a considerably longer period of time than the minimum required, then this state of affairs is reversed, and the energy consumption at the higher speeds becomes greater than that associated with the lower ones. The reason for this lies in the fact that a comparatively high energy expenditure is required to keep the paste flowing at the higher speeds.

It would appear, therefore, that if the shearing time is fixed at any given value, then a suitable optimum speed can be chosen so that the plastic viscosity is reduced to the required value at or near the

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EFFECT OF ANGULAR SPEED ON TOTAL
ENERGY INPUT 5 MIN. AFTER START
OF BREAKDOWN

FIG. 124

EFFECT OF ANGULAR SPEED ON NET
BREAKDOWN ENERGY 5 MINUTES AFTER
START OF BREAKDOWN

FIG. 125

TYPICAL
VARIATION OF TOTAL ENERGY INPUT TO
PASTE WITH TIME
FIG. 126

TYPICAL VARIATION OF NET BREAKDOWN

ENERGY WITH TIME

FIG. 127

end of the prescribed shearing time. Such a speed would give the most economical rate of shear as far as the paste alone is concerned, and may have to be modified if the friction and other losses in the motor and the driving unit are found to be high - these losses being normally dependent on the speed.

Measurement of workability

An important aspect of this work lies in developing a method for measuring the workability of the paste. The rotational viscometer seems to provide a unique means for measuring this property because the net energy input to the paste can be directly estimated without the need of assessing the losses in the driving mechanism.

At first it was thought that the net breakdown energy ($W_T - W_E$), at the end of the test, would give a reasonable measure of the workability. But when this quantity was plotted against the water content in the paste expressed as a percentage by weight (Figure 128), it was found that the points were rather scattered at the higher speeds.

On the other hand, when the corresponding total energy input W_T to the paste was plotted against the percentage water content by weight (Figure 129), the experimental results gave a smooth curve for every one of the speeds investigated. The quantity W_T was therefore, taken as a measure of the workability in preference to $(W_T - W_E)$. Another reason for this selection lies in the fact that whereas $(W_T - W_E)$ depends almost entirely on the breakdown of the paste, W_T depends

NET BREAKDOWN ENERGY W_TWE (JOULES)

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ANGULAR SPEED IN R.P.M. =

RELATION BETWEEN THE NET BREAKDOWN
ENERGY (5 MIN. AFTER START OF
BREAKDOWN) AND THE WATER CONTENT

FIG. 128

RELATION BETWEEN THE TOTAL ENERGY
INPUT (5 MIN. AFTER START OF
BREAKDOWN) AND THE WATER CONTENT

FIG. 129

on the breakdown as well as the flow properties governing the value of the equilibrium torque. This is considered an added advantage because, in practice, the flow of cement pastes, fresh mortars, and concrete (during placing), depends on the same two factors.

The degree of sensitivity in the measurement of the workability is governed by the steepness of the W_T versus water content curve (Figure 129). This in turn, is dictated by the angular speed. A wide range of sensitivity is therefore available. For the cement pastes investigated, a speed lying between 30 and 40 r.p.m. would give a reasonable degree of sensitivity.

Another quantity that comes to mind when considering the workability is the initial plastic viscosity U_o . The variation of U_o with W_T at each of the speeds used (Figures 130 - 134 inclusive) indicates that the two quantities are linearly related so that one is a constant multiple of the other. This simple relationship confirms the adequacy of W_T as a measure of workability, and serves as a useful check on the results because each of the two variables in question is determined by a completely independent method.

The yield value is also linearly related to W_T (Figure 135) but, the straight lines do not pass through the origin. Since, however, the yield value is comparatively small, this relationship appears to have little or no effect on that existing between W_T and U_o .

As previously stated in Chapter III, the principle involved in

RELATION BETWEEN TOTAL ENERGY INPUT
(AFTER A PERIOD OF 5 MIN.) AND INITIAL
PLASTIC VISCOSITY U_0

FIG. 130

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RELATION BETWEEN TOTAL ENERGY INPUT
(AFTER A PERIOD OF 5 MIN.) AND INITIAL PLASTIC
VISCOSITY U_0

FIG. 131

RELATION BETWEEN TOTAL ENERGY INPUT
(AFTER A PERIOD OF 5 MIN.) AND INITIAL PLASTIC
VISCOSITY U_o

FIG. 132

FIG. 133

RELATION BETWEEN TOTAL ENERGY INPUT
(AFTER A PERIOD OF 5 MIN.) AND INITIAL PLASTIC
VISCOSITY U_0

FIG. 134

RELATION BETWEEN TOTAL ENERGY
INPUT (AFTER A PERIOD OF 5 MIN.)
AND YIELD VALUE

FIG. 135

the measurement of workability by the Vebe apparatus, is based on the assumption that the rate of energy input to the concrete remains constant throughout the remoulding operation irrespective of the consistency of the mix. In other words, at equal remoulding times, the concrete absorbs equal amounts of energy. In an attempt to test the validity of this assumption for cement pastes, the time required to obtain 90% of the breakdown was plotted against the corresponding energy input W_T to the paste as shown in Figure 136. It will be noted that there is a wide scatter of points around the straight lines drawn through the results. In fact, some of the results tend to suggest that equal breakdown times are not associated with equal energy consumptions as far as the paste is concerned.

A better illustration of this effect is given in Figure 137 where typical curves for the variation of the total energy input W_T with time, are shown. These curves, which tend to become straight lines as the breakdown approaches completion, do not appear to support the assumption that the rate of energy input to the paste is constant. Actually, Figure 137 indicates that the stiffer the paste, the higher is the rate of energy input. Bearing in mind that fresh concrete is essentially a suspension of inert particles in a cement paste matrix, the above behaviour must cast considerable doubt on the validity of the assumption (discussed in Chapters III and IV) that a constant rate of energy input exists during the remoulding and the compaction

RELATION BETWEEN TOTAL ENERGY INPUT
REQUIRED TO OBTAIN 90% OF BREAKDOWN TAKING
PLACE IN FIRST 5 MIN. AND TIME REQUIRED
TO ACHIEVE THIS

FIG. 136

TYPICAL CURVES FOR VARIATION OF
TOTAL ENERGY INPUT w_t WITH TIME

FIG. 137

of concrete.

Perhaps it ought to be stated that during the compaction of concrete by vibration, the energy required to keep the concrete in constant movement may not be as much as that necessary to keep the material flowing in a rotational viscometer. But the curves for the variation of the energy consumption with time for concrete, would probably have the same general shape as those shown in Figure 137, although the straight portions may be less steep.

It may be concluded therefore, that if the consistencies of concrete mixes are compared on the basis of the remoulding times obtained from the Vebe test, a slightly misleading picture of the relative workability will be presented because this method will unduly favour the drier mixes and show them to be more workable than they really are. For instance, if two mixes A and B require remoulding times t and $1.1 t$, respectively, the energy taken by mix B may be, say, 1.25 times the energy taken by mix A, as it has been established that the rate of energy input increases with the stiffness of the mix. It would appear, therefore, that a better basis for comparison of concrete mixes may be obtained, if the workability, as determined by the Vebe apparatus, is taken to be proportional to t^n where t is the Vebe time and n is a number greater than unity.

This behaviour may explain Keene's statement (47) that the time of vibration, required for the transparent plate of the Vebe apparatus

to fall to a position $6\frac{3}{4}$ in. below the top of the cone, appeared to show insufficient discrimination between mixes of different workability.

Check on slip

While the investigation of the behaviour of cement pastes under constant rate of shear was in progress, it was considered essential to determine whether any slipping did take place between the paste and the metal surfaces. To do this, the viscometer was filled with bentonite and allowed to stand for a few hours, to promote the formation of an extremely thin film of rust. This film was, in fact, so fine that it was nothing more than a light dye. It was thought that this film would disappear if any slipping between the paste and the cylinders took place.

After performing a large number of shear tests on various pastes in the viscometer, it was found that the film remained intact, thus indicating the absence of slip. Actually the film persisted even when cement-sand mortars were tested in the viscometer.

Summary of results in section (e)

In view of the fact that this section has been lengthy, and digressions have been frequent, a summary of the main conclusions reached is given below:

- i) The water content appears to have a marked effect on the equilibrium yield value, but the actual magnitude

of the latter remains comparatively small.

- ii) While the extrapolated value of the initial deflection d_0 , as determined from the $\log(d - d_E)$ -time graph, is of the same order as the maximum observed value, it appears, in most cases, to be too low. This can be attributed to the fact that a substantial part of the initial torque is used up in accelerating the middle cylinder and its attachments. For the minimum speed used, however, the breakdown is considerably slower than for other speeds (see ix below) and consequently the inertia effects may be regarded as being very small. The initial plastic viscosity was therefore determined from the extrapolated value of the deflection obtained from the minimum speed test, and used to calculate the true value of the initial deflection at other speeds.
- iii) When $\log(d - d_E)$ is plotted against the time, two straight lines appear to fit the results better than one. But if a single straight line, passing through the point corresponding to the calculated d_0 , is fitted through the results between $t = 0$ and $t = 60$ seconds, an approximate single exponential expression can be derived for the whole deflection-time curve.
- iv) A power expression for the breakdown is also suggested

and the deflection-time curve associated with it is in closer agreement with the experimental results than is the case with the single exponential expression referred to in (iii). But a number of objections are levelled against the use of "power laws" on theoretical grounds, and also because they cannot be used to describe the condition of the paste at $t = 0$ or $t = \infty$.

- v) An increase in the rate of shear is associated with an increase in the rate of breakdown. The magnitude of the breakdown also increases with the rate of shear, but it appears, however, that this increase becomes progressively smaller. In this respect, there seems to be a critical rate of shear beyond which there is little change in the magnitude of the breakdown as the rate of shear is increased.
- vi) The viscosity-time curves tend to indicate that the breakdown of cement pastes in a rotational viscometer, is similar to the breakdown occurring in concrete under vibration. It is suggested that some close relationship exists between the compaction and the plastic viscosity on the one hand, and between the vibrator's acceleration and the viscometer's rate of shear on the other.
- vii) Both the initial plastic viscosity and the yield value

seem to be very sensitive to small changes in the water content to which they are exponentially related.

- viii) At the same rate of shear, the relative magnitudes of the plastic viscosities prevailing 5 seconds after the start of the breakdown are approximately the same as the relative magnitudes of their respective initial plastic viscosities.
- ix) Irrespective of the water/cement ratio, the breakdown time is found to be proportional to $N^{-3.3}$ where N is the angular speed of the viscometer. This relationship lends support to the comment made in (ii) regarding the comparatively slow rate of breakdown associated with low speeds.
- x) The energy required to reduce the viscosity of the paste to any given value is least when the speed is highest, provided that the shearing of the paste is discontinued immediately after the required viscosity is reached. If, on the other hand, the shearing action is to last for a longer period than the minimum necessary to achieve the required breakdown, then the higher speeds cease to be economical. For any given value of breakdown time, there appears to be an optimum speed to produce the required breakdown with minimum energy consumption.

- xi) A method of measuring the workability of cement pastes is suggested, whereby the total energy expenditure, i.e., the energy represented by the area under the torque-time curve, is taken as a measure of the workability. This energy appears to be directly proportional to the initial plastic viscosity of the paste.
- xii) The rate of energy input to the paste appears to be far from constant, especially when pastes having different consistencies are compared. Actually, the stiffer the paste, the higher is the energy absorption per unit time. This behaviour casts some doubt on the validity of the assumption that the rate of energy input to the concrete under vibration remains constant during the remoulding and the compaction processes. It is therefore suggested that if the workability of concrete is taken to be proportional to some power (greater than unity) of the Vebe time, then, more realistic results may be obtained from the Vebe test.

(f) Further investigation of the variation of the yield value with time

In view of the fact that the main study of the variation of the yield value with time under a constant rate of shear in section (d)

was carried out with the second cement batch, it was considered desirable to carry out a series of tests similar to those described in that section using the third cement batch which was used in the major part of the work.

The water/cement ratio used was 0.31 and the top speed was 40 r.p.m.

The down-curves obtained in this series of tests are shown in Figure 138, and a summary of the results is given in Table 17. A plot of the variation of the yield value intercept with time (Figure 139), shows similar tendencies to those observed in Series I and II in section (d), and confirms the conclusions already drawn regarding the disappearance of the yield value on application of shear. It is to be noted that the final yield value intercept of 2.5 divisions obtained from Figure 139, is in close agreement with the value of 2.4 divisions (see Table 6) determined by extrapolation from the down-curves run at the end of the constant speed tests in section (e).

Table 17

Water/cement ratio = 0.31 Cem. Batch III Top speed = 40 r.p.m.				
Test No.	Time at top speed in seconds	Yield value intercept in divisions	Yield value in dynes/sq. cm.	Plastic viscosity in poises
85	5	1.18	142	20.2
79	10	1.62	194	18.0
78	20	2.03	244	15.3
115	30	2.25	270	14.6
116	40	2.57	308	14.3

$W/C = 0.31$

C. B. III

TOP SPEED = 40 R.P.M.

STRAIGHT FIRST DOWN-CURVES

FIG. 138

$W/C = 0.31$

C.B. III

TOP ANGULAR SPEED = 40 R.P.M.

EFFECT OF SHEARING TIME AT TOP
ANGULAR SPEED ON YIELD VALUE

INTERCEPT

FIG. 139

(g) Breakdown of the cement paste in the B.R.S. viscometer

As a check on the work carried out with the double-gap viscometer, the Building Research Station single-gap viscometer was used to investigate the breakdown, at various rates of shear, of a cement paste having a water/cement ratio of 0.32. In this series of tests, the torque was measured directly by noting the movement of the light spot on the transparent scale. The torque measuring system used consisted of two close-coiled helical springs restraining the movement of the bob by applying tangential forces to it, as shown in Figure 67.

It can be seen from the typical calibration graph for the springs shown in Figure 140 that the curves obtained during the loading and the unloading cycles, are not coincident. This behaviour may be attributed to friction. But since the breakdown of the paste resulted in a continuous reduction in the torque, the unloading curve was taken as the true calibration curve.

