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THE RHEOLOGY OF FRESH MORTAR – A REVIEW

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ABSTRACT

The rheology of fresh mortar is described and selected features of its behaviour interpreted from a rheological perspective, highlighting research from the past 20 years. Mortar conforms to the Bingham model and therefore requires measurement of two parameters – yield stress and plastic viscosity – for its characterisation. Additionally, cement-based mortar undergoes structural breakdown when sheared and this requires carefully standardised mixing and testing procedures to be used. Most rheometers for mortar are rotational, and very little work has been done on compressive rheology. Rheology can be related to the results of empirical tests such as slump and flow but the latter are criticised on fundamental grounds, since they are incapable of providing the necessary minimum of information to characterise the material unambiguously. Mix composition affects these two parameters in different ways and this enables rheology to be used for quality and mix formulation control. This is especially useful in view of the complex effect of sand grading. Finally it is shown that the behaviour of mortar when being spread by trowel can be understood in terms of the Bingham model.

Keywords: Rheology, flow, mixes, sand, workability

1. INTRODUCTION

This paper reviews the rheology of fresh mortar. In most uses of mortar the material is applied by hand in the freshly mixed state ("fresh mortar") to perform as a bedding filler for the units, as levelling and smoothing material for floors and walls, plastering and rendering, and as fine grained repair and conservation material. After application it stiffens and hardens to be sufficiently strong and durable for the particular situation. In all these situations flow behaviour is important and it can be effectively studied using the concepts and techniques of rheology (Tattersall and Banfill, 1983).

In the case of masonry walling the ease with which a mortar flows from the trowel and can be spread on the masonry units is an important user parameter which is part of what the mason regards as workability. Cohesion, grittiness and water retention are others and together they affect the bond developed between units and the overall performance of the wall. When a sand with a high water demand is used in a mortar to which water is added to achieve a given consistence the mortar will be weaker and less durable.

This paper aims to review the main features of the rheology of fresh mortar, defined as a blend of water, sand and binder, with or without admixtures, and where the binder may be based on cement or lime, either hydraulic or non-hydraulic.

2. RHEOLOGY

Rheology is the science of the deformation and flow of matter, and the emphasis on flow means that it is concerned with the relationships between stress, strain, rate of strain, and time. Flow is concerned with the relative movement of adjacent elements of liquid and in shear flows liquid elements flow over or past each other. Imaginary parallel layers of liquid move in response to a shear stress to produce a velocity gradient, which is referred to as the shear rate, and is equivalent to the rate of increase of shear strain. The rich variety of material behaviour can be characterised in various ways, of which the flow curve, showing how shear stress and shear rate are related is very common, but equally data may be presented as the variation of viscosity (the ratio of shear stress to shear rate) with shear rate or time.

In the flow and remoulding of mortar, liquid-like behaviour is likely to be important and can be measured in a variety of viscometers, both rotational and compressive. Well established formulae enable shear stress and shear rate to be calculated from the torque and speed of rotation respectively in a rotational viscometer (Barnes, 2000). However, there are also situations where solid-like behaviour is important. Visual observation confirms the existence of a yield stress: mortars are able to stand unsupported without flowing under their own gravity and during setting they develop strength and stiffness. The simplest analysis involving solid-like behaviour is that of the Bingham model

$$\tau = \tau_o + \mu\dot{\gamma} \qquad (1)$$

where the material is an elastic solid at shear stress $\tau < \tau_o$, the yield stress, but flows at higher stresses, (μ is the plastic viscosity, $\dot{\gamma}$ the shear rate). The yield stress is a consequence of the interparticle forces, but these links are often broken irreversibly by shear and the measured shear stress is found to depend on time and previous shear history as well as on shear rate. The yield stress can be determined from equation (1) by extrapolation, but also directly by controlled stress rheometers (Banfill and Kitching, 1991) where the shear stress to initiate flow is measured, by penetrometers (Bombled, 1970) in which the force needed to insert a needle into the material is measured, by vanes (Barnes and Carnali, 1991) where the shear stress to overcome the internal structure and set the material in motion is measured, and by the pulse shearometer (Gregory, 1987) where the shear modulus can be determined from the velocity of propagation of a shear wave.

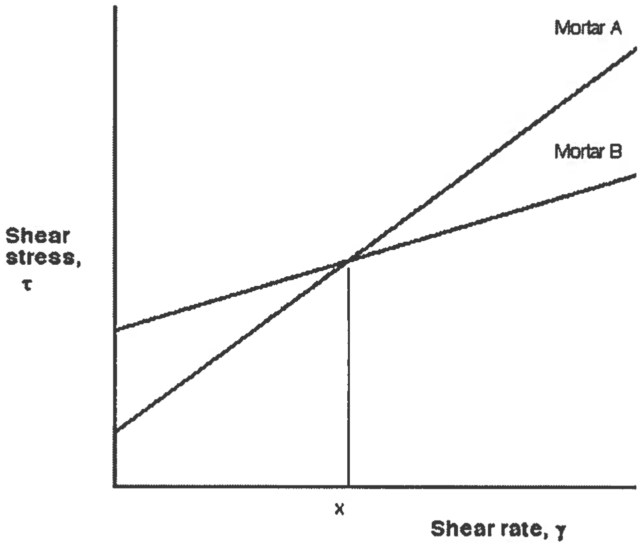

Figure 1 - Examples of the Bingham flow curves for two mortars.

In principle, two measurements at different shear rates or shear stresses are the minimum required to characterise a Bingham material. The importance of this, termed the two-point principle by Tattersall and Banfill (1983), can be shown by reference to Figure 1, which shows schematically the Bingham flow curves of two mortars, A with a lower yield stress and higher plastic viscosity than B. If the workability of the two mortars is compared on the basis of a single measurement of shear stress at some fixed shear rate then the rank order will depend on the shear rate used in the test. Mortar A is stiffer (higher shear stress) at $\dot{\gamma} > x$, while mortar B is stiffer at $\dot{\gamma} < x$. When measurements are taken at $\dot{\gamma} = x$ the mortars will be ranked identical.

3. TESTING METHODS

3.1 Rotational rheometry

There are well-established rules for the sizes of a coaxial cylinders viscometer and sample to ensure that rheological measurements are reliable, chiefly that any gap must be 10 times the size of the largest particles and that the ratio of outer cylinder radius to inner must be less than 1.2. This applies to other geometries and means, for example, that the cone and plate geometry cannot be used for suspensions because the gap is zero under the apex of the cone. Banfill (1987,1991a) demonstrated the feasibility of a coaxial cylinders viscometer for mortar testing, but found his design to be inconvenient and concentrated instead on the use of the Viskomat (Banfill, 1994, Anon, 2005a) essentially a small calibrated mixer (Figure 2). More recently Jin (2002) used an interrupted helix scaled down from the one used for concrete in an extensive study of the mortar fraction for design of self compacting concrete.

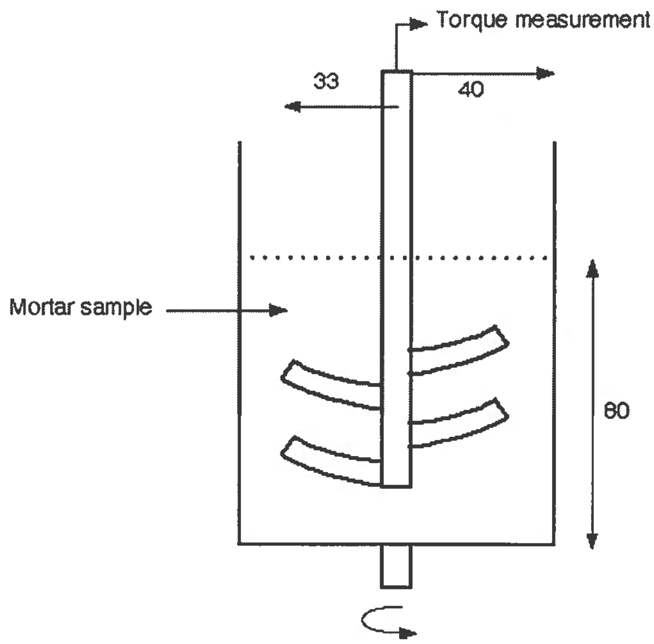

Figure 2 - Schematic diagram of the Viskomat measuring system (dimensions in mm).

OH Wallevik persevered with the coaxial cylinders approach and developed the Con-Tec rheometer (Anon, 2005b) for mortar, a smaller version of his successful design for concrete and using similar deeply ribbed cylinders to minimise slippage. It was described and analysed in depth by JE Wallevik (2003). The only other commercially available rotational instrument is the Paar Physica KMS system, which uses an offset ball of 10mm diameter which describes a circular path of radius 25mm through the mortar (Läuger et al, 1999). This is claimed to give good results for pastes and mortars (Anon, 2000).

3.2 Compressive rheology

This is the term increasingly given to the study of rheology under uniaxial compression and an extensive review by de Kretser et al (2003) described the analysis of systems involving sedimentation under self weight and externally applied compression. The latter is, of course, particularly relevant to the work of the mason. Meeten's relatively simple apparatus (Meeten, 2002a) employed a constant squeezing force between two plates and measured the velocities of approach and spread from which yield stress and plastic viscosity of a Bingham material can be calculated. He tested a wide range of materials and obtained satisfactory agreement between the compressive yield stress and that determined in rotational rheometry for many pastes and gels but in other the compressive yield stress was much lower (Meeten, 2002b). He did not test any cement-based materials. No results on mortars have been reported, but Min et al (1994) studied cement pastes in squeeze flow. They were unable to find any measure of agreement between squeeze flow and rotational shear flow experiments. However, this would seem to be a potentially fertile field for further development.

3.3 Test methods with a practical focus

Many empirical tests for mortar rheology have been developed and standardised by national bodies. They are all single point tests, i.e. they measure flow at a single shear rate, and the discussion above shows that they are incapable of characterising mortar fully. Such tests may involve slump or spread under gravity from conical or cylindrical moulds, spreading across a plate as a result of jolting, and remoulding under vibration. They were not developed on the basis of any rheological approach but they are in such wide use in industry that various attempts have been made to analyse their performance in rheological terms and relate the measurements to rheology (Showalter and Christensen, 1998, Roussel, 2004, Pashias et al, 1996).

4. RESULTS

This section summarises some important features of the rheology of mortars.

4.1 Structural breakdown

Mortars undergo structural breakdown and the measured data are sensitive to the previous shear history of the sample, but the equilibrium flow curve conforms to the Bingham model (Banfill, 1994). Breakdown manifests itself in two ways. First, the material breaks down during the test and hysteresis loops are obtained where the downcurve falls to lower stresses than the upcurve. Second, the material has a yield stress which decreases, in line with reductions in the apparent viscosity indicated by the rest of the curve, as the total amount of shearing energy experienced by the mortar increases (Banfill, 1991b, 1992). This mirrors the behaviour of binder pastes, where successive hysteresis loops fall to progressively lower values of torque in a coaxial cylinders viscometer (Tattersall, 1955), yield stress and plastic viscosity fall to an equilibrium value as the time of mechanical mixing is increased (Banfill, 1981) and the effect can be quantified in terms of the total shear energy received by the sample prior to the test (Orban et al, 1986, Hodne et al, 2000).

4.2 Comparison of mortar with cement paste and concrete

Table 1 shows that there is a trend in the rheological properties of cement-based materials, as quoted in the literature, which can be explained semiquantitatively by the presence of aggregate in the coarser grained materials. The flow properties of suspensions are governed 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 in one comparison, two cements which gave pastes whose rheological parameters differed by a factor of two produced concretes of indistinguishable flow behaviour (Tattersall and Banfill, 1983).

The yield stress and plastic viscosity increase as the maximum particle size increases. 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. The increased plastic viscosity is partly due to the increased interparticle contact and surface interlocking, and partly due to the inability of the aggregate to be sheared: when an overall shear rate $\dot{\gamma}$ is applied to an imaginary material consisting of aggregate and binder paste the shear rate within the solid aggregate particles is zero and that in the paste is much higher than $\dot{\gamma}$. This higher shear rate results in a higher stress and resistance to flow in the paste which in turn accounts for the increase in measured plastic viscosity of the bulk material.

Table 1 - Rheology of cement paste, mortar and concrete

Material	Cement paste, grout	Mortar	Flowing concrete	Self-compacting concrete	Concrete
Yield stress Pa	10-100	80-400	400	50-200	500-2000
Plastic viscosity Pa s	0.01-1	1-3	20	20-100	50-100
Structural breakdown	Significant	Slight	None	None	None

A structural model capable of explaining the irreversible breakdown which occurs on shearing cement-based systems, and which is different from thixotropic behaviour, was proposed by Tattersall and Banfill (1983), and is consistent both with the instantaneous formation of a protective layer on cement (Sujata and Jennings, 1992), and with the notion of links between particles first proposed by Tattersall (1955).

4.3 General effects of composition

Using data from a number of sources, the effects of composition can be efficiently summarised on a plastic viscosity - yield stress graph (Figure 3), which shows at a glance the direction of changes in the two parameters when changes in composition or raw material take place.

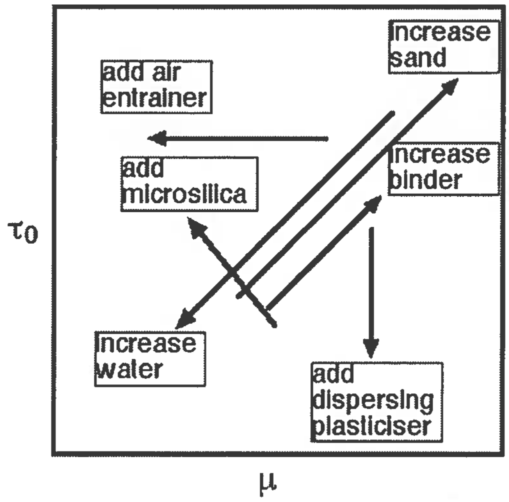

Figure 3 – Summary of the effects of composition on the rheology of fresh mortar.

4.4 Fineness and clay content in sand

Mortar sands may contain widely varying amounts of very fine particles and clay contaminants. While sieve analysis gives an overall picture, the effect of very fine particles on workability and water demand depends on their nature, as a sand containing 8% silt behaves very differently from one containing 8% clay. Yool and Lees (1995) analysed samples of 154 natural building sands from the UK by sieving and determined the Methylene Blue Value (MBV) as an indication of the clay content. The range of percentage passing a 63µm sieve was 0 - 12.1 % and the range of MBV was 0 - 5.24 g dye adsorbed per kg sand. To explore the effect of this range on the rheology Banfill (1999) subsequently made mortars with thirty sands, chosen from these samples, and tested them in the Viskomat.

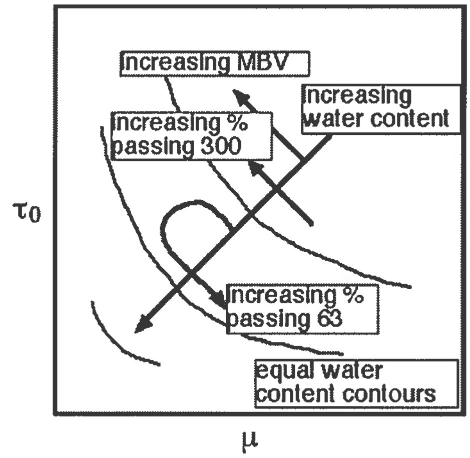

Figure 4 - Summary of the effect of fineness parameters on the rheology of fresh mortar.

The results confirmed that the fineness parameters affect rheology in different ways and the effects are summarised in Figure 4, where the curved lines are contours of approximately equal water content and the arrows reflect the individual trends. Increasing MBV increased the water demand and changed the sensitivity to water quantity. In terms of Figure 4 increasing MBV at constant water content moves the point (μ, τ_0) upwards and to the left, but because τ_0 is the parameter which dominates the overall level of workability this new point corresponds to a stiffer mortar to which more water must be added. As a consequence the water needed to achieve the original workability increases. This behaviour probably reflects the role of the very fine clay particles, whose high surface area needs a lot of water to form a continuous film and whose absorbency soaks up water for swelling. These two features account for the high yield stress, but once the mortar is flowing the fine particles act as lubricant in the spaces between the coarser sand particles and the plastic viscosity is then relatively insensitive to water content.

Overall grading, expressed as the percentage passing 300µm, changed the water demand and the rheology, as expected from previous work (Banfill, 1995), in just the same way and for analogous reasons as MBV. The observed effect of percentage passing 63µm was less clear cut because there was only one full set of data and the trend may be confused by differences in the other parameters between the sands tested. The complexity of Figure 4 shows that responding to a change in fineness by changing the water content might result in a mortar which behaves entirely differently and this could have implications for the quality control of production.

5. APPLICATIONS OF RHEOLOGY TO PARTICULAR SITUATIONS

5.1 Trowelling

Trowelling is a very common process in applying mortar to a substrate and the behaviour of mortar under the trowel can be analysed in terms of the Bingham model. Naniwa (1983) devised a trowellability apparatus, in which a trowel passed over a bed of fresh mortar and the various forces were measured (see Figure 5). The blade is held at a shallow angle to the mortar bed (of thickness E) and moves with velocity v over the surface generating forces F_t and F_n respectively parallel and perpendicular to the bed. If the mortar is a Bingham material and there is no slip under the trowel it is easily shown that

$$F_t \cos\theta = a + b\,(v/E) \qquad (2)$$

where a and b are proportional to yield stress and plastic viscosity respectively. Naniwa presented a graph of F_t against v for a series of six mortars and each gave a straight line intercepting the force axis at a value greater than zero. From the limited information given in the paper the intercepts suggest yield stresses of 80-400 Pa, which agree well with the values given in Table 1. However, one problem is that the same mortar should give the same intercept regardless of the value of E, but this was not the case and this could be attributed to the existence of slippage layers under the trowel. This interesting work does not seem to have been followed up.

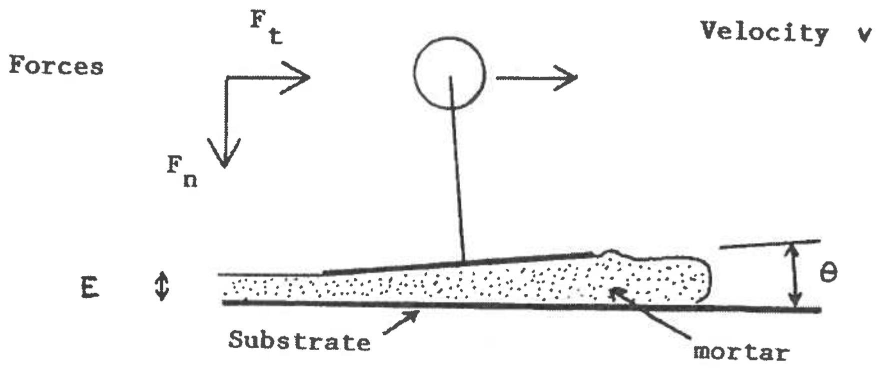

Figure 5 - The forces and flow during trowelling.

5.2 Quality control of production

It has been shown that rheological testing can offer considerable advantages for the quality control of fresh concrete production (Tattersall and Banfill, 1983), because the effects of changes in relative proportions and characteristics of ingredients on the two measured parameters are complex and that very complexity provides sensitivity. An example could be a formulated product containing cement, sand, microsilica and plasticiser. Using the information provided in the summary (Figure 3), if the yield stress during production falls below the specified target value and the plastic viscosity rises above it, this could only be the result of too little microsilica in the batch. This conclusion is reached by a process of elimination, because too much plasticiser reduces only the yield stress, while changes in the amounts of water, sand and cement either increase or decrease both parameters together. Similarly an increase in yield stress with no change in plastic viