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## STRUCTURE AND RHEOLOGY OF CEMENT-BASED SYSTEMS

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### ABSTRACT

Fresh concrete and mortar conform closely to the Bingham model, but the rheology of cement pastes is more complex and structural breakdown occurs. This can be explained by the existence of forces between the surfaces of individual particles which are less significant in the coarser grained materials. The requirements of apparatus to determine the rheology of these materials are described and typical results reported. The behaviour of the materials in practical applications such as pumping, vibration and trowelling can be explained by the rheological parameters so obtained, and a consistent view of the performance of cement based materials may be developed.

### INTRODUCTION

Fresh cement-based materials are concentrated suspensions of chemically reacting cement particles and inert aggregate particles in water. The size of the aggregate determines the use to which the material is put: concrete contains particles up to 20mm or more, mortar up to 2-5mm and grout up to about 0.2mm. All uses rely upon the working time provided by the nature of the chemical reaction between cement and water: an initial coating of hydration products is followed by a period of slow reaction (the dormant period) after which setting and hardening occur. If there were no dormant period to allow handling of the fresh mix for up to a few hours after mixing many of the uses of cement that we know today would be impossible.

In all situations the fresh material, in its plastic state, is placed into the moulds or cavities to be filled, perhaps with the aid of vibration to expel air bubbles and facilitate flow to give a dense structure which sets and hardens to a strong durable product. The hardened state, with its desirable engineering properties, cannot be achieved without first passing through the plastic state and if the latter is not appropriate for the available means of placing and compaction, then satisfactory engineering properties may not be achieved.

It follows that the role of rheology is crucial in characterising the fresh mix and in establishing what properties might be desirable for a particular job.

### RHEOLOGICAL MEASUREMENTS

The Deborah number,  $De$

$$De = t_r / t_0 \quad (1)$$

gives an indication of whether solid-like (Hookean) behaviour or liquid-like (Newtonian) behaviour is likely for a particular material. When the relaxation time,  $t_r$ , is similar to the time of the experiment,  $t_0$ , the material exhibits both types of behaviour (viscoelasticity). Such behaviour is shown by dispersions of solids in water, since because of the interparticle forces which result from surface charges and the electrical double layer,  $t_r$  is typically between  $10^{-4}$  and  $10^{+4}$  seconds which is within the range of most laboratory apparatus.

In the flow and remoulding of cement based materials the liquid-like behaviour may be considered to be more important. It may be measured in a variety of viscometers, either rotating or tubular. Formulae based on the dimensions of the apparatus are well established to enable shear stress to be calculated from the torque and shear rate from the speed of rotation. In a tube viscometer the material flows in response to an applied pressure and again shear stress may be

Deborah number

calculated from the pressure gradient and tube radius and shear rate from the velocity.

That cement based materials also have solid-like behaviour is evident from the observation that they will stand unsupported in a pile without flowing under their own weight. The simplest analysis involving solid-like behaviour is that of the Bingham model:

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (2)$$

where the material is taken to be an elastic solid for  $\tau > \tau_0$ , the yield stress, but flow occurs at higher stresses, ( $\mu$  is the plastic viscosity). As already noted the yield stress is a consequence of the interparticle forces, but the links between particles are often broken irreversibly by shear and the measured shear stress is found in practice to depend on time and previous shear history as well as on shear rate. The recent advent of controlled stress viscometers enables yield stress to be calculated from the torque at which flow first occurs [1].

An indication of solid-like properties can also be obtained from penetrometers [2], in which the force needed to insert a needle into the material is measured; vanes [3], where the shear stress to overcome the internal structure and set the material in motion is measured; and the pulse shearometer [4], where the shear modulus can be determined from the velocity of propagation of a shear wave. Finally, oscillatory rotational and translational shear, enabling the elastic and viscous components of the material's response to be separated, and stress relaxation methods have been used to a limited extent [5, 6, 7, 8].

#### Dimensions of viscometers for cement-based materials

The dimensions of viscometers for cement-based materials must comply with well-established rules. These rules give the minimum sizes of apparatus and samples shown in Table I. Clearly, an ideal coaxial cylinders viscometer for concrete is quite impractical, whereas a specially designed one for mortar is feasible [9, 10] and cement pastes are well within the capability of any of the wide range of laboratory instruments available commercially.

These principles are equally applicable to other geometries and mean, for example, that the cone and plate viscometer cannot be used for suspensions because the gap is zero under the apex of the cone. This led to the development of the truncated and annular plate and cone [1] geometries.

Because of the impracticability of using a coaxial cylinders viscometer of anything like ideal dimensions for fresh concrete, and because the results obtained by those workers who used coaxial cylinders of practical size but non-ideal dimensions differ by orders of magnitude, it is necessary to consider using measurements made during a mixing process. This was done by Tattersall and co-workers and has resulted in a highly successful and practical apparatus in which an interrupted helical impeller (Figure 1) rotates in a cylindrical bowl of fresh concrete.

Table I. Desirable dimensions of coaxial cylinders viscometer (mm)

	Test material		
	Cement paste	Mortar	Concrete
Maximum particle size	0.1	2	20
Minimum gap width	1	20	200
Minimum inner cylinder radius to give $R_{outer}/R_{inner} < 1.2$	5	100	1000
Height of inner cylinder	5	100	1000
Minimum volume of sample	1.7cm <sup>3</sup>	1.4dm <sup>3</sup>	2.6m <sup>3</sup>
Minimum mass of sample	3.4g	3.0kg	6200kg

maximum particle size  
 minimum gap width  
 minimum inner cylinder radius  
 height of inner cylinder  
 minimum volume of sample  
 minimum mass of sample

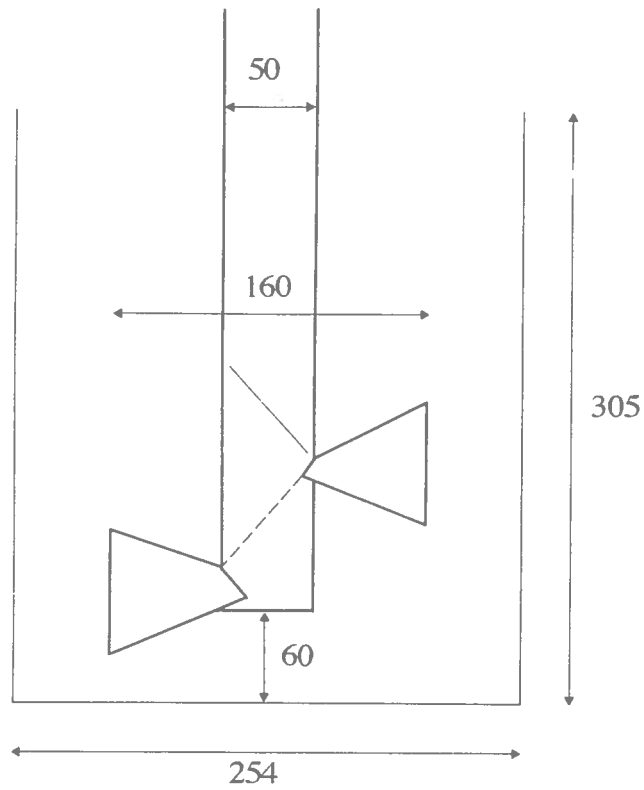


Figure 1. Interrupted helical impeller and bowl (dimensions in mm).

The impeller is driven through a variable speed hydraulic transmission in which the pressure in the hydraulic fluid is proportional to the torque. The flow curve of fresh concrete is determined by measuring pressure and speed at a number of points from which torque is plotted against speed. Theoretical treatment shows that torque,  $T$ , and speed  $N$ , are proportional to shear stress and shear rate respectively and experimental results indicate that fresh concrete conforms to the Bingham model over the range of shear rates used in the test (Figure 2):

$$T = g + hN \quad (3)$$

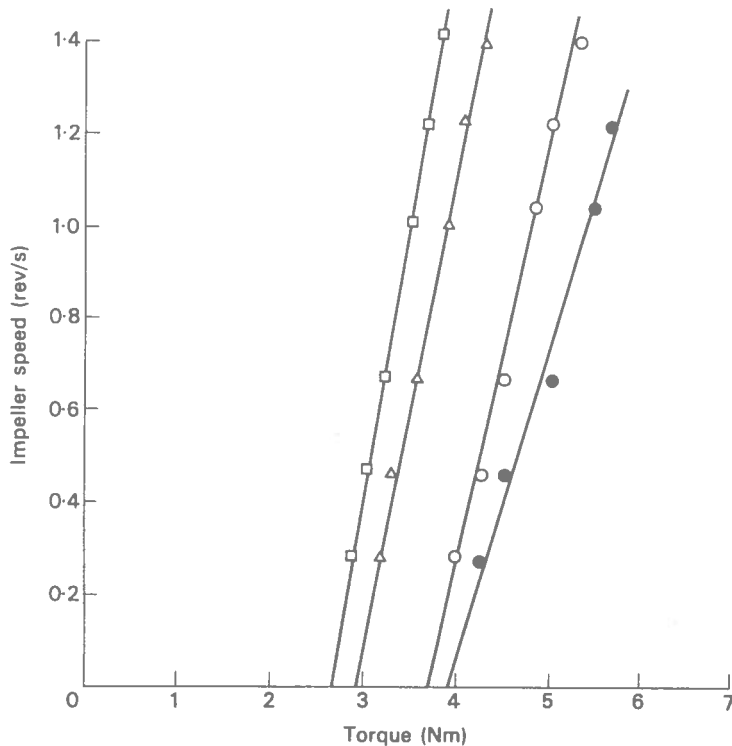


Figure 2. Typical flow curves obtained with fresh concrete.

Having established experimentally that the apparatus operates in laminar flow, it is possible to apply the postulate of Metzner and Otto [11] that the average shear rate in a mixer may be regarded as simply proportional to the speed. It can then be shown that the equation for a Bingham material is:

$$T = (G/K) \tau_0 + G\mu N \quad (4)$$

Where G is a constant obtained by calibration with Newtonian liquids and K is a constant obtained by calibration with non-Newtonian liquids whose apparent viscosities vary with shear rate in a known way, determined in separate experiments using a conventional viscometer.

Comparing equations (4) and (2) shows that:

$$\tau_0 = (K/G) g \quad (5)$$

$$\mu = (1/G) h \quad (6)$$

and hence both yield stress and plastic viscosity can be readily expressed in fundamental units.

## RHEOLOGY OF CEMENT-BASED MATERIALS - RESULTS

It might be expected that the rheology of the more complex material, concrete, containing a wider range of particle sizes, would be more complicated than that of one of its constituent materials, cement paste, and that an understanding of the latter would be a prerequisite for understanding the former. In fact, as this section will show, this is not the case and while a full understanding of the complex rheology of cement paste is still a long way off, fresh concrete has proved to be simpler and considerable progress has been made with it and, more recently, with mortars.

### Cement pastes

There is much disagreement between the results reported by different research workers. The flow curve for cement paste has been fitted to several different mathematical forms, all of which indicate the existence of a yield stress:

Bingham	$\tau = \tau_0 + \mu \dot{\gamma}$	(2)
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Herschel-Bulkley	$\tau = \tau_0 + A \dot{\gamma}^n$	(7)
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Robertson-Stiff	$\tau = A (\dot{\gamma} + C)^B$	(8)
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Ostwald-De Waele	$\dot{\gamma} = B \sinh \{(\tau - \tau_0)/A\}$	(9)
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where A, B and C are constants.

Additionally the numerical values reported for the rheological parameters cover a very wide range, which cannot be wholly explained by the variations in the cement used. It can only be accounted for by accepting that differences in experimental technique and apparatus of different workers have a much greater effect than has been generally realised. Banfill [12] showed that differences in the shear history at the time of test, undetected plug flow (where flow is incomplete across the gap of an instrument, giving higher effective shear rates than those calculated from the gap dimensions) and slippage at the smooth surfaces of a viscometer could all combine to give experimental variations as large as those reported.

However, in spite of the qualitative and quantitative disagreements between various workers, there is general agreement on two fundamental qualitative aspects of the behaviour of cement pastes.

First, the material breaks down during the test and hysteresis loops giving the downcurve at lower stresses than the upcurve are obtained when the flow curve is determined over a short cycle time. Banfill and Saunders [13] found that the shape changed progressively with increasing cycle time through loops with a crossover point to loops showing structural build up. They attributed this to chemical reaction during the test, but Hattori [14] has explained the effect in terms of the competition between coagulation and deflocculation processes.

Second, the material has a yield stress which decreases, in line with reductions in the

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apparent viscosity indicated by the rest of the curve, as the total amount of shearing energy experienced by the paste increases. Thus, Tattersall showed that successive hysteresis loops fell to progressively lower values of torque in a coaxial cylinders viscometer [15]. Banfill demonstrated that yield stress and plastic viscosity fell to an equilibrium value as the time of mechanical mixing was increased [16]. Orban, Parcevaux and Guillot [17] quantified the effect in terms of the total shear energy received by the sample prior to the test and confirmed Banfill's results but found that further shearing increased the yield stress, perhaps due to enhanced chemical reactivity in the highly sheared paste.

This structural breakdown has been amply confirmed by experiments carried out under continuous steady shear [18] where the torque drops exponentially from an initially high reading to reach an equilibrium value and under continuous steady stress where the shear rate increases with time [1]. The relationship between torque and time is affected by the shear rate in the experiment and was explained theoretically by Tattersall [15] using a linkage theory, in which the links between particles are broken by the work done in shearing the paste.

Space precludes any discussion of the large amount of work carried out on the effect of experimental variables on the rheological parameters of cement pastes. It is sufficient to note that investigations have included [18, 19] paste concentration (water/cement ratio or % solids) cement chemical composition (portland cements) and fineness, aluminous cement, oilwell cement, non-shrinking cements, flyash/portland cement blends, presence of chemical admixtures and polymer latexes, age and temperature.

### Mortars

In addition to work with mortars in a coaxial cylinders viscometer [9, 10], Banfill has developed the ViscoCorder as a more convenient apparatus [20, 21]. It is a small variable speed mixer consisting of a cylindrical beaker in which the mortar is placed and which is mounted on a rotating turntable. A concentric paddle is mounted on a torque measuring head and a flow curve can be constructed by measuring the torque at a series of speeds. By appropriate calibration, analogous to that used for concrete, the yield stress and plastic viscosity of the equilibrium flow curve may be expressed in fundamental units. Mortars undergo structural breakdown and measured data are sensitive to the previous shear history of the sample, but the equilibrium flow curve conforms to the Bingham model. The effects of composition are similar to those observed in fresh concrete.

### Concretes

Much work has been done by a number of workers on the effects on the rheology of concrete, as measured using the apparatus described above, of mix constituents and their relative proportions, cement properties and admixtures and cement blending agents [18, 22]. Concrete conforms to the Bingham model and does not show structural breakdown over the range of shear rates used in the test. The fact that yield stress and plastic viscosity vary in a complex fashion with composition makes rheology measurement a versatile way of controlling the quality of fresh concrete production [22].

### Comparison of cement pastes, mortar and concrete

Table II shows that there is a trend in the rheological properties of cement-based materials as shown in a bulk test, representative of the material. This can be explained semiquantitatively by the presence of aggregate in the coarser grained materials.

Table II Rheology of cement paste, mortar and concrete

	Cement paste	Mortar	Flowing Concrete	Concrete
Yield stress $N/m^2$	10-100	80-400	400	1000
Plastic viscosity $Ns/m^2$	0.01-1	1-3	20	100
Structural breakdown	Significant	Slight	None	None

7140 1 1000000

The flow properties of suspensions are determined by the interfaces between solid and water and, in terms of the surface area of contact, the dominant contribution is due to the cement-water interface. This is progressively diluted by the presence of aggregate. Thus, for example, two cements which give pastes whose rheological parameters differed by a factor of two produced concretes of identical flow behaviour.

It may be noted that the yield stress and plastic viscosity increase as the maximum particle size increase. This is because in a typical concrete at least 50% by volume is in the form of aggregate which is capable of withstanding the applied stresses without deformation: consequently the yield stress is higher, a point confirmed by the increase with increasing aggregate content in concrete [18]. The increased plastic viscosity is partly due to the increased interparticle contact and surface interlocking, as demonstrated by the fact that for two concretes with the same yield value containing rounded and angular coarse aggregates, the plastic viscosity of the latter is higher. It is also partly due to the inability of the aggregate to be sheared: when an overall shear rate  $\dot{\gamma}$  is applied to an imaginary concrete consisting of aggregate and paste 50:50 per cent by volume, the shear rate within the solid aggregate particles is zero and that in the paste is  $5\dot{\gamma}$ . This higher shear rate results in a higher stress and resistance to flow in the paste which accounts for the increase in measured plastic viscosity of the bulk material.

In contrast, it should be noted that the yield stress and plastic viscosity of cement paste increase as the cement gets finer, which reflects the dominance of the water-cement interface in this system. Evidently the influence of particle size is a surface area effect in fine grained pastes and a simple volume effect in the coarser grained concretes. Perhaps further work on mortar will suggest the particle size range where the change from one influence to the other occurs.

The trend in structural breakdown behaviour (Table II) may be explained qualitatively in a similar way. The work of shearing done on a material in unit time is proportional to the square of the shear rate. Structural breakdown experiments on cement paste show that the breakdown resulting from this work is rapid at first and complete in a few minutes and also that the rate of decay is proportional to the square of the shear rate. Thus in the 50:50 concrete mentioned above the total shear work done on the paste by the end of a three minute mixing period at a mean rate of  $10 \text{ sec}^{-1}$  is equivalent to that done in a viscometer in 45 seconds at  $100 \text{ sec}^{-1}$  or 12 seconds at  $200 \text{ sec}^{-1}$ . This is enough to give almost complete breakdown and explains the absence of structural breakdown when concrete is tested: all the breakable structure has been broken down before the material leaves the mixer. Furthermore, the higher the aggregate content, the higher the shear rate in the paste and the more complete the breakdown at the end of mixing.

## A STRUCTURAL MODEL FOR CEMENT-BASED SYSTEMS

Banfill [21] applied a structural model, which takes into account the instantaneous formation of a skin or membrane of hydrated minerals around cement particles [23], to the observed breakdown behaviour. The yield stress can be accounted for by the usual Van der Waals attraction and electrical double layer repulsion effects, which result in links between particles reforming reversibly when the particles come to rest, but the irreversibly destroyed structure is much stronger than this. He proposed that when dry cement powder first comes into contact with water the hydrated skin or membrane may form around pairs or groups of particles (Figure 3 stage (a)). When the skin is broken by the action of shear and the particles separate, that region of one particle which was in contact with other particles is exposed and hydrates to heal the interrupted skin (stage (b)). Because of this healing these links cannot then reform in the same way when the structure comes to rest, i.e. the breakdown of skin linkage is irreversible (stage (c)).

Based on experiments with the structural breakdown of mortars and assuming reasonable values for the strength of a membrane bridge he was able to conclude that between a sixth and a third of the surface area of the cement particles took part in the bridges. In these experiments, the work done in overcoming the structure and giving a fully broken down material agreed with estimates of the mixing energy imparted to an industrially mixed cement paste [17] and in a controlled stress rheometer [1], lending support to the model.

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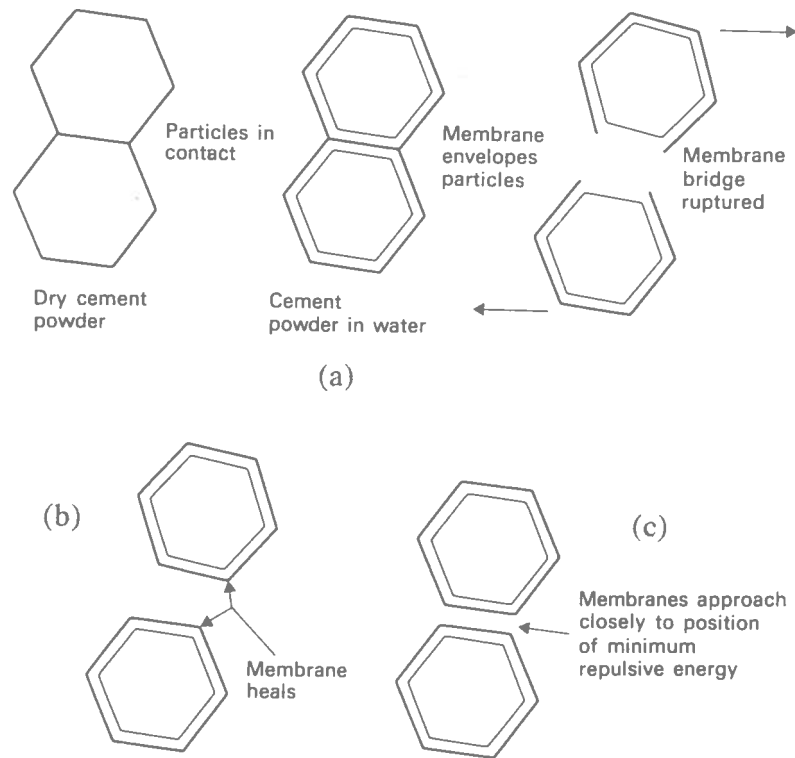


Figure 3. Schematic model for irreversible structural breakdown

## PRACTICAL USES OF CEMENT BASED MATERIALS

In order to establish what properties of cement based materials might be desirable for a particular use it is important to consider the relationship between rheology and practical processes.

### Pumping

Transport of concrete, mortar, grout and oilwell cement slurry by pumping along a pipeline is quite common and full size experiments on fresh concrete were carried out by Weber [24] and reported before the applicability of the Bingham model to concrete was discovered.

He expresses the flow down a pipe in terms of the shear stress at the wall,

$$\tau = Pa/2l \quad (10)$$

where  $P$  is the pressure,  $a$  the internal radius and  $l$  the length of the pipe. He gives experimental results which show a very good linear relationship between  $\tau$  and the concrete velocity,  $v$ .

$$\tau = k_1 + k_2v \quad (11)$$

which is of the form of the Bingham equation, taking the velocity to be proportional to the shear rate.

However, observation shows that concrete emerges from a pipe in the form of a lubricated plug of sometimes uncompacted granular material, suggesting that shear flow does not occur in the bulk of the concrete. This behaviour can also be explained in terms of the Bingham model as the shear stress increases linearly from zero at the axis of the pipe to a maximum at the wall. Therefore the stress near the axis can never exceed the yield stress of the material and consequently the material there is never sheared - it merely flows as a solid plug. The Buckingham-Reiner equation for flow down a pipe is:

$$Q = (\pi a^4/8\mu l).(P - 4p/3 + p^4/3P^3) \quad (12)$$

71 ps / d not used



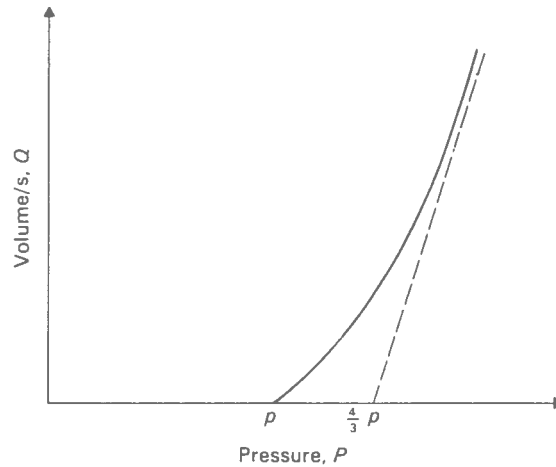


Figure 4. The Buckingham-Reiner relationship

where  $Q$  is the total volume flowing per second at pressure  $P$  and  $p$  is the minimum pressure at which flow begins. The radius of the plug is  $pa/P$ . A graph of  $Q$  against  $P$  is therefore a curve which asymptotically approaches a straight line of slope  $\pi a^4/8\mu l$  which intercepts the  $P$  axis at  $4P/3$  (Figure 4). This would not be expected to give the straight line relationship between concrete velocity  $v (= Q/\pi a^2)$  and wall shear stress  $\tau (= Pa/2l)$  which is reported by Weber.

However, because the solid particles tend to move away from the wall during shear flow it is quite likely that the material at the wall acts as a lubricating layer. To account for this the equation of flow has to be modified by the addition of terms relating to the shear flow in a lubricating layer of thickness  $\epsilon$ . Thus for fresh concrete with a Bingham lubricating layer of mortar or cement paste (plastic viscosity  $\mu_L$ , minimum pressure to initiate flow  $p_L$ ):

$$Q = (\pi a^4/8\mu_c l).(P - 4p_c/3 + p_c^4/3P^3) + (\pi a^3 \epsilon/2\mu_L l).(P - p_L) \quad (13)$$

where the suffixes  $c$  and  $L$  denote concrete and layer respectively. For mortar or cement paste with a Newtonian lubricating layer of water:

$$Q = (\pi a^4/8\mu_c l).(P - 4p_c/3 + p_c^4/3P^3) + (\pi a^3 \epsilon P/2\eta_L l) \quad (14)$$

Equations 13 and 14 show that if the plastic viscosity of a Bingham lubricating layer or the viscosity of a Newtonian layer are small compared to the plastic viscosity of the concrete itself, as Table II shows is likely to be the case, then the correction terms involving the layers become large compared to rest of the right hand side of those equations and the flow is predominantly due to slippage. In these circumstances  $Q$  varies approximately linearly with  $P$  and Weber's observations of a linear relationship between  $v$  and  $\tau$  become consistent with the theory. Evidently the pipe flow of concrete depends on the rheology of the layer and the flow properties of the bulk material are irrelevant. However, this conclusion could not have been reached without first considering the rheology.

In view of this conclusion it is perhaps fortunate that research into the pumpability of concrete has concentrated on factors which affect the ability of the concrete to establish and maintain the lubricating layer. The factors in mix composition which affect this will also affect the rheology of the bulk material and perhaps the relationship may be close enough to enable rheology to be used to predict layer-forming ability. However, this is a matter for future research.

## Vibration of fresh concrete

The use of vibrators for the placing and compaction of concrete is a long established practice, which has been little understood until recently. Just as ordinary casual observation shows that fresh concrete possesses a yield stress, so it is also obvious that when vibrated the effective yield stress is much reduced, perhaps to zero, so that the concrete flows under its own weight and fills a mould. Most early experiments were done on the hardened properties achieved as a result of vibration and it was only with the advent of the fresh concrete apparatus described earlier, whose bowl can be mounted on a vibrating table, that it became possible to obtain a flow curve for a material when it is not being vibrated and for the same material when it is being vibrated.

Tattersall and Baker [25, 26] mounted the bowl of the apparatus on an electromagnetic vibrator whose amplitude and frequency could be varied independently. A flow curve for unvibrated concrete was obtained in the usual way, then the impeller was run at its top speed and the vibrator switched on, resulting in a very rapid drop in torque followed by a slower rise, which was attributed to compaction in the bowl. The minimum torque was taken as an indication of the effect on the concrete and gave one point on the flow curve of the concrete under vibration. The concrete was then remixed, replaced in the bowl and measurements repeated at a lower speed to give another point. In this way the vibrated flow curve was constructed, and the results were of the form shown in Figure 5.

The flow curve for the vibrated concrete appears to start from the origin and this indicates that the yield value has been reduced to zero. Therefore, at low shear rates, such as those produced by flow under self weight, concrete subjected to vibration may be regarded as a Newtonian liquid whose flow properties can be characterised by the viscosity  $\eta$  or fluidity  $\phi$ , its reciprocal, which is given by the tangent to the curve at the origin. For two mixes, studied at 24 combinations of frequency and acceleration, the results fitted a relationship of the form:

$$\phi = c_1 \{1 - \exp[c_2 A(f - F_c)]\} \quad (15)$$

where  $A$  is amplitude,  $f$  is frequency and  $F_c$  some small critical frequency which must be exceeded for there to be any effect at all.

The evidence of Newtonian behaviour at low shear rates suggested a much simpler experimental set up to study the rate of fall of a column of concrete contained in a 10mm vertical pipe when vibration was applied at the bottom. The height  $H$  of a Newtonian liquid should fall according to:

$$dH/dt = -bH \quad (16)$$

where  $b$  is proportional to the fluidity  $\phi$ . This was found to be so and a large number of observations on several different mixes at 48 combinations of frequency and acceleration fitted a relationship of the form:

$$b = c_3 (A - A_0) \ln(1 - f/F) \quad (17)$$

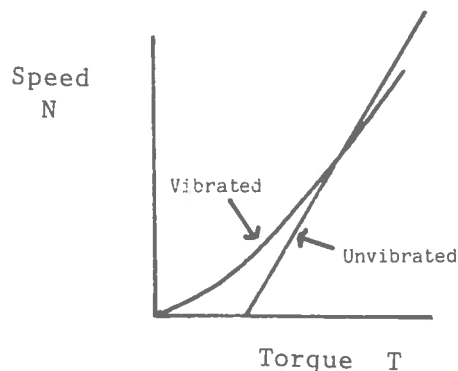


Figure 5. The effect of vibration on the flow curve of fresh concrete.

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 21 10 1. 1. d mnt vms

where  $A_0$  is a small critical amplitude and  $F$  a large critical frequency in excess of 200 Hz. Good correlation between  $\phi$  from the flow curve experiments and  $b$  from the vertical pipe experiments was found.

Equations (15) and (17) show that away from the critical values of  $A$  and  $f$  the effect of vibration on rheology is a function of the product of amplitude and frequency, i.e. the maximum velocity. This finding has considerable implications for the design of vibrating equipment for peak efficiency, as hitherto, it had been thought that the important parameter was the acceleration (proportional to the product of amplitude and the square of the frequency). This information could only have been found by application of rheological considerations. Not enough work has yet been done on a sufficiently wide range of concrete mixes to show the role of concrete properties on the response to vibration, but it might be expected that, for example, the damping of the vibration by the concrete would be affected by its composition.

### Hand trowelling

Fine grained mortars and plasters are almost invariably applied by hand on large areas like wall, floor and ceiling surfaces and on small areas in laying brick and blockwork masonry and on damaged concrete when filling it with repair compounds. In these situations the flow of the material beneath the trowel (its trowellability) is vitally important in order to produce a finished job of good quality.

The action of the trowel may be understood by reference to Figure 6. The worker presses the flat blade of the trowel against the wall at a shallow angle and moves it across the surface in the direction shown. The material is sheared through the narrow gap and experiences a shear rate given by:

$$\dot{\gamma} = v/E \quad (18)$$

where  $v$  is the velocity and  $E$  the thickness of the bed of material left on the surface after the trowel has passed. The shear stress at the trowel surface is given by the component of force in the direction of motion:

$$\tau = F_t \cos \theta / a_t \quad (19)$$

where  $a_t$  is the area of contact.

Thus for a Bingham we expect:

$$F_t \cos \theta / a_t = a_0 + a_1 v/E \quad (20)$$

where  $a_0$  and  $a_1$  are constants. Under conditions of constant thickness, blade angle and blade size this reduces to:-

$$F_t = a_0' + a_1' v \quad (21)$$

where  $a_0'$  and  $a_1'$  are proportional to yield stress and plastic viscosity.

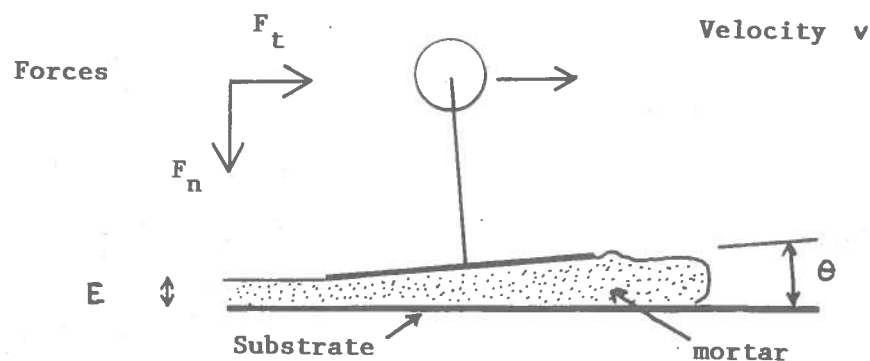


Figure 6. The forces under a trowel while spreading mortar over a surface.

Naniwa [27] built an apparatus in which a trowel was passed over a bed of mortar at constant speed and the components of force measured by an arrangement of transducers. His results show that the relationship between force and velocity is indeed linear and seem to confirm the validity of equation (21).

Within the limits of accuracy possible by reading values from the small graphs in Naniwa's original paper, the Bingham parameters of the mortars which he used may be calculated from the reported geometry of the apparatus and are in the range of yield stress 100-390 N/m<sup>2</sup> and plastic viscosity 0.35-0.5 Ns/m<sup>2</sup>. The agreement between these values and those quoted in Table II is very encouraging and seems to confirm the validity of the analysis.

Therefore it seems likely that the trowellability of cement based materials may be simply understood in terms of their Bingham rheological parameters and that the recent developments in testing mortars [9, 10, 20, 21] might enable mortars and related materials to be assessed more reliably for their intended end uses.

## CONCLUSION

The rheology of cement-based materials is important because of the scope it offers for characterising fresh cement paste, grout, mortar and concrete and for understanding how they behave in practical applications. Without satisfactory fresh properties, it is unlikely that the desirable engineering properties of the hardened materials will be achieved.

The rheology is dominated by the structure which exists in the cement paste, but in mortar and concrete the structure has been partially or fully broken down during mixing. As a result fresh concrete and mortar conform closely to the Bingham model and the behaviour of these materials during pumping, vibration and hand trowelling can be explained by reference to that model.

A reliable apparatus for testing fresh concrete is available and one for mortar has recently been developed from it. In contrast cement paste has been tested in many different rotational and other viscometers giving apparently conflicting results, which are probably due to the different experimental techniques and sample preparation procedures used by different research workers. The important effect of shear history on the results obtained in a viscometer is only now being generally understood.

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