Before starting the motor, enough weights were placed in the pans to eliminate any slackening in the spring fastenings. This pre-loading had the advantage of increasing the actual torque by a value dictated by the amount of weights used, and thus it was possible, by carefully selecting the load, to limit the torque variation to the straight portion of the calibration curve.

The effect of the rate of shear on the plastic viscosity of the paste, is illustrated in Figure 141. It is to be noted that the

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TYPICAL CALIBRATION FOR CLOSE-COILED
HELICAL SPRINGS USED WITH B.R.S. VISCOMETER

FIG. 140

BREAKDOWN OF PASTE UNDER CONSTANT
RATE OF SHEAR IN BUILDING RESEARCH
STATION VISCOMETER

FIG. 141

curves shown are very similar to those obtained with the double-gap viscometer. The same can be said regarding the variation of $\log(d - d_E)$ with time. This similarity is rather remarkable as the two viscometers are radically different in their construction especially with regards to the grooving of the cylindrical surfaces.

(h) Effect of breakdown on strength

In an effort to determine the effect of the breakdown on the cube crushing strength of the paste, a number of 4 in. cubes were cast from neat cement pastes which were previously mixed for different periods of time in a Liner pan-mixer (Figure 142).

The reason for using a neat cement paste in this investigation was to eliminate the "arching" effect (associated with the use of aggregates), which is accompanied by air entrapment. The water/cement ratio chosen for this work was 0.31 because it was considered that this would produce a paste which is fluid enough not to require any vibration for complete compaction.

Two batches of cubes, each one consisting of 21 cubes, were cast, and the cubes in each batch were divided into three groups - each one associated with a different mixing time. For each group of 7 cubes, the procedure adopted was to mix 40 lbs. of dry cement in the mixer for three minutes, and then to add the appropriate amount of water. The mixing operation was then continued for a period of three minutes for the first group, six minutes for the second group and nine

The Liner pan mixer

Figure 142

minutes for the third group.

In order to vary the degree of breakdown achieved after filling, 3 cubes, in each group, were left unvibrated, 2 cubes were vibrated for $\frac{1}{2}$ a minute on a Westool-Stewart vibrating table (Figure 143), and the remaining 2 cubes were vibrated for one minute.

Immediately after casting, the cubes were covered with wet sacking. Twenty-four hours later, the cubes were stripped and cured under water, at a temperature of $65 \pm 5^{\circ}\text{F}$.

The cubes in the first batch were crushed at 17 days while those in the second were crushed at 28 days. The crushing was carried out in a Denison testing machine (Figure 144) provided with a pacer to give a constant rate of loading, which, in this particular case, was 2080 lbs./sq. in./min. On examining the crushed cubes, it was observed that the penetration of water into them was limited to $\frac{3}{16}$ in.

The results of this series of tests, which are given in Tables 18 and 19, indicate that the difference between the cube crushing strengths, for any one batch of cubes, is small. This seems to suggest that the cubes tend to reach the same strength irrespective of the degree of breakdown imparted to the paste. Hence, it may be concluded that the broken structure of the paste is rebuilt, but whether the rebuilding is due to the chemical reaction acting alone or in conjunction with a thixotropic growth, is not known.

Nevertheless, it would appear that the vibration of concrete

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The Westool-Stewart vibrating table

Figure 143

The Denison testing machine

- A - pacer
- B - control panel
- C - cube under test

Figure 144

Table 18

Cube No.	Weight in gms.	Crushing strength at 17 days in p.s.i.	Mean strength in p.s.i.	⁺ Mean strength per group in p.s.i.	Standard deviation per group in p.s.i.	Mixing time in min.	Vibration time in min.
1	2237	11,400)	10,740	10,900	380	3	0
2	2270	10,440)				3	0
3	2238	10,380)				3	0
4	2220	11,290)	10,980			3	1/2
5	2228	10,670)				3	1/2
6	2234	11,180)	11,070			3	1
7	2217	10,960)				3	1
8	2250	10,970)	11,120	11,000	200	6	0
9	2270	11,200)				6	0
10	2260	11,190)				6	0
11	2235	11,160)	10,880			6	1/2
12	2247	10,600)				6	1/2
13	2237	11,000)	10,950			6	1
14	2245	10,900)				6	1
15	2256	10,820)	10,900	11,200	300	9	0
16	2260	10,720)				9	0
17	2256	11,170)				9	0
18	2240	11,400)	11,420			9	1/2
19	2255	11,430)				9	1/2
20	2242	11,520)	11,510			9	1
21	2240	11,500)				9	1

⁺ The mean strength of 21 cubes is 10,930 lbs./sq. in. and the standard deviation is 330 lbs./sq. in.

Table 19

Cube No.	Weight in gms.	Crushing strength at 28 days in p.s.i.	Mean strength in p.s.i.	⁺ Mean strength per group in p.s.i.	Standard deviation per group in p.s.i.	Mixing time in min.	Vibration time in min.
22	2270	11,730)	11,600	12,070	460	3	0
23	2240	11,770)				3	0
24	2235	11,300)				3	0
25	2254	12,750)	12,490			3	1/2
26	2255	12,230)					3
27	2244	12,380)	12,320			3	1
28	2246	12,250)					3
29	2242	12,420)	12,190	12,220	440	6	0
30	2274	11,900)				6	0
31	2262	12,250)				6	0
32	2260	11,700)	11,950			6	1/2
33	2262	12,200)					6
34	2270	12,000)	12,580			6	1
35	2272	13,150)					6
36	2265	10,700)	11,600	12,130	630	9	0
37	2242	11,900)				9	0
38	2238	12,200)				9	0
39	2260	12,560)	12,480			9	1/2
40	2264	12,400)					9
41	2280	12,700)	12,600			9	1
42	2270	12,500)					9

⁺ The mean strength of 21 cubes is 12,140 lbs./sq. in. and the standard deviation is 520 lbs./sq. in.

generally results in a higher strength, not because the strength of the paste, as such, is increased, but primarily by reason of the expulsion of the entrapped air bubbles which in turn results in a closer packing and a greater density being achieved.

CHAPTER VII

BREAKDOWN OF FRESH CEMENT MORTARS

A. General

In this part of the work, single-sized samples of oven-dried sand were included in the mix, and tests were carried out to investigate the effects of the rate of shear and the specific surface of the sand on the breakdown. The range of the cement/sand ratios (by weight) investigated, was between 0.75 and 3.0, and the third batch of cement was used throughout.

B. Details of experiemntal work

The work was divided into four sections to include the following:

1. Preparation of the sand.
2. Determination of the specific surface of the sand.
3. Investigation of the effect of the rate of shear on breakdown.
4. Investigation of the effects of the cement/sand ratio and the sand specific surface on breakdown.

1. Preparation of the sand

Air-dried Ham River sand passing B.S. sieve No. 14 was continuously sieved in small quantities (1 lb. at a time) for 30 minutes

in an electric shaker (Figure 145), and separated into the following sizes:

- (a) Sand passing B.S. sieve No. 25, retained on B.S. sieve No. 36
- (b) Sand passing B.S. sieve No. 36, retained on B.S. sieve No. 44
- (c) Sand passing B.S. sieve No. 44, retained on B.S. sieve No. 52
- (d) Sand passing B.S. sieve No. 52, retained on B.S. sieve No. 72
- (e) Sand passing B.S. sieve No. 72, retained on B.S. sieve No. 100

The sieved samples of sand were then oven-dried at 110°C for 24 hours and stored in polythene bags placed inside air-tight drums.

For the above choice of particle sizes, the ratio of the width of the outer gap of the viscometer to the geometric mean diameter of the sand particles, was not less than the previously adopted figure of six (see Chapter V).

In view of the fine limits imposed on the sizes of sand used, the process of separating the sand into the required sizes proved to be very slow and time consuming. Consequently, the sand falling into the chosen range could not be obtained in sufficient quantities to enable any workability tests to be carried out with the Vebe apparatus.

2. Determination of the specific surface of the sand

The specific surface is defined as the surface area of particles per unit volume of material. This property appears to have a marked

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The electric sand shaker

Figure 145

effect on the consistency of concrete mixes (60 and 61) and was therefore adopted by the writer as a basis for comparing various cement mortars.

The specific surface is usually determined by measuring the flow characteristics of a liquid, having a known kinematic viscosity, as it passes through a bed of the material to be investigated. A knowledge of the porosity of the bed is also essential for the evaluation of the specific surface. This is done by making use of Carman's expression (62) which, when rearranged in a more convenient form, may be written as

$$S = \frac{14e^{1.5}}{(1-e)} \sqrt{\frac{A H}{L Q \nu}} - C \quad (112)$$

where S = the specific surface of the particles in cm.^{-1} .

e = the porosity of the bed.

A = the cross-sectional area of the bed, normal to the direction of flow in cm.^2

L = the length of the bed in cm.

H = the loss of head of the fluid in passing through the bed in cm.

Q = the volume of liquid passing per unit time in c.c./sec.

ν = the kinematic viscosity of the liquid in c.g.s. units.

C = the correction for the resistance to flow offered by the walls of the container.

For a cylinder, Carman has shown that the correction C may be taken as

$$C = 1/R(1 - e) \quad (113)$$

where R is the radius of the cylinder

The apparatus used by the writer to determine the specific surface, is shown in Figures 146 and 147. It consists of a vertical perspex cylinder 10 cms. in diameter and 51 cms. high, resting on a perforated metal plate covered with a No. 170 mesh to retain the material. Water, from a constant head tank, enters the cylinder at the top and passes downwards through the sand bed to the outlet at the lower end. The rate of flow through the cylinder is regulated by means of a clip attached to the rubber tubing at the inlet. This rate is determined by measuring the time required for a given quantity of water to pass through the bed, by means of a stop-clock and a measuring cylinder.

To measure the loss of head along the bed, four manometer nozzles, equally spaced along the length of the cylinder at 10.24 cm. intervals, were provided.

The procedure adopted for filling the cylinder with sand, was to drop the material from a constant height of 6 ins. to minimize the variation in the degree of compaction achieved. When the cylinder was filled with sand to the required level, the top surface of the sand was covered with a No. 7 mesh. A thin layer of $\frac{3}{4}$ in. aggregate was

General view of the constant head permeameter

- A - perspex cylinder
- B - constant head tank
- C - manometer tubes
- D - water inlet

Figure 146

A close-up of the permeameter

- A - perspex cylinder containing sand sample
- B - constant head drainage tank
- C - inlet tube
- D - nozzles leading to manometer tubes
- E - manometer tubes and scales
- F - clip regulating flow
- G - a layer of coarse aggregate

Figure 147

then placed on the mesh to break the water jet at the inlet and to act as a diffuser.

The height of the sample, whose weight was determined in advance, was measured with a scale at different points along the circumference of the cylinder. This was necessary to evaluate the porosity of the bed.

Different rates of flow were used, and in each case, the manometer readings were taken after steady flow conditions were reached. A thermometer was used to measure the temperature of the water and the corresponding kinematic viscosity was determined from a table given by Capper and Cassie (63).

The above procedure was repeated for a number of single-sized samples of sand. For each sample, the average head loss between adjacent manometers was plotted against the corresponding rate of flow and a straight line passing through the origin was drawn through the points (Figure 148). The slope of the line thus obtained was substituted in equation (112) to represent H/Q and, knowing the values of the other variables, the specific surface was calculated.

The geometric mean diameter D , which is defined as the square root of the product of the nominal limits of size of each sample, is given in Table 20, together with the corresponding specific surface S . If S is plotted against $1/D$, a straight line passing through the origin is obtained (Figure 149). The relation between these two

RELATION BETWEEN WATER HEAD LOSS AND
RATE OF FLOW OF WATER THROUGH SAND BED

FIG. 148

RELATION BETWEEN SAND SPECIFIC SURFACE
AND GEOMETRIC MEAN DIAMETER OF PARTICLES

FIG. 149

quantities, within the range considered, is given by

$$S = \frac{77}{D} \quad (114)$$

where S = the specific surface in cm.^{-1}

and D = the geometric mean diameter in mm.

This simple relationship indicates that the sand particles used were geometrically similar.

Table 20

Sand passing sieve No.	Retained on sieve No.	Geometric mean diameter D in mm.	Specific surface in cm.^{-1}
25	36	0.503	169
36	44	0.387	205
44	52	0.322	227
52	72	0.249	305 ⁺
72	100	0.179	438

⁺ Average of two independent tests.

Shacklock and Walker (64) conducted similar tests to those described above on aggregates of various sizes. The relevant parts of their results are given in Table 21. It will be noted that the figures quoted for the specific surface are of the same order as those given in Table 20.

Table 21

Aggregate	Particle size	Specific surface cm. ⁻¹
Rounded gravel	No. 14 - No. 25	105.4
	No. 25 - No. 52	159
	No. 52 - No. 100	260 ⁺
	Passing No. 100	520 ⁺
Crushed stone	No. 14 - No. 25	103.5
	No. 25 - No. 52	164
	No. 52 - No. 100	290 ⁺
	Passing No. 100	580 ⁺

⁺ Extrapolated values.

3. Investigation of the effect of the rate of shear on breakdown

The mixing procedure adopted in the preparation of the mortar paste was identical to that previously described for neat cement pastes except that the dry ingredients were mixed together in the glass container for 3 minutes prior to the addition of water. A cement/sand ratio of 1.0 was used and the sand was of a single size passing sieve No. 52 and retained on sieve No. 72. Tests were carried out at

different constant rates of shear and readings of time and deflection were taken at various intervals for a period of 3 minutes before the down-curve was run.

A summary of the results is given in Table 22, and the variation of the plastic viscosity with time is shown in Figure 150. The evaluation of the plastic viscosity was based, as before, on the assumption that the yield value intercept remains constant at a value equal to half its maximum value. The curves in Figure 150 show that the breakdown is much more rapid, at corresponding viscometer speeds, for mortars than for neat cement pastes. Another feature of the curves, is the tendency of the viscosity to increase after reaching a minimum value.

The first of the above two phenomena, namely, the fast rate of breakdown, can be attributed to the fact that the presence of sand particles increases the local rate of shear by virtue of the particles' rigidity and thus radically alters the distribution of the rate of shear across the gap. The second phenomenon, i.e., the increase in the viscosity towards the end of the test, can be accounted for by the relative movement between sand particles in close proximity. This results in a grinding action breaking the cement particles into still finer sizes, and the increase in the specific surface thus achieved produces an increase in viscosity.

It is to be noted that the down-curves for the mortar (Figure 151)

Table 22

<u>Water/cement ratio = 0.42</u> <u>Cement/sand ratio = 1.0</u> <u>Yield value intercept = 4.8 div.</u>										
<u>C.B. III</u> <u>Sand passing sieve No. 52 retained on sieve No. 72</u>										
Test No.	Speed in r.p.m.	Extrapolated d_o in div.	Observed max.defl. d_m in div.	Calculated d_o in div.	U_o in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules
129	10.5	8.7	8.1	8.7	24.9	12.4	0.0535	3.2	154	9
131	21.0	13.9	13.6	15.0	24.9	11.4	0.1231	6.9	277	17
127	30.0	19.5	18.5	20.4	24.9	10.6	0.1669	10.3	816	24
132	38.0	21.3	20.8	25.2	24.9	9.7	0.2281	13.9	1151	32
130	50.0	29.0	25.4	32.6	24.9	8.9	0.3489	19.4	1769	41

VARIATION OF PLASTIC VISCOSITY
WITH TIME

FIG. 150

WATER/CEMENT RATIO = 0.42
CEMENT/SAND RATIO = 1.0
SAND PASSING SIEVE No. 52
RETAINED ON SIEVE No. 72

TENDENCY OF DOWN-CURVES TO MEET
AT A COMMON POINT

FIG. 151

display a tendency (observed with neat cement pastes) to meet the torque axis at a common point. The curve showing the variation of the minimum plastic viscosity with the angular speed (Figure 152) indicates that the speed has a smaller effect on the magnitude of the breakdown than that encountered with cement pastes at corresponding speeds. This behaviour may again be attributed to the high local rates of shear prevailing between the sand particles, in view of the tendency of the viscosity to approach a constant value at high rates of shear.

If the effect of the grinding action is ignored, it appears that, in the case of mortars, the curve for the variation of the deflection with time can be satisfactorily represented by a single exponential expression of the form

$$d - d_E = (d_0 - d_E) e^{-B \cdot t}$$

where d is the deflection at any time t , d_0 is the initial value of d , d_E is the minimum value of d , and B is a constant depending on the consistency and the speed. The typical plot of $\log(d - d_E)$ against t shown in Figure 153, suggests that the error involved in evaluating d from an expression similar to that given above is fairly small. To give a better illustration of this agreement, the curve represented by the straight line in Figure 153 is shown in Figure 154 together with the one corresponding to the observed results. When B is plotted against the square of the angular speed,

WATER/CEMENT RATIO = 0.42
CEMENT/SAND RATIO = 1.0
SAND PASSING SIEVE No. 52
RETAINED ON SIEVE No. 72

EFFECT OF ANGULAR SPEED ON MINIMUM
PLASTIC VISCOSITY

FIG. 152

TYPICAL STRAIGHT LINE FITTED
 THROUGH LOG (d-de) - TIME PLOT
 BY WRITER'S "WEIGHTED" METHOD
 OF LEAST SQUARES

FIG. 153

TEST 159

WATER/CEMENT RATIO = 0.42

CEMENT/SAND RATIO = 0.91

SAND PASSING SIEVE No. 52

RETAINED ON SIEVE No. 72

SPEED = 30 R.P.M.

TYPICAL GRAPH SHOWING AGREEMENT BETWEEN
OBSERVED AND EXPONENTIAL CURVES FOR
VARIATION OF DEFLECTION WITH TIME

FIG. 154

a straight line, not passing through the origin, is obtained (Figure 155).

As a result of the relatively fast rate of breakdown achieved with mortars, at all the speeds used, the curves showing the variation of the net breakdown energy with time (Figure 156) are much steeper than those obtained for the neat pastes. These energy curves were drawn on the assumption that the equilibrium torque is equal to the minimum value reached. Thus, the grinding effect (which is unlikely to occur during the vibration of concrete) was partly eliminated.

In order to investigate the variation of the yield value with time, under a constant rate of shear, a number of tests similar to those described in Chapter VI, section (d), were carried out. A sample of sand from a new batch passing sieve No. 52 and retained on sieve No. 100, was used. The water/cement ratio for these tests was 0.42, while the cement/sand ratio was 1.0. The down-curves for this series are shown in Figure 157, and the variation of the yield value with time is shown in Figure 158. It will be noted that these results are very similar to those obtained for cement pastes, except that in this case, the rebuilding of the yield value appears to take place more rapidly. In concrete vibration, however, a rate of shear as high as the one for which the curve in Figure 158 was obtained, is not likely to occur except, perhaps, in the immediate vicinity of the vibrator. It would appear, therefore, that the shape of the curve for the

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RELATION BETWEEN B AND
SQUARE OF ANGULAR SPEED

FIG. 155

WATER/CEMENT RATIO = 0.42
CEMENT/SAND " = 1.0
SAND PASSING SIEVE No. 52
RETAINED ON " No. 72

TYPICAL VARIATION OF NET
BREAKDOWN ENERGY WITH TIME

FOR MORTARS

FIG. 156

WATER/CEMENT RATIO = 0.42
CEMENT/SAND RATIO = 1.0
SAND PASSING SIEVE No. 52
RETAINED ON SIEVE No. 100
TOP SPEED = 30 R.P.M.
C.B. III

STRAIGHT FIRST DOWN-CURVES
FOR MORTARS

FIG. 157

WATER/CEMENT RATIO = 0.42
CEMENT/SAND RATIO = 1.0
SAND PASSING SIEVE No. 52
RETAINED ON SIEVE No. 100
TOP SPEED = 30 R.P.M.
C.B. III

EFFECT OF SHEARING TIME AT TOP
ANGULAR SPEED ON YIELD VALUE
INTERCEPT

FIG. 158

variation of the yield value with time, for concrete under vibration, will be nearer to that obtained for cement pastes (Figure 98). It should be stated in this context, that although the curve in Figure 98 was obtained for an angular speed of 50 r.p.m. while that in Figure 158 corresponds to only 30 r.p.m. the rate of shear in the latter case was considerably greater than that associated with the former. This is due to the presence of sand particles in the mortar.

Here again, as for cement pastes, no attempt is made to find an empirical expression for the yield value, because it is considered that its variation with time needs to be subjected to a more thorough investigation before such an expression can be established with confidence.

It may be concluded, therefore, that apart from the grinding effect and the fast rate of breakdown, the behaviour of fresh mortars is similar in every respect to that associated with cement pastes.

4. Investigation of the effects of the cement/sand ratio and the sand specific surface on breakdown

All the tests included in this section were carried out at a constant angular speed of 30 r.p.m., and each of the single-sized sand samples listed in section (1) of this Chapter, was investigated for various cement/sand ratios. A constant water/cement ratio of 0.42 was used throughout this investigation except when the cement/

sand ratio exceeded 2.0, in which case, a water/cement ratio of 0.34 was adopted.

A summary of the results of this work is given in Tables 23 - 27 inclusive.

Typical sets of the viscosity-time curves and the corresponding down-curves, are shown in Figures 159 and 160, respectively. It is to be noted from these graphs that the viscosity and the yield value intercept become more sensitive to small changes in the cement/sand ratio as this decreases. Also, the build-up due to the grinding action becomes more pronounced as the cement/sand ratio decreases, because of the increased sand content in the mix. Figures 161 and 162 illustrate the effect of the cement/sand ratio on the yield value intercept and the total energy input (at the end of the test), respectively, for the various sand sizes used. It can be seen from these graphs that the curves associated with the larger sizes of sand are closely grouped so that a change from one size to the next makes only a small difference to the properties of the paste. This may be attributed to the fact that the difference between the specific surfaces of the larger sizes of sand used was comparatively small (see Table 20).

In view of the fact that, at the speed used in these tests, a substantial part of the torque was lost in accelerating the middle cylinder and its attachments, the initial viscosity could not be estimated accurately and therefore the plastic viscosity U_5 ,

Table 23

<u>Water/cement ratio = 0.42</u> <u>Viscometer speed = 30.0 r.p.m.</u> <u>C.B. III</u>											
<u>Sand passing sieve No. 72 retained on sieve No. 100</u>											
Test No.	Cem./sand ratio by weight	Extra-polated d_o in div.	Observed max.defl. d_m in div.	U_5 in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	Yield value intercept in div.	Yield value in dynes/sq. cm.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules
162	1.00	21.0	22.1	25.6	15.1	0.0467	5.2	9.7	1162	1312	43
164	1.11	20.2	20.1	18.6	11.7	0.1372	8.7	6.1	732	926	25
163	1.33	19.2	19.1	17.5	10.5	0.1495	9.7	3.8	456	772	28
165	1.60	13.9	13.9	12.6	9.4	0.1239	6.1	2.0	240	634	20

Table 24

<u>Water/cement ratio = 0.42</u> <u>Viscometer speed = 30.0 r.p.m.</u> <u>C.B. III</u>											
<u>Sand passing sieve No. 52 retained on Sieve No. 72</u>											
Test No.	Cem/sand ratio by weight	Extra-polated d_o in div.	Observed max.defl. d_m in div.	U_5 in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	Yield value intercept in div.	Yield value in dynes/sq. cm.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules
134	0.80	23.3	23.0	26.2	14.8	0.1203	7.8	9.7	1162	1239	28
159	0.91	20.6	20.6	21.0	11.0	0.1089	9.5	6.4	768	920	37
127	1.00	19.5	18.5	18.0	10.6	0.1669	10.3	4.8	576	816	24
136	1.11	18.0	16.9	16.5	9.6	0.1616	9.1	4.0	480	729	24
135	1.33	13.3	13.0	13.9	9.4	0.1314	5.2	2.7	324	658	18
161 ⁺	2.63	20.1	20.3	15.2	13.0	0.0925	9.6	2.3	276	900	70
160 ⁺	3.00	22.9	22.5	15.5	13.2	0.1300	12.5	1.8	216	898	75

⁺ The water/cement ratio for this test = 0.34

Table 25

Water/cement ratio = 0.42												Viscometer speed = 30.0 r.p.m.		C.B. III	
Sand passing sieve No. 44 retained on sieve No. 52															
Test No.	Cem./sand ratio by weight	Extra-polated d_o in div.	Observed max.defl. d_m in div.	U_5 in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	Yield value intercept in div.	Yield value in dynes/sq. cm.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules				
168	0.75	20.6	20.1	20.5	12.7	0.1586	8.3	6.2	744	981	22				
169	0.83	18.6	17.3	17.5	10.6	0.2215	8.8	4.3	517	792	18				
167	0.91	17.4	16.9	17.0	10.6	0.1544	7.9	3.7	444	769	23				
166	1.00	14.8	15.2	15.1	9.6	0.0992	6.4	2.9	348	694	32				

Table 26

Water/cement ratio = 0.42 Viscometer speed = 30.0 r.p.m. C.B. III											
Sand passing sieve No. 36 retained on sieve No. 44											
Test No.	Cem./sand ratio by weight	Extra-polated d_o in div.	Observed max. defl. d_m in div.	U_5 in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	Yield value intercept in div.	Yield value in dynes/sq. cm.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules
142	0.75	20.9	19.8	22.6	13.2	0.1613	8.4	5.9	707	1003	27
144	0.83	20.8	19.7	17.6	10.7	0.1703	11.0	4.2	504	800	30
143	0.91	13.6	14.2	15.8	10.5	0.0671	4.3	3.4	408	761	29
141	1.00	12.1	12.6	13.9	9.7	0.0673	3.8	2.6	312	678	24

Table 27

<u>Water/cement ratio = 0.42</u> <u>Viscometer speed = 30.0 r.p.m.</u> <u>C.B.III</u>											
<u>Sand passing sieve No. 25 retained on sieve No. 36</u>											
Test No.	Cem./sand ratio by weight	Extra-polated d_o in div.	Observed d_m max.defl. in div.	U_5 in poises	U_{min} in poises	B	$(d_o - d_E)$ in div.	Yield value intercept in div.	Yield value in dynes/sq. cm.	W_T after 180 secs. in joules	$(W_T - W_E)$ after 180 secs. in joules
175	0.75	20.0	19.7	20.4	13.2	0.1430	7.7	5.5	660	999	23
174	0.83	15.2	15.3	16.9	11.4	0.1166	4.9	4.1	492	833	19
173	1.00	11.7	12.3	12.8	9.3	0.0649	4.0	1.9	228	632	26

TYPICAL VARIATION OF PLASTIC VISCOSITY
WITH TIME AT DIFFERENT CEMENT/SAND

RATIOS

FIG. 159

DETERMINATION OF YIELD VALUE INTERCEPT
BY EXTRAPOLATION OF DOWN-CURVES RUN
AT END OF TESTS FOR MORTARS

FIG. 160

VARIATION OF YIELD VALUE INTERCEPT
WITH CEMENT / SAND RATIO (BY WEIGHT)

FIG. 161

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EFFECT OF CEMENT/SAND RATIO ON TOTAL
ENERGY INPUT 3 MIN. AFTER START OF
BREAKDOWN

FIG. 162

prevailing 5 seconds after the starting of the motor, was taken as a guide to the initial consistency of the mortars. This method of relating the initial plastic viscosity to U_5 was previously described in Chapter VI, section (e), and found to yield satisfactory results for cement pastes. Figure 163 shows that the variation of the total energy input W_T , at the end of the test, with the plastic viscosity U_5 , for various sand sizes and cement/sand ratios, can be represented by a straight line passing through the origin as in the case of neat cement pastes. This relationship indicates that W_T can again be taken as a measure of the workability.

For a cement/sand ratio of 1.0, the effects of the specific surface of the sand on the viscosity U_5 and the yield value, are shown in Figures 164 and 165, respectively. The same quantities are plotted on logarithmic bases in Figures 166 and 167, from which the following empirical expressions are derived:

$$U_5 = 0.3 S^{0.75} \quad (115)$$

$$\text{and } f = 22 S^{1.75} \quad (116)$$

where U_5 = the plastic viscosity of the mortar in poises

f = the yield value in dynes/sq. cm.

S = the specific surface of the sand used in cm.^{-1}

Since it has been established that the total energy input W_T

RELATION BETWEEN TOTAL ENERGY INPUT
(3 MIN. AFTER START OF BREAKDOWN)
AND PLASTIC VISCOSITY U_5 FOR VARIOUS
SAND SIZES AND CEMENT/SAND RATIOS

FIG. 163

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EFFECT OF SAND SPECIFIC SURFACE
ON INITIAL PLASTIC VISCOSITY
REPRESENTED BY U_5

FIG. 164

EFFECT OF SAND SPECIFIC SURFACE
ON YIELD VALUE

FIG. 165

RELATION BETWEEN PLASTIC VISCOSITY U_5
AND SAND SPECIFIC SURFACE S

FIG. 166

RELATION BETWEEN YIELD VALUE
AND SAND SPECIFIC SURFACE

FIG. 167

is directly proportional to the initial viscosity, represented in this particular case by U_5 , we may rewrite equation (115) as

$$W_T = K.S^{0.75} \quad (117)$$

where K is a constant.

Hence, at constant water/cement and cement/sand ratios, the term $S^{0.75}$ may be taken as a measure of the workability. This has some bearing on the results of Newman and Teychné's work (60) on the classification of natural sands for concrete mix design. In this, they established that if, at a constant "total" water/cement ratio, the combined aggregate grading for a concrete mix is changed so that the overall specific surface is kept constant, then concrete having the same properties can be obtained.

Newman and Teychné's finding, in fact, tends to suggest that the power to which the specific surface S is raised in equation (117) should be 1.0 instead of 0.75. To establish the effect of this difference on the workability computation, let us assume that a certain hypothetical mortar mix is to have an average sand specific surface of, say, 300 cm.^{-1} and that 5 single-sized samples of sand A, B, C, D and E, whose specific surfaces are 100, 200, 300, 400, and 500 cm.^{-1} , respectively, are available. These will cover a bigger range of sand sizes than that investigated by the writer. Assuming, for simplicity, that the sand for any one mix is to consist, at the most, of two

sizes, and using equation (117) to calculate the theoretical workability, the following table is obtained for a constant cement/sand ratio (by weight):

Table 28

Each of the mixes listed below has an average sand specific surface of 300 cm. ⁻¹							
Mix No.	Percentage of sand by weight					Calculated workability W _T	$\frac{W_T}{W_T \text{ (mean)}}$
	A	B	C	D	E		
1	33.3	0	0	66.7	0	70.7 K	0.998
2	0	66.7	0	0	33.3	71.0 K	1.003
3	0	0	100	0	0	71.8 K	1.014
4	50.0	0	0	0	50.0	68.8 K	0.972
5	0	50.0	0	50.0	0	71.9 K	1.016

$$W_T \text{ (mean)} = 70.8 \text{ K}$$

The negligible variations in workability indicated by the figures in the last column of Table 28 seem to suggest that Newman and Teychenne's finding applies to mortars as well, and that the power to which S is raised need not necessarily be unity.

Further support to the writer's results is given in Shacklock and Walker's conclusion (64) that the effective water/cement ratio required to produce a particular compacting factor, for any given

richness of mix, is directly proportional to the mean specific surface of the aggregate, for concrete mixes which would normally be regarded as over-sanded. This statement indicates that if, for a given water/cement ratio, the mean specific surface of the aggregate is kept constant, then the workability remains constant. Table 28 in fact shows this to be the case.

The above agreements between the writer's results and those obtained from tests on concrete, serve as an additional check on the adequacy of using W_T as a measure of workability.

C. Mechanics of concrete vibration

Having established that cement mortars behave in much the same manner as neat cement pastes under shear, it now remains to explain the mechanics of concrete vibration in the light of the conclusions drawn so far. To do this, it is useful to study briefly the work carried out by Farrar (37 and 65) on the propagation of longitudinal vibrations through concrete during compaction.

Farrar established that the vibration amplitude A at a distance x from the vibration source is given by

$$A = A_0 \cdot \cosh (Nx) \quad (118)$$

where A_0 is the amplitude of vibration at $x = 0$ while N is a constant depending on the density, the elastic modulus, and the viscosity of the mix.

In the theoretical derivation of this equation, he assumed, among other things, that the viscosity of concrete remains constant during vibration. In view of the experimental evidence presented by the writer (Figures 116, 117, 150 and 159) this assumption appears to be far from correct. The change in the plastic viscosity perhaps accounts for Farrar's finding that his equation did not become valid until a few minutes after the start of the vibration, by which time most of the breakdown would have taken place, and the assumption of constant viscosity would tend to be approximately correct.

In order to establish how shearing stresses arise in concrete mixes during vibration, it is necessary to consider the decay of the vibration waves as they pass through a mass of fresh concrete during compaction on a vibrating table. Let us assume, in this context, that the concrete has a large cross-sectional area so that the side effects of the container walls can be regarded as local. Now, if we consider an elementary column of height dx , in the centre of the concrete mass, at a distance x from the vibration source, then Farrar's equation shows that a differential amplitude of $[N \cdot A_0 \sinh(Nx) \cdot dx]$ exists between the top and the bottom of the column. This difference in amplitude will be accompanied by a difference in acceleration which results in a net force being applied to the elementary column. This force will in turn produce shearing stresses on certain planes which are inclined to the column axis.

Although the phase difference associated with the propagation of the vibration waves, together with the viscosity variation, would modify the force distribution in the mix to a considerable extent, it seems reasonable to assume that shearing stresses will always be induced. It is suggested here that these stresses are responsible for the breakdown of the cement paste forming the concrete matrix.

With the above picture in mind, the ineffectiveness of low acceleration in concrete vibration can be attributed to the fact that the low shearing stresses induced by such accelerations, would produce only small amounts of breakdown. This may be responsible for the inadequate compaction achieved. In other words, this state of affairs is not unlike that associated with low angular speeds, (i.e. low rates of shear) in the rotational viscometer.

At equal accelerations, the effect that the amplitude appears to have is to expose new surfaces to the breakdown. It is therefore not surprising that low amplitudes were found (52 and 53) to be comparatively ineffective. On the other hand, the influence of the frequency is to control the time during which a certain rate of shear persists.

Since it has been established that the rate of breakdown as well as its magnitude increases with the rate of shear, it would appear that, at equal times, the breakdown achieved under a high acceleration must be far greater than that achieved under a low one. Consequently,

THICKENED LINES REPRESENT
USEFUL PART OF CYCLE

THE VIBRATION CYCLES

FIG. 168

in any one vibration cycle, the maximum value of the acceleration would seem to be most important since the useful part of the cycle is that corresponding to high accelerations (Figure 168).

At low frequencies, the time intervals during which the acceleration may be regarded as constant (to within $\pm 5\%$ of the maximum value, say) is increased in duration, and therefore, some breakdown will take place at the lower accelerations of the cycle as well (Figure 168).

At the higher frequencies, however, most of the breakdown will take place at the higher accelerations of the cycle. This may result in a better compaction of concrete. But, if the maximum acceleration is limited to a given value, then an increase in the frequency will be associated with a reduction in the amplitude, and, in view of the role played by the latter in exposing new surfaces of the mix to the shear action, it is evident that the increase in the frequency can be carried too far for the efficiency to increase.

It would appear, therefore, from the above reasoning, that an optimum frequency, at which the maximum efficiency is achieved, may exist. Indeed, this may explain the existence of the optimum frequencies referred to by a number of investigators (49, 52 and 53) in the field of concrete vibration. Provided the acceleration (or the rate of shear induced) is sufficiently high, the full breakdown will take place at any one of a whole range of frequencies. The effect of the frequency on the compaction of concrete should then be very small.

CHAPTER VIII

THEORY OF BREAKDOWN UNDER SHEAR

Tattersall (20, 22 and 23) presented a theory for the breakdown of cement pastes when subjected to a constant rate of shear in a rotational viscometer, five minutes after the first drop of water is added. He found experimentally that the curve for the torque variation with time could be represented by the following equation:

$$T - T_E = (T_O - T_E) \cdot e^{-B \cdot t} \quad (54)$$

where T is the torque required to shear the paste at a time t , T_O and T_E are the initial and the final values of the torque, respectively, and B is a constant depending on the consistency of the paste and the rate of shear.

In Tattersall's derivation of equation (54), the paste structure was considered to consist of some type of links and it was assumed that the amount of energy required to break any one link, at any given rate of shear, was constant. An objection to this assumption, concerning Green's requirements (3) for a satisfactory model of thixotropy, has already been raised in Chapter II. These requirements stipulate that the bonds between particles cannot all have the same strength.

From the experimental work carried out by the writer, it appears

that the breakdown curve for cement pastes, subjected to a constant rate of shear twelve minutes after the mixing is started, may be best represented by two distinct equations of the type given above - one being valid from $t = 0$ to $t = t_1$, and the other from $t = t_1$ onwards, where t_1 lies between 10 and 25 seconds. But a reasonable approximation to the breakdown curve can still be obtained if only one exponential equation is taken to represent the whole curve. To give an idea of the degree of approximation involved, some typical curves obtained by the two methods mentioned above are shown in Figure 169.

In the case of cement mortars, however, a single exponential equation was found to fit the results quite well, and, therefore, no attempt was made to represent the curve in any other way.

In view of the importance of equation (54), especially in conjunction with wave propagation in fresh concrete, a modified theoretical derivation of it is given below:

Let us assume that the paste structure is an oriented one (to explain the time lag as discussed in Chapter I) and consists of a number of links. Let the energy required to break any one link be represented by one of the following values:

$$e_1, e_2, e_3, \dots, e_n$$

where n is a positive integer, while e_1 and e_n are the amounts of energy required to break the weakest link and the strongest one, respectively.

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ALL CURVES ARE FITTED BY WRITER'S "WEIGHTED"
METHOD OF LEAST SQUARES

REPRESENTATION OF VARIATION OF TORQUE
WITH TIME BY EXPONENTIAL CURVES

FIG. 169

Let

$$e_2 - e_1 = e_3 - e_2 = \dots = e_n - e_{(n-1)} = p \quad (119)$$

where p is a constant.

For the purpose of this analysis, any link requiring an energy amount lying between $e_2 + p/2$ and $e_2 - p/2$ is classified under e_2 , and any link requiring an amount of energy lying between $e_3 + p/2$ and $e_3 - p/2$ is classified under e_3 , and so on.

Let x be the number of broken links per unit volume of material at any time t after the start of the breakdown. x may be expressed as

$$x = x_1 + x_2 + x_3 + \dots + x_n \quad (120)$$

where

x_1 is the number of links requiring an energy e_1 ,

x_2 is the number of links requiring an energy e_2 ,

x_3 is the number of links requiring an energy e_3 ,

.....,

and x_n is the number of links requiring an energy e_n .

Let

$$x_1 : x_2 : x_3 : \dots : x_n = 1 : a_2 : a_3 : \dots : a_n \quad (121)$$

and

$$e_1 : e_2 : e_3 : \dots : e_n = 1 : b_2 : b_3 : \dots : b_n \quad (122)$$

where a_2 , a_3 , etc., and b_2 , b_3 , etc. are constants.

Using the relationship given in equation (121), equation (120) may be rewritten as

$$x = x_1 (1 + a_2 + a_3 + \dots + a_n) \quad (123)$$

Now, differentiating equation (123) with respect to t , we get

$$\frac{dx}{dt} = \frac{dx_1}{dt} (1 + a_2 + a_3 + \dots + a_n) \quad (124)$$

Assuming the relationship given in equation (121) remains valid throughout the breakdown process, then after a small time increment dt , equation (121) becomes

$$\begin{aligned} (x_1 + \frac{dx_1}{dt} \cdot dt) : (x_2 + \frac{dx_2}{dt} \cdot dt) : (x_3 + \frac{dx_3}{dt} \cdot dt) : \\ \dots : (x_n + \frac{dx_n}{dt} \cdot dt) = 1 : a_2 : a_3 : \dots : a_n \end{aligned} \quad (125)$$

and therefore,

$$\begin{aligned} (\frac{dx_1}{dt} \cdot dt) : (\frac{dx_2}{dt} \cdot dt) : (\frac{dx_3}{dt} \cdot dt) : \\ \dots : (\frac{dx_n}{dt} \cdot dt) = 1 : a_2 : a_3 : \dots : a_n \end{aligned} \quad (126)$$

where

$\frac{dx_1}{dt} \cdot dt$, $\frac{dx_2}{dt} \cdot dt$, $\dots$, etc. represent the increase in

x_1 , x_2 , $\dots$, etc. in time dt .

During the breakdown, the torque is reduced from an initial value T_o to a final (or equilibrium) value T_E . If, as in Tattersall's theory, the torque T_E is assumed to represent the torque required to overcome the viscous forces alone, then the "excess" torque $(T - T_E)$ represents the component responsible for the breakdown.

Equating the breakdown energy expended in time dt , to the work done in breaking the links, we get

$$\begin{aligned} \frac{dx_1}{dt} \cdot dt \cdot e_1 + \frac{dx_2}{dt} \cdot dt \cdot e_2 + \frac{dx_3}{dt} \cdot dt \cdot e_3 + \\ \dots\dots\dots + \frac{dx_n}{dt} \cdot dt \cdot e_n = 2 \pi N(T - T_E) \cdot dt \end{aligned} \quad (127)$$

Using equations (122) and (126), equation (127) can be rewritten as

$$\begin{aligned} \frac{dx_1}{dt} \cdot e_1 (1 + a_2 \cdot b_2 + a_3 \cdot b_3 + \dots\dots\dots + a_n \cdot b_n) \\ = 2 \pi N(T - T_E) \end{aligned} \quad (128)$$

where N is the angular speed in r.p.m.

Making the assumption that the loss of torque $(T_o - T)$ is proportional to the number of links broken, and using suffixes 1, 2, 3,, n , to denote the parts of this torque due to x_1 , x_2 , x_3 ,, x_n , respectively, the following equations may be written:

$$(T_o - T)_1 = Q \cdot x_1$$

$$(T_o - T)_2 = Q \cdot x_n$$

.....

$$\text{and } (T_o - T)_n = Q \cdot x_n$$

where Q is a function of the rate of shear (i.e., a function of N).

But,

$$T_o - T = (T_o - T)_1 + (T_o - T)_2 + \dots + (T_o - T)_n \quad (129)$$

therefore,

$$T_o - T = Q \cdot [x_1 + x_2 + \dots + x_n] \quad (130)$$

or

$$T_o - T = Q \cdot x \quad (131)$$

i.e.,

$$x = \frac{1}{Q} \cdot (T_o - T) \quad (132)$$

Differentiating equation (132) with respect to t we get

$$\frac{dx}{dt} = - \frac{1}{Q} \cdot \frac{dT}{dt} \quad (133)$$

From equation (124) we can write

$$\frac{dx_1}{dt} = \frac{dx}{dt} \cdot \frac{1}{(1 + a_2 + a_3 + \dots + a_n)} \quad (134)$$

Substituting for $\frac{dx}{dt}$ from equation (133) in equation (134), the following expression is obtained

$$\frac{dx_1}{dt} = -\frac{1}{Q} \cdot \frac{dT}{dt} \cdot \frac{1}{(1 + a_2 + a_3 + \dots + a_n)} \quad (135)$$

On substituting for $\frac{dx_1}{dt}$ from equation (135) in equation (128) we get

$$-\frac{e_1}{Q} \cdot \frac{(1 + a_2 \cdot b_2 + a_3 \cdot b_3 + \dots + a_n \cdot b_n)}{(1 + a_2 + a_3 + \dots + a_n)} \cdot \frac{dT}{dt} = 2 \pi N (T - T_E) \quad (136)$$

or

$$-\frac{e_1}{Q} \cdot \frac{Z_1}{Z_2} \cdot \frac{dT}{dt} = 2 \pi N (T - T_E) \quad (137)$$

where

$$Z_1 = (1 + a_2 \cdot b_2 + a_3 \cdot b_3 + \dots + a_n \cdot b_n)$$

$$\text{and } Z_2 = (1 + a_2 + a_3 + \dots + a_n)$$

Re-arranging the terms in equation (137), we obtain

$$\frac{dT}{(T - T_E)} = -\frac{2 \pi N Q Z_2}{e_1 \cdot Z_1} \cdot dt \quad (138)$$

On integrating equation (138), we get

$$T - T_E = C \cdot e^{-\left[\frac{2 \pi N Q Z_2}{e_1 \cdot Z_1} \right] \cdot t} \quad (139)$$

where C is the integration constant.

Equation (139) may be rewritten as

$$T - T_E = C \cdot e^{-B \cdot t} \quad (140)$$

$$\text{where } B = \frac{2 \pi N Q Z_2}{e_1 \cdot Z_1}$$

But, when $t = 0$, $(T - T_E) = (T_O - T_E) = C$, hence equation (140) may be written as

$$T - T_E = (T_O - T_E) \cdot e^{-B \cdot t} \quad (141)$$

which is identical with equation (54).

If the yield value is small, a constant value may be substituted for it as indicated in Chapters VI and VII. Then the variation of the plastic viscosity U with time t , may be given by

$$(U - U_E) = (U_O - U_E) \cdot e^{-B \cdot t} \quad (142)$$

where U_O and U_E are the initial and the final values of U respectively.

Since, in the above theoretical approach, the existence of links having unequal strengths was assumed, it appears that the theory presented here constitutes an improvement on the theories presented hitherto by other workers.

CHAPTER IX

CONCLUSIONS, PRACTICAL IMPLICATIONS AND CRITICISMS

A. Summary of results and conclusions

1. The viscometers

It would appear from the work presented in this thesis that the double-gap viscometer designed by the writer is quite suitable for measuring the flow properties of neat cement pastes and fresh cement mortars, and there seems to be no need for grooving the cylinders since no slipping was observed between the paste and the surfaces in contact with it. The double-gap viscometer is to be preferred to a single-gap viscometer of the cup-and-bob variety for the following reasons:

- (a) The ease of introduction of the paste into the gap permits a wide range of viscosities to be investigated.
- (b) The "end effects" for a double-gap viscometer are considerably smaller than those associated with a single-gap viscometer of comparable dimensions.
- (c) The presence of a major part of the paste in the gap is considered to be an advantage because it reduces any adverse effects due to sedimentation, slight non-uniformity in mixing, or segregation (as in the case of mortars).

When the double-gap viscometer is to be used to investigate thixotropic or similar materials, i.e., those materials whose structure breaks down under shear, it seems imperative that the radii be so chosen as to ensure that the same rate of shear is induced in both gaps.

2. Cement pastes

The effect of subjecting the cement paste to shear in the rotational viscometers, was to induce a considerable amount of breakdown in the structure of the paste. When a series of up-curves and down-curves were run, the paste displayed the characteristic hysteresis loops associated with thixotropic materials. Most of the breakdown appeared to occur during the running of the first up-curve, whereas the first down-curve was a straight line indicating that little or no breakdown took place when the rate of shear was being reduced.

The first down-curve and all subsequent up-curves and down-curves tended to meet the torque axis at a common point. This indicated that the yield value remained approximately constant. But it is to be noted that this tendency occurred only after most of the breakdown had taken place (i.e., after the running of the first up-curve). Once the breakdown was completed, the paste behaved as a Bingham plastic with coincident up-curves and down-curves.

Tests carried out at constant rates of shear indicated that there was only a very small rise in the temperature of the paste

during breakdown. In other words, the breakdown is essentially an isothermal process - a characteristic of thixotropic breakdowns.

When the paste was allowed to rest, after the completion of the breakdown, there was a tendency for the broken structure to rebuild itself very slowly. But whether this rebuilding was due to the chemical reactions acting alone or to a combination of chemical reactions and thixotropic build-up, was far from clear.

If the assumption is made, however, that in the absence of the chemical reactions the broken-down paste would eventually regain its original plastic viscosity, if allowed to rest for a sufficiently long time, the breakdown would be a reversible isothermal process and the paste may then be classified as a thixotropic material in the broad sense of the word.

The main conclusions drawn from the tests carried out at constant rates of shear, are listed below:

- (a) Irrespective of the water/cement ratio used (between 0.28 and 0.33), an increase in the rate of shear is associated with an increase in the rate of breakdown. The magnitude of the breakdown also increases with the rate of shear, but it appears, however, that there is a critical value for the rate of shear beyond which only a small increase in the magnitude of the breakdown is achieved.
- (b) The yield value seems to change with time and its

variation may be divided into three distinct stages as follows:

- (i) A period characterised by a complete absence of the yield value.
 - (ii) A period of rapid increase in the yield value.
 - (iii) A period of relative inactivity in which the yield value remains practically constant.
- (c) The decay of torque with time, under a constant rate of shear, can be approximately represented by the following exponential expression:

$$T - T_E = (T_O - T_E) \cdot e^{-B \cdot t}$$

where T is the torque at time t , T_O and T_E are the initial and the final (or equilibrium) torques, respectively, and B is a constant depending on the consistency of the paste and the rate of shear.

- (d) A power function of the form

$$T = C \cdot t^{-m}$$

- where T is the torque at time t , C is a constant equal to the value of T at $t = 1$ second, and m is a constant dependent on the rate of shear alone - appears

to fit the results better than the exponential expression in (c), but it suffers from the drawback that the dimensions of T (and consequently those of the viscosity) depend on m . In addition to this, the above power function has no meaning when $t = 0$ or $t = \infty$.

- (e) It is misleading to estimate the initial torque (corresponding to the initial plastic viscosity) by extrapolation from the $\log (T - T_E)$ - time graph, except when low rates of shear are used. The reason for this lies in the fact that part of the initial torque developed is used up in accelerating the middle cylinder and its attachments, thus resulting in a reduction in the observed value of the torque.
- (f) The water content of the paste appears to have a marked effect on the initial plastic viscosity U_0 and the equilibrium yield value f , but the actual value of the latter remains comparatively small. Empirical exponential expressions relating U_0 and f to the percentage (by weight) p of the water present are given in the detailed part of the thesis.
- (g) The time t required to reduce the viscosity from an initial value U_0 to any given value U on the viscosity - time curve, is proportional to $1/N^{3.3}$ - where

N is the angular speed.

- (h) The total energy input W_T represented by the area under the entire torque-time curve, appears to be directly proportional to the initial plastic viscosity and is also linearly related to the yield value. W_T is therefore taken as a measure of workability.
- (i) All the graphs for the variation of W_T with the percentage water content p in the paste show that the points fall on smooth curves with little scatter. These curves increase in steepness as the speed increases and hence, the higher the speed, the greater is the "sensitivity".
- (j) The rate of energy absorption by the paste is found to be far from constant, especially when pastes having different consistencies are compared. The stiffer the paste the higher is the rate of energy input.

Cubes made from neat cement pastes having different degrees of breakdown, but a common water/cement ratio, were found to have virtually the same crushing strength, indicating that the breakdown has little or no effect on the strength of the paste.

3. Cement mortars

The permeability tests performed on various samples of sand have

shown that the permeameter used was quite adequate for measuring the specific surface of sand, and capable of yielding reproducible results.

In the range investigated, the specific surface of sand was found to be directly proportional to the reciprocal of the particle size - indicating that the sand particles were geometrically similar.

The general behaviour of cement mortars under constant rates of shear was very similar to that already described for cement pastes. The presence of sand, however, gave rise to the following:

- (a) At corresponding viscometer speeds, the breakdown of mortars appeared to take place at much faster rates than was the case with cement pastes, due to the increase in the local rate of shear.
- (b) As a result of the increased rate of breakdown, the curves showing the variation of the torque, the plastic viscosity and the energy input, with time were all much steeper than those obtained for neat cement pastes.

In the case of mortars, the decay of torque with time seemed to be well represented by the exponential expression suggested for the neat pastes.

The graph for the relationship between the initial plastic viscosity (represented in this case by the viscosity U_5 prevailing 5 seconds after the start of the breakdown) and the total energy input W_T gave a straight line passing through the origin over a

wide range of sand sizes and consistencies. The use of W_T as a measure of workability was, therefore, extended to cement mortars as well.

At constant water/cement and cement/sand ratios (by weight), the relation between the sand specific surface S and the initial plastic viscosity (represented by U_5) is given by:

$$U_5 = 0.3 S^{0.75}$$

But since U_5 is directly proportional to W_T , we can modify this equation to

$$W_T = K \cdot S^{0.75}$$

where K is a constant. It is shown in Chapter VII that this simple equation is actually in agreement with the results of some of the important work on the effect of the specific surface of the aggregate on the workability of concrete.

4. Theoretical approach

A theoretical derivation of the exponential expression for the torque variation with time, under a constant rate of shear, is presented. This assumes, among other things, that the paste structure consists of some type of links and that the loss of torque is proportional to the number of links broken. One of the main advantages of this theory is the fact that it takes into consideration the

likelihood that the links may have unequal strengths.

B. Practical implications

When the breakdown of cement pastes and fresh mortars in the viscometer is compared with the behaviour of concrete under vibration, the following similarities become apparent:

- (a) The existence of a critical rate of shear beyond which little increase in the magnitude of the breakdown takes place, is analogous to the existence of a critical acceleration, in concrete vibration, beyond which only a small increase in the compaction of concrete is achieved.
- (b) Low rates of shear are ineffective in breaking down the paste in the viscometer. Low accelerations are equally ineffective in producing full compaction of concrete under vibration.
- (c) A comparison between the curves for the variation of the viscosity with time at different rates of shear (Figures 86, 116 and 117) and the curves for the variation of concrete strength (which is dependent on compaction) with time of vibration at different accelerations (Figures 43 - 45), seems to suggest that a close relationship exists between the rate of shear of the viscometer and the acceleration of the vibrator on the one hand, and between the plastic viscosity and the compaction on the other.

Bearing in mind that concrete is in fact a suspension of inert particles in a cement paste matrix, it would appear from the above similarities that when fresh concrete is vibrated, a structural breakdown under shear does take place. The necessary shearing stresses may arise from the axial forces induced by the existence of differential accelerations throughout the mix.

It seems imperative, therefore, that this breakdown should be taken into account in any satisfactory theoretical approach to the problem of concrete vibration. Unfortunately, this point has been ignored in a recent comprehensive approach to the problem by Saul (66).

The disappearance of the yield value, on the application of the shearing action, would probably be duplicated in the vibration of concrete. Such a behaviour would account, at least in part, for the marked increase in fluidity in the immediate vicinity of poker vibrators during the vibration of concrete. The absence of the yield value would also promote better compaction by causing the material which is only partly broken down to flow under its own weight.

The method used by the writer for measuring the energy input to the paste, being a direct method of measurement, yields accurate and reproducible results, and is to be preferred, where possible, to the wattmeter method, used by some investigators, which is dependent on the difference between two quantities of comparable magnitudes.

The fact that the stiffer the paste, the higher is the rate of

energy input, casts some doubt on the validity of the commonly accepted assumption that when concrete is vibrated it absorbs energy at a constant rate. Since this assumption underlies the principles on which the Vebe test is based, it would seem that if the workability is taken to be proportional to the Vebe remoulding time, then the Vebe test would show the drier mixes to be more workable than they really are. This anomaly can, probably, be rectified to a certain extent by taking the workability to be proportional to some power of the Vebe time, greater than unity. The above conclusions regarding the rate of energy input would explain Keene's finding (47) that the Vebe time required for the transparent plate to fall to a position $6\frac{3}{4}$ in. below the top of the cone, showed insufficient discrimination between mixes of different workability.

In view of the fact that the total energy input W_T is directly proportional to the initial plastic viscosity and is linearly related to the yield value, the suggested method of measuring the workability, which seems to be quite reliable, would appear to be also rheologically acceptable. This method would probably be suitable for measuring the consistency of grouts and mortars over a wide range. With the recent introduction of reinforced cement-mortar construction under the name of "Ferro-cement" (41), this approach to the measurement of workability should prove to be particularly useful.

C. Criticisms

Although the double-gap viscometer was found to be adequate for studying the rheology of cement pastes and mortars, it suffered from the following minor defects:

- (a) The use of weights in the torque measuring system is considered as a drawback because, when a sudden torque is applied to the middle cylinder, the weights will have to be accelerated.
- (b) The cleaning of the viscometer proved to be a lengthy process and on removing the outer cylinder the broken-down paste could not be prevented from entering the threaded holes in the base supporting the moving cylinders. These holes had to be cleaned after every test by means of a threaded tap.
- (c) Since the viscometer was made from mild steel, it was susceptible to rust, and to guard against this, all the exposed surfaces had to be oiled at the end of every day's work.

D. Future work

Due to the fact that the viscometer was not primarily designed to study the variation of the yield value with time under constant rates of shear, the writer's investigation into this field was rather limited. There seems, therefore, to be a need for a more detailed

study of this aspect of the behaviour of the paste.

For such a study to be successful, it is essential that the driving unit for the viscometer should be capable of continuous speed variation down to zero. Since the breakdown is very fast at the higher speeds, it seems necessary that a secondary unit (probably in the form of a small motor) be incorporated in the main driving unit to ensure a constant rate of speed reduction. A recording camera to record directly the movement of the middle cylinder would be an added advantage as the human error can then be considerably reduced. Such a viscometer could incorporate the torque measuring system used with the writer's double-gap viscometer, but it would then be desirable to replace the weights in the pans by a spring system.

The next step in the development of the rotational viscometer for the rheological study of fresh concrete, would be to remove the inner cylinder so that ultimately a suitable viscometer can be designed to consist of a bob in the form of a hollow cylinder open at the bottom which can be introduced into a cup filled with concrete.

In addition to the above, there seems to be an interesting field of study in the direct correlation between the behaviour of cement mortars in a rotational viscometer and their behaviour under the action of vibration. This work can perhaps be extended to concrete at a later stage.

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APPENDIX I

DETAILED DRAWINGS

In this Appendix the detailed drawings of the individual components of the double-gap viscometer are given. The reduced scale of these drawings is half full-size.

It will be seen from drawing No. 1 that the specified maximum allowable variation in the gap was ± 0.002 in. When the actual variation in the gap width was measured, however, it was found to be within ± 0.0025 in.

As mentioned in Chapter V, a round mild steel bar was used as the torsion bar and the end fixing details shown on drawings Nos. 3 and 8, were superseded and replaced by those shown in Figure 54.

SECTION THROUGH

ROTATIONAL VISCOMETER

THIS END OF SHAFT TO BE
WELDED TO A 12" X 12" X 1/2"
PLATE USING 3/16" FILLET
WELD

ELEVATION
(SHAFT) ①

12" X 12" X 1/2" PLATE

PLAN

8 - 3/32" DIA. HOLES EQUALLY
SPACED ROUND CIRCUMFERENCE

4 - 1/8" DIA. THREADED HOLES
EQUALLY SPACED ROUND
CIRCUMFERENCE - EACH
END

ELEVATION
(LOWER SLEEVE) ②

END ELEVATION

6-1/2 DIA. THREADED HOLES
EQUALLY SPACED ROUND
CIRCUMFERENCE.

6-1/2 DIA. THREADED HOLES
EQUALLY SPACED ROUND
CIRCUMFERENCE.

4-3/4 DIA. THREADED
HOLES EQUALLY SPACED
ROUND CIRCUMFERENCE.

4-3/4 DIA. HOLES EQUALLY
SPACED ROUND CIRCUMFERENCE.

6-1/2 DIA. THREADED HOLES EQUALLY
SPACED ROUND CIRCUMFERENCE

2-3/8 DIA. THREADED HOLES

PLAN
⑦

SECTION A-A

ELEVATION

ELEVATION

6- 5/16 DIA. HOLES TO ACCOMMODATE 1/2 DIA. COUNTER-SUNK SCREWS, EQUALLY SPACED ROUND CIRCUMFERENCE

TWO-DIAMETRICALLY OPPOSITE 1/2 DIA. THREADED HOLES FOR DRAINAGE WITH PLUGS TO MATCH

4- 3/16 DIA. THREADED HOLES EQUALLY SPACED ROUND CIRCUMFERENCE

PLAN

(OUTER CYLINDER) (11)

6- 5/16 DIA. HOLES TO ACCOMMODATE 1/2 DIA. COUNTER-SUNK SCREWS, EQUALLY SPACED ROUND CIRCUMFERENCE

PLAN

(INNER CYLINDER)

ELEVATION

ELEVATION

6- $\frac{5}{16}$ DIA. HOLES TO ACCOMMODATE
 $\frac{1}{2}$ DIA. COUNTER-SUNK SCREWS
 EQUALLY SPACED ROUND CIRCUMFERENCE

4- $\frac{3}{16}$ DIA. THREADED HOLES
 EQUALLY SPACED ROUND CIRCUMFERENCE

2- $\frac{1}{2}$ DIA. THREADED HOLES
 DIAMETRICALLY OPPOSITE

PLAN
 (OUTER CYLINDER)

11A

PLAN
 (INNER CYLINDER)

9A

SECTION A-A

4 - 5/32\"/>

PLAN 15

SECTION B-B

4 - 5/32\"/>

PLAN 13

SECTION C-C

4 - 5/32\"/>

PLAN 14

SECTION D-D

PLAN

UPPERMOST BEARING COVER

16

SPACER TUBES FOR UPPER BEARINGS

17

18

SHAFT NUT
(THREADED)

19

VIEW IN DIRECTION
OF ARROW 'X'

PLAN

No. 2 THUS (HANDLES)

20

ELEVATION

2 - 7/32\"/>

2 - 5/32\"/>

2 - 5/32\"/>

2 - 7/32\"/>

THIS PART TO BE BEAT
TO A RADIUS OF 3 3/4\"/>

SECTION A-A

4 - 5/16 DIA. THREADED HOLES
EACH END

2 - 5/16 DIA. THREADED
HOLES

PLAN
(UPPER SLEEVE)

(23)

SE

4 - 5/32 DIA. HOLES IN FLANGE

B

5/16 DIA.

2 - 5/32 DIA. HOLES, EQUALLY
SPACED ROUND CIRCUMFERENCE
AT THE TOP

(TOP)

APPENDIX II

"WEIGHTED" METHOD OF LEAST SQUARES

In order to derive mathematical expressions to represent the various experimental curves obtained, the writer was faced with the problem of fitting the best curve through the experimental results. To do this, the method of least squares was used.

In general, the method of least squares can be directly applied to the case in which the observed quantities, which are subject to error, are linearly related to a number of unknown quantities. Such a simple relationship can be expressed as

$$\begin{array}{rcl}
 a_1 \cdot x + b_1 \cdot y + c_1 \cdot z + \dots + f_1 \cdot t & = & n_1 \\
 a_2 \cdot x + b_2 \cdot y + c_2 \cdot z + \dots + f_2 \cdot t & = & n_2 \\
 \dots\dots\dots & & \\
 a_s \cdot x + b_s \cdot y + c_s \cdot z + \dots + f_s \cdot t & = & n_s
 \end{array}
 \begin{array}{l}
) \\
) \\
) \\
) \\
)
 \end{array}
 \quad (143)$$

where $x, y, z, \dots, t$ are the unknown quantities whose values are to be determined, while the other quantities in the above equations are known from direct observation or otherwise. The above equations are generally called the condition equations.

Let the number s of equations be greater than the number of unknowns and let $E_1, E_2, \dots, E_s$ represent the "errors". Thus,

$$\begin{array}{rcl}
 E_1 & = & a_1 \cdot x + b_1 \cdot y + c_1 \cdot z + \dots + f_1 \cdot t - n_1 \\
 E_2 & = & a_2 \cdot x + b_2 \cdot y + c_2 \cdot z + \dots + f_2 \cdot t - n_2 \\
 & & \dots \dots \dots \\
 E_s & = & a_s \cdot x + b_s \cdot y + c_s \cdot z + \dots + f_s \cdot t - n_s
 \end{array} \quad \begin{array}{l}) \\) \\) \\) \\) \end{array} \quad (144)$$

For the case in which equal weights are given to each one of the condition equations, the best values of the variables are obtained when the sum of the squares of the errors is least, that is when

$$E_1^2 + E_2^2 + \dots + E_s^2$$

is a minimum. The method of determining the values of $x, y, z, \dots, t$ to satisfy this condition is a standard one and is fully explained in a number of textbooks on the subject (68).

When the variables in the condition equations are not linearly related, the equations are usually converted to a linear form, if possible, by equating logarithms or by some other means. This procedure was adopted in the case of the following equations:

$$(a)^+ \quad (d - d_E) = (d_o - d_E) \cdot e^{-B \cdot t}$$

$$(b)^I \quad d = C \cdot t^{-m}$$

⁺ See page 215

^I See page 219

Equating the logarithms of both sides of the equation in (a) gives

$$\log_e (d - d_E) = \log_e (d_o - d_E) - B.t \quad (145)$$

In general both sides of equation (145) will not be exactly equal and we can rewrite this equation as

$$\delta [\log_e (d - d_E)] = \log_e (d - d_E) - \log_e (d_o - d_E) + B.t \quad (146)$$

where $\delta [\log_e (d - d_E)]$ is the error in equation (145). Equation (146) is a linear expression in B and $\log(d_o - d_E)$. By writing a similar equation to this for each observed result on the deflection-time graphs (i.e., $d - t$ graph), the writer obtained a number of equations similar to equations (144). These were solved in the usual manner to give the best values of B and $\log(d_o - d_E)$ which are the two unknown quantities in question. But on examining the curve represented by these calculated variables (Figure 170), it was found that the curve obtained was clearly not the best fit through the results.

It was realised that the reason for this behaviour lay in the fact that the effect of a small change in $\log_e (d - d_E)$ on the value of $(d - d_E)$ was dependent on the order of magnitude of $(d - d_E)$. To determine this relationship, let

$$z = \log_e (d - d_E) \quad (147)$$

Differentiating equation (147) with respect to $(d - d_E)$, we get

$$\frac{\delta z}{\delta (d - d_E)} = \frac{1}{(d - d_E)} \quad (148)$$

-370-

TEST 98

$w/c = 0.29$

SPEED = 38 R.P.M.

C. B. III

----- EXPERIMENTAL CURVE
- - - - - "WEIGHTED" METHOD OF LEAST SQUARES
_____ ORDINARY METHOD OF LEAST SQUARES

TYPICAL AGREEMENT BETWEEN EXPERIMENTAL
CURVE AND EXPONENTIAL CURVES FITTED BY
ORDINARY AND "WEIGHTED" METHODS OF LEAST
SQUARES

FIG. 170

hence,

$$\delta(d - d_E) = \delta z \cdot (d - d_E) \quad (149)$$

$$\text{i.e. } \delta(d - d_E) = \delta[\log_e (d - d_E)] \cdot (d - d_E) \quad (150)$$

The best exponential curve that fits the results is that which makes $\sum [\delta(d - d_E)]^2$ a minimum. To satisfy this requirement, equation (146) was replaced by

$$\delta(d - d_E) = (d - d_E) \left[\log_e (d - d_E) - \log_e (d_0 - d_E) + B.t \right] \quad (151)$$

Equation (151) is in fact the same as equation (146), except that now the equation is a "weighted" one with a weight proportional to $(d - d_E)^2$. This modified equation did in fact give the best curve through the experimental results as shown in Figure 170.

A similar approach was used for the equation in (b) as follows:

By equating the logarithms of both sides of the equation we get

$$\log_e d = \log_e C - m \cdot \log_e t \quad (152)$$

But since both sides of equation (152) will not be exactly equal when the variables are determined experimentally, we can rewrite this equation as

$$\delta[\log_e d] = \log_e d - \log_e C + m \cdot \log_e t \quad (153)$$

To determine the effect on d of a small variation in $[\log_e d]$, let

$$z = \log_e d \quad (154)$$

Differentiating with respect to d , we get

$$\frac{\delta z}{\delta d} = \frac{1}{d} \quad (155)$$

$$\text{i.e.,} \quad \delta d = \delta z \cdot d \quad (156)$$

$$\text{hence,} \quad \delta d = \delta [\log_e d] \cdot d \quad (157)$$

Using the relationship given in equation (157), we can replace equation (153) by

$$\delta d = d \cdot [\log_e d - \log_e C - m \cdot \log_e t] \quad (158)$$

In other words, equation (158) can be directly obtained from equation (153) if a weight proportional to d^2 is given to the observation.

The method of weighting presented here was found to be very useful in fitting curves of the types given above, and is referred to in this thesis as the "weighted" method of least squares.

APPENDIX III

DETAILED RESULTS

To assess the general properties of the cement used, tests were carried out in accordance with B.S.12 (67) to determine the following:

- (a) The quantity of water required to produce a cement paste of standard consistence.
- (b) The initial setting time.
- (c) The final setting time.
- (d) The expansion as obtained from "Le Chatelier" test.
- (e) The specific surface.

It was considered desirable that the above tests be performed by someone with a certain amount of experience in this field. The Cement Marketing Company was approached regarding the matter and they kindly agreed to carry out the tests in question.

The results obtained were as follows:

Cement batch I

Standard cement paste	26.5% water
Initial setting time	170 minutes
Final setting time	205 minutes
Expansion	1.0 mm.
Specific surface	4040 sq. cm./g.

Cement batch II

Standard cement paste	25% water
Initial setting time	165 minutes
Final setting time	205 minutes
Expansion	1.0 mm.
Specific surface	3476 sq. cm./g.

Cement batch III⁺

Standard cement paste	24.8% water
Initial setting time	164 minutes
Final setting time	198 minutes
Expansion	0.5 mm.
Specific surface	3422 sq. cm./g.

For the fourth cement batch (C.B. IV), which was supplied by the Building Research Station, the specific surface was given as 3720 sq. cm./g.

On the following pages the relevant parts of the detailed experimental results, for both viscometers, are given in tabular forms. Where the results are obtained from tests in the Building Research Station viscometer, this is clearly indicated. All other results correspond to tests carried out with the double-gap viscometer.

⁺ The results given for this batch are the average of three different tests.

CEMENT PASTES									
TEST No.	3	4	10	13	84	32	28	45	33
C. B.	I	I	I	I	II	II	II	II	II
W/C	0.30	0.30	0.32	0.32	0.31	0.31	0.31	0.31	0.31
SPEED IN R.P.M.	38	38	162	162	10½	21	38	50	61
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.								
1							30.2		42.4
2				52.3	17.9				
5		37.0	39.8	41.3	17.6	20.8	29.7	33.0	37.4
10	33.0	30.0	35.8	36.3	16.1	20.8	26.2	29.3	30.9
15	30.0	28.0	32.8	33.3	14.8	19.8	23.8	27.9	28.6
20	28.0	26.4	31.1	32.1	13.9	18.8	22.6	26.3	26.2
25	27.5	25.2	29.4	29.3	13.3	17.8	21.8	25.3	24.9
30	26.8	24.2	28.3	28.3	12.8	17.1	21.6	24.4	23.9
40	25.7	23.5	26.0	26.3	12.5	16.5	20.3	23.1	22.8
50	24.0	22.6	24.8	25.3	12.0	16.2	19.1	22.1	21.7
60	22.7	21.9	24.1	24.3	11.4	15.5	18.3	21.3	20.9
75	21.2	20.5	23.2	23.4	11.1	15.1	17.7	20.5	20.2
90	20.4	19.8	22.6	22.6	10.7	14.5	17.3	19.8	19.6
105	19.9	19.4	22.1	22.1	10.5	14.2	16.8	19.3	19.3
120	19.3	19.0	21.7	21.8	10.4	13.7	16.5	18.8	18.9
135	19.1	18.6	21.3	21.6	10.2	13.5	16.3	18.4	18.6
150	19.1	18.5	21.0	21.3	9.9	13.4	16.0	18.1	18.3
165	18.9	18.3	20.7	21.0	9.9	13.0	15.7	17.9	18.1
180	18.8	18.2	20.5		9.9	12.7	15.4	17.6	17.9
210	18.4	18.0	20.2	20.7	9.8	12.5	15.1	17.4	17.6
240	18.1	17.8	19.9	20.3	9.6	12.4	14.8	17.1	17.3
270	17.9	17.5	19.7	20.2	9.4	12.2	14.6	16.9	17.1
300	17.8	17.3	19.6	20.1	9.1	12.1	14.5	16.7	17.0

CEMENT PASTES									
TEST No.	41	34	35	86	87	90	88	89	91
C. B.	II	II	II	III	III	III	III	III	III
W/C	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.30
SPEED IN R.P.M.	70	80	102	10½	21	30	38	50	10½
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.								
1		46.5	46.8		16.7	23.3	24.2	31.0	15.0
2									
5	37.8	37.5	40.5	12.5	15.7	19.5	20.5	23.5	13.5
10	33.8	31.5	34.5	11.9	14.5	16.9	18.1	21.0	13.0
15	30.3	27.5	30.8	11.3	13.6	15.7	17.3	19.7	12.5
20	27.8	25.5	28.8	10.7	12.7	15.1	16.3	19.2	11.7
25	26.3	24.4	27.2	10.5	12.1	14.7	15.6	18.6	11.0
30	25.3	23.5	26.2	9.8	11.7	14.4	15.3	18.2	10.6
40	23.7	22.1	25.0	9.3	11.1	13.6	14.8	17.5	10.2
50	22.6	21.1	24.0	8.6	10.7	13.1	14.3	17.0	9.7
60	21.8	20.3	23.3	8.2	10.4	12.7	13.9	16.7	9.5
75	21.0	19.7	22.4	8.0	9.9	12.4	13.6	16.2	9.3
90	20.4	19.1	21.8	7.8	9.7	12.1	13.3	15.8	9.1
105	19.9	18.7	21.4	7.6	9.4	11.8	13.2	15.5	8.9
120	19.5	18.4	21.0	7.5	9.3	11.7	13.0	15.2	8.6
135	19.2	18.1	20.7	7.2	9.2	11.5	12.8	15.0	8.5
150	18.9	17.8	20.4	7.1	9.0	11.4	12.6	14.8	8.3
165	18.6	17.6	20.2	6.9	8.9	11.3	12.5	14.5	8.2
180	18.4	17.4	20.0	6.8	8.9	11.3	12.4	14.4	8.1
210	18.2	17.1	19.7	6.7	8.8	11.2	12.3	14.1	7.8
240	18.0	16.9	19.4	6.6	8.7	11.1	12.2	13.9	7.8
270	17.8	16.7	19.2	6.5	8.6	11.0	12.1	13.8	7.5
300	17.6	16.6	19.1	6.4	8.5	10.9	12.0	13.6	7.3

CEMENT PASTES								
TEST No.	92	99	93	94	107	103	104	105
C. B.	III	III	III	III	III	III	III	III
W/C	0.30	0.30	0.30	0.30	0.28	0.28	0.28	0.28
SPEED IN R.P.M.	21	30	38	50	10½	21	30	38
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
1	19.7	25.0	28.3	36.4	19.5		33.9	39.4
4						26.3		
5	17.7	22.3	22.8	26.9	18.5		29.0	31.8
10	16.7	19.8	20.0	23.1	16.6	22.9	26.7	27.3
15	15.4	18.3	19.0	21.9	16.1	20.4	26.0	25.3
20	14.7	17.4	18.0	20.9	15.5	19.7	24.0	24.5
25	13.9	16.8	17.2	19.9	15.0	19.0	22.8	23.0
30	13.7	16.0	16.9	19.4	14.8	18.3	21.7	21.8
40	13.2	15.3	16.1	18.6	14.3	17.0	20.4	21.5
50	12.8	14.8	15.5	18.0	13.8	16.4	19.5	20.4
60	12.6	14.5	15.3	17.6	13.6	15.9	18.6	19.9
75	11.8	14.1	14.9	17.0	13.3	15.2	17.5	18.9
90	11.4	13.8	14.5	16.5	12.9	14.8	16.7	18.7
105	11.1	13.4	14.3	16.1	12.7	14.4	16.2	18.5
120	10.8	13.2	14.2	15.9	12.5	14.2	15.8	18.0
135	10.6	13.0	14.0	15.7	12.4	13.9	15.4	17.8
150	10.4	12.8	13.8	15.4	11.7	13.3	15.0	17.6
165	10.2	12.7	13.7	15.2	11.3	13.2	14.7	17.5
180	10.1	12.5	13.6	15.1	11.2	12.9	14.4	17.3
210	10.0	12.4	13.5	14.7	11.1	12.2	14.1	17.1
240	9.9	12.3	13.4	14.5	10.4	11.8	13.8	17.1
270	9.8	12.2	13.3	14.2	10.2	11.5	13.7	16.9
300	9.7	12.1	13.3	14.1	10.0	11.6	13.7	16.8

CEMENT PASTES								
TEST No.	106	109	100	97	98	110	119	111
C. B.	III	III	III	III	III	III	III	III
W/C	0.28	0.29	0.29	0.29	0.29	0.29	0.32	0.32
SPEED IN R.P.M.	50	10½	21	30	38	50	10½	21
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
1	48.0		25.9	28.0	32.2	41.8		
2								14.5
3		16.3						
5	35.0	15.9	23.9	25.3	26.2	32.8	10.8	13.9
10	31.5	15.0	21.3	22.7	22.7	26.8	10.3	12.6
15	29.5	14.4	19.8	20.6	21.6	24.5	9.8	11.9
20	27.5	13.8	18.3	19.4	19.9	23.3	9.0	11.3
25	27.2	13.2	17.3	18.7	19.6	22.3	8.8	10.9
30	26.7	12.8	16.6	17.9	19.3	21.6	8.6	10.6
40	25.8	12.3	15.5	17.0	18.2	20.8	8.2	10.3
50	24.8	11.9	14.7	16.4	17.4	20.0	7.9	10.0
60	24.1	11.4	14.0	15.9	16.9	19.6	7.7	9.8
75	23.6	10.7	13.5	15.0	16.7	19.1	7.5	9.4
90	23.2	10.1	13.2	14.6	16.2	18.6	7.2	9.2
105	22.9	9.9	13.0	14.2	16.0	18.3	7.0	9.1
120	22.7	9.7	12.6	13.8	15.8	18.1	6.9	9.0
135	22.6	9.6	12.1	13.6	15.7	17.9	6.8	8.9
150	22.4	9.5	12.0	13.4	15.6	17.7	6.7	8.8
165	22.2	9.4	11.8	13.2	15.4	17.5	6.5	8.7
180	22.0	9.3	11.6	13.2	15.2	17.4	6.5	8.6
210	21.8	9.4	11.4	12.8	15.0	17.2	6.4	8.6
240	21.7	9.1	11.2	12.7	14.9	16.9	6.3	8.5
270	21.5	8.8	11.0	12.6	14.8	16.7	6.1	8.4
300	21.4	8.6	10.9	12.5	14.7	16.6	6.0	8.4

TEST No.	CEMENT				PASTES			
	112	120	113	114	122	123	124	125
C. B.	III	III	III	III	III	III	III	III
W/C	0.32	0.32	0.32	0.32	0.32	0.33	0.33	0.33
SPEED IN R.P.M.	30	30	38	50	50	10½	30	50
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
1	20.9	19.3	25.1	30.6	29.2		17.8	27.1
3								
5	17.4	17.1	19.6	21.1	21.5	8.5	14.3	20.5
10	15.4	15.5	17.1	19.3	19.7	7.6	13.1	18.6
15	14.4	14.7	16.2	18.2	18.7	7.0	12.5	17.7
20	13.8	13.9	15.6	17.4	18.0	6.8	12.0	16.9
25	13.4	13.5	15.1	16.8	17.4	6.7	11.8	16.5
30	13.1	13.0	14.8	16.5	16.9	6.5	11.5	16.1
40	12.5	12.7	14.4	15.7	16.3	6.3	11.1	15.3
50	12.2	12.3	14.0	15.0	15.6	6.1	10.9	14.7
60	11.9	12.2	13.7	14.5	15.2	6.0	10.6	14.1
75	11.6	12.0	13.5	13.9	14.6	5.8	10.5	13.3
90	11.4	11.7	13.1	13.4	14.0	5.7	10.3	12.8
105	11.3	11.5	12.8	13.0	13.6	5.6	10.2	12.5
120	11.1	11.4	12.6	12.7	13.3	5.5	10.0	12.2
135	11.0	11.3	12.4	12.5	13.2	5.3	9.9	12.0
150	10.9	11.2	12.2	12.3	13.0	5.2	9.8	11.8
165	10.8	11.1	12.1	12.1	12.7	5.1	9.7	11.6
180	10.7	11.0	12.0	11.9	12.5	5.1	9.6	11.5
210	10.6	10.9	11.7	11.7	12.4	5.0	9.5	11.3
240	10.5	10.8	11.5	11.5	12.2	5.0	9.4	11.1
270	10.4	10.7	11.4	11.3	12.1	5.0	9.3	11.0
300	10.3	10.6	11.2	11.2	12.0	4.9	9.2	10.9

CEMENT PASTES								
DOWN-CURVES RUN AT END OF CONSTANT SPEED TESTS								
TEST No.	87	88	89	92	99	93	94	103
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
50			13.0				14.4	
45			12.5				13.3	
40			12.0				12.7	
38		11.2				12.8		
35		10.8	11.4			12.4	11.9	
30		10.0	10.7		12.1	11.4	11.2	
25		9.2	9.8		10.8	10.3	10.1	
21	8.3			9.7				11.6
20		8.1	8.7	9.4	9.5	9.1	8.9	11.0
16	6.8	7.0	7.5					
15				7.7	7.8	7.5	7.3	9.2
10½	5.4	5.3	5.9	6.4	6.4	6.2	6.0	7.7

TEST No.	104	105	106	100	97	98	110	111
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
50			20.8				16.4	
45			19.7				15.6	
40			18.4				14.8	
38		16.7				14.7		
35		15.9	17.1			14.1	13.9	
30	13.7	14.6	15.4		12.5	12.7	12.9	
25	12.3	13.1	13.9		11.2	11.4	11.7	
21				10.9				8.4
20	10.9	11.6	12.2	10.5	9.8	9.9	10.3	8.1
17½							9.5	7.4
15	9.0	9.9	10.3	8.8	8.1	8.3	8.6	6.6
12½							7.7	5.9
10½	7.5	8.5	8.6	7.3	6.6	7.2	7.2	5.3

CEMENT PASTES							
DOWN-CURVES RUN AT END OF CONSTANT SPEED TESTS							
TEST No.	112	120	113	114	122	124	125
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.						
50				11.2	12.0		10.9
45				10.7	11.4		10.4
40				10.1	10.9		9.8
38			11.2				
35			10.9	9.6	10.3		9.3
30	10.3	10.6	10.1	9.0	9.6	9.2	8.8
25	9.4	9.7	9.4	8.3	8.9	8.5	8.1
21							
20	8.3	8.6	8.4	7.5	8.0	7.5	7.3
17½	7.6	7.8	7.7	6.9	7.4	6.8	6.9
15	6.9	7.0	6.9	6.2		6.1	6.3
12½	6.1	6.2	6.1	5.4	5.8	5.3	5.5
10½	5.6	5.6	5.5	4.8	5.3	4.8	4.9

CEMENT PASTES TESTED IN B. R. S. VISCOMETER					
TEST No.	244	242	241	240	232
C.B.	III	III	III	III	III
W/C	0.32	0.32	0.32	0.32	0.32
SPEED IN R.P.M.	23	33	42	56	119
TIME IN SECS.	TORQUE IN GMS. ACTING AT LEVER ARM OF 2.59 CMS.				
1	933		928		1070
2	377	338	493		668
3				385	
4					
5	321	288	369	365	500
10	296	275	331	338	473
15	283	263	317	320	431
20	274	249	289	307	415
25	268	233	273	295	400
30	258	225	260	280	386
40	238	208	243	261	365
50	225	200	230	246	353
60	219	195	220	234	343
75	206	184	211	225	327
90	200	181	203	216	315
105	194	175	193	207	308
120	183	172	188	198	298
135	175	166	184	192	293
150	169	163	178	189	288
165	166	160	175	186	285
180	163	157	172	183	281
210	153	151	166	177	273
240	143	145	159	171	264
270	137	139	156	165	259
300	134	136	150	157	256

CEMENT PASTES TESTED IN B.R.S. VISCOMETER				
DOWN-CURVES RUN AT END OF CONSTANT SPEED TESTS				
TEST No.	244	242	241	240
SPEED IN R.P.M.	TORQUE IN GMS. ACTING AT LEVER ARM OF 2.59 CMS.			
56				157
48				151
44				148
42			150	
36			144	142
33		136		
30			135	
28		130		132
24			126	
23	134			
20	131	121		122
18			117	
16	125			
14		110		113
12	119			
10		101	102	
8	113			98
4	103			
2	89	85	77	77

CEMENT PASTES												
FIRST DOWN-CURVES: TOP SPEED = 50 R.P.M. , C.B.II , W/C = 0.31												
TEST No.	44	47	46	49	48	50	51	52	53	55	56	54
TIME AT TOP SPEED IN SECS.	10	15	20	25	30	35	37	45	50	75	135	300
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.											
50	28.4	27.2	23.3	21.2	20.8	22.4	21.7	25.1	20.8	20.9	17.2	15.6
45	25.0	23.8	20.9	19.1	18.8	20.5	19.8	23.3		19.6	16.3	14.9
40	21.4	20.4	18.6	17.2	17.1	18.7	18.1	21.1	17.8	18.5	15.5	14.4
35	18.3	18.2	16.4	15.3	15.2	16.8	16.3	18.8	16.1	16.8	14.4	13.6
30	15.9	15.5	14.1	13.4	13.5	15.0	14.5	16.8	14.4	15.2	13.3	12.8
25	13.5	13.6	12.3	11.4	11.6	13.0	12.7	14.5	12.5	13.4	12.0	11.7
21	12.0	12.1	10.9	10.3	10.4	11.6	11.3	13.0	11.1	11.9	10.9	10.9

FIRST DOWN-CURVES: TOP SPEED = 70 R.P.M. , C.B.II , W/C = 0.31						
TEST No.	59	63	64	60	67	66
TIME AT TOP SPEED IN SECS.	5	15	15	20	30	40
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.					
70		29.3	29.6	28.3	24.8	23.2
63		24.8	25.1	24.9	22.6	21.6
60	29.3					
56		21.8	22.1	22.3	20.8	20.1
50	23.5					
49		19.1	19.7	20.3	18.9	18.6
42		16.7	17.0	18.4	17.1	16.7
40	19.3					
35		14.5	14.8	16.0	15.4	15.2
30	14.3					
28		12.3	12.7	13.6	13.3	13.4
21	11.0	10.2	10.4	11.0	11.0	11.0
14		7.7	8.2		8.5	8.3
10 1/2		6.6	6.9		7.1	7.1

CEMENT PASTES					
FIRST DOWN - CURVES					
TOP SPEED = 40 R.P.M. , C.B. III , W/C=0.31					
TEST No.	85	79	78	115	116
TIME AT TOP SPEED IN SECS.	5	10	20	30	40
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.				
40	21.6	19.6	16.7	16.4	16.4
35	17.8	16.7	15.0	14.6	14.5
30	14.9	14.0	13.2	12.7	12.8
25	12.6	12.0	11.4	11.0	11.2
21	10.9			9.4	
20		10.3	9.4		9.7
16	9.2	8.5	7.9	7.8	8.0
10½	7.3	6.8	5.9	6.1	6.2

CEMENT MORTARS									
TEST No.	129	131	127	132	130	134	159	136	135
C. B.	III	III	III	III	III	III	III	III	III
W/C	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
SAND BET. SIEVE NOS.	52-72	52-72	52-72	52-72	52-72	52-72	52-72	52-72	52-72
CEM/SAND RATIO	1.0	1.0	1.0	1.0	1.0	0.80	0.91	1.11	1.33
SPEED IN R.P.M.	10 1/2	21	30	38	50	30	30	30	30
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.								
1		13.6	18.5	20.8	25.4	23.0	20.6	16.9	13.0
2		12.6		15.8					
3							16.6		
4					17.4	19.5			
5	8.1	11.1	13.0	14.4		18.9	15.1	11.9	10.0
7					15.6				
10	7.2	10.0	11.8	13.3	13.5	17.6	13.6	10.5	9.2
15	6.8	9.4	11.4	12.4	13.8	17.0	13.1	10.0	8.8
20	6.5	9.0	10.9	12.0	13.5	16.6	12.8	9.5	8.7
25	6.3	8.7	10.5	11.6	13.4	16.2	12.1	9.3	8.5
30	6.2	8.4	10.3	11.5	13.3	15.8	11.6	9.1	8.4
40	6.0	8.3	10.2	11.4	13.3	15.5	11.3	9.0	8.3
50	5.8	8.2	10.1	11.3	13.2	15.5	11.2	8.9	8.2
60	5.7	8.1	10.1	11.4	13.2	15.6	11.1	8.9	8.1
75	5.6	8.1	10.2	11.5	13.3	15.9	11.1	8.9	8.1
90	5.6	8.2	10.2	11.6	13.5	16.2	11.1	8.9	8.1
105	5.5	8.2	10.3	11.7	13.6	16.9	11.3	9.0	8.1
120	5.5	8.3	10.4	11.9	13.7	16.8	11.5	9.1	8.1
135	5.5	8.4	10.5	12.0	13.9	17.1	11.7	9.1	8.1
150	5.5	8.5	10.6	12.1	14.0	17.2	11.9	9.2	8.1
165	5.6	8.6	10.7	12.2	14.1	17.2	12.0	9.3	8.1
180	5.7	8.7	10.8	12.1	14.2	17.3	12.2	9.3	8.2

CEMENT MORTARS									
TEST No.	161	160	162	164	163	165	168	169	167
C. B.	III	III	III	III	III	III	III	III	III
W/C	0.34	0.34	0.42	0.42	0.42	0.42	0.42	0.42	0.42
SAND BET. SIEVE Nos.	52-72	52-72	72-100	72-100	72-100	72-100	44-52	44-52	44-52
CEM/SAND RATIO	2.63	3.0	1.0	1.11	1.33	1.60	0.75	0.83	0.91
SPEED IN R.P.M.	30	30	30	30	30	30	30	30	30
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.								
1	20.3	22.5	22.1	20.1	19.1	13.9	20.1	17.3	16.9
2					14.1				
3	16.0	16.5	19.1	15.1		10.9	16.3		13.3
4								12.9	
5	15.2	15.5	18.5	13.4	12.6	9.1	14.8	12.6	12.3
10	14.6	14.0	17.7	13.2	11.6	9.2	13.5	11.0	11.3
15	13.5	13.1	17.1	12.7	10.7	8.7	13.2	10.3	10.5
20	12.9	12.6	17.4	12.4	10.3	8.4	13.1	10.1	10.1
25	12.5	12.3	16.8	12.1	10.1	8.3	12.8	9.9	9.9
30	12.1	12.1	16.6	12.0	9.9	8.2	12.6	9.9	9.8
40	11.8	11.7	16.7	11.8	9.7	8.0	12.4	9.8	9.6
50	11.5	11.4	16.9	11.5	9.6	8.0	12.3	9.8	9.5
60	11.2	11.3	16.4	11.5	9.5	7.9	12.3	9.8	9.5
75	11.0	11.0	16.3	11.6	9.5	7.8	12.4	9.9	9.5
90	10.9	10.8	15.8	11.7	9.6	7.8	12.5	10.0	9.5
105	10.7	10.7	16.2	11.8	9.8	7.8	12.6	10.1	9.6
120	10.6	10.6	16.7	11.9	9.9	7.9	12.8	10.2	9.6
135	10.6	10.5	17.0	12.1	9.9	7.9	12.9	10.4	9.7
150	10.5	10.5	17.2	12.3	10.0	8.0	13.1	10.6	9.8
165	10.5	10.4	17.3	12.4	10.0	8.0	13.3	10.7	9.8
180	10.5	10.4	17.4	12.5	10.1	8.1	13.5	10.9	9.9

CEMENT MORTARS								
TEST No.	166	142	144	143	141	175	174	173
C. B.	III	III	III	III	III	III	III	III
W/C	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
SAND BET. SIEVE NOS.	44-52	36-44	36-44	36-44	36-44	25-36	25-36	25-36
CEM/SAND RATIO	1.0	0.75	0.83	0.91	1.0	0.75	0.83	1.0
SPEED IN R.P.M.	30	30	30	30	30	30	30	30
TIME IN SECS.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
1	15.2	19.8	19.7	14.2	12.6	19.7	15.3	12.3
2								
3	11.7				10.6	15.7	12.8	9.5
4			14.7	11.7				
5	10.9	16.3	12.7	11.4	10.0	14.7	12.2	9.2
10	10.1	14.0	11.7	10.8	9.5	14.6	11.5	8.8
15	9.7	13.3	10.9	10.6	9.2	13.2	11.2	8.7
20	9.4	13.0	10.4	10.3	9.1	12.8	10.9	8.5
25	9.2	12.9	10.3	10.1	8.9	12.7	10.8	8.4
30	9.0	12.7	10.2	10.0	8.8	12.6	10.7	8.4
40	8.8	12.6	10.0	9.8	8.8	12.5	10.5	8.2
50	8.6	12.6	9.9	9.7	8.7	12.3	10.4	8.1
60	8.6	12.5	9.8	9.6	8.6	12.3	10.4	8.0
75	8.5	12.5	9.8	9.5	8.4	12.3	10.3	7.9
90	8.5	12.5	9.8	9.4	8.4	12.3	10.3	7.8
105	8.5	12.6	9.8	9.3	8.3	12.3	10.3	7.8
120	8.5	12.6	9.9	9.3	8.3	12.4	10.4	7.7
135	8.5	12.7	10.0	9.3	8.3	12.5	10.4	7.7
150	8.5	12.9	10.0	9.3	8.3	12.7	10.5	7.7
165	8.4	13.0	10.1	9.4	8.3	12.8	10.6	7.7
180	8.4	13.1	10.3	9.4	8.3	12.9	10.7	7.7

CEMENT				MORTARS					
DOWN - CURVES RUN AT END OF CONSTANT SPEED TESTS									
TEST No.	131	127	132	130	134	159	136	135	161
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.								
50				14.2					
45				13.6					
40				12.7					
38			12.1						
35			11.6	12.0					
30		10.8	10.9	11.1	17.3	12.2	9.3	8.2	10.5
25		10.1	10.0	10.2	16.4	11.8	8.7	7.5	9.5
21	8.7								
20	8.6	9.2	9.1	9.2	15.2	11.1	7.9	6.7	8.4
17½	8.1	8.7	8.5	8.7	14.6	10.5	7.4	6.2	7.7
15	7.6	8.2	8.0	8.2	13.8	9.9	6.9	5.8	7.1
12½	7.1	7.5	7.4	7.6	13.1	9.3	6.4	5.3	6.4
10½	6.7	7.2	7.0	7.1	12.6	8.9	6.0	4.9	5.9

CEMENT MORTARS								
DOWN-CURVES RUN AT END OF CONSTANT SPEED TESTS								
TEST No.	160	162	164	163	165	168	169	167
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
30	10.4	17.4	12.5	10.1	8.1	13.5	10.9	9.9
25	9.4	16.6	11.8	9.4	7.3	12.9	10.1	9.2
20	8.3	15.5	10.9	8.6	6.6	11.8	9.2	8.3
17½	7.6	14.9	10.3	8.0	6.1	11.1	8.7	7.8
15	7.0		9.8	7.5	5.6	10.5	8.1	7.2
12½	6.2	13.6		6.9	5.1	9.9	7.5	6.6
10½	5.6	13.0	8.9	6.5	4.7	9.4	7.0	6.3

TEST No.	166	142	144	143	141	175	174	173
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.							
30	8.4	13.1	10.3	9.4	8.3	12.9	10.7	7.7
25	7.7	12.3	9.5	8.6	7.6	12.1	10.0	7.0
20	6.8	11.2	8.5	7.8	6.8	11.1	9.0	6.2
17½	6.4	10.6	7.9	7.2	6.4	10.4	8.5	5.8
15	6.0	9.9	7.4	6.7	5.8	9.7	7.9	5.3
12½	5.5	9.1	6.7	6.1	5.3	9.0	7.3	4.7
10½	5.1	8.6	6.3	5.8	4.9	8.5	6.9	4.4

CEMENT		MORTARS			
FIRST		DOWN - CURVES			
TOP SPEED = 30 R.P.M. , C. B. III , W/C = 0.42					
CEM/SAND RATIO = 1.0 , SAND BETWEEN SIEVE Nos. 52-100					
TEST No.	153	154	156	157	158
TIME AT TOP SPEED IN SECS.	2	3	10	15	20
SPEED IN R.P.M.	DEFLECTION OF MIDDLE CYLINDER IN DIV.				
30	14.4	13.4	12.1	10.9	9.8
25	11.2	11.2	10.3	9.4	8.5
20	9.1	9.1	8.6	8.0	7.5
15	7.6	7.4	7.2	6.7	6.3
10½	6.4	6.2	6.3	5.9	5.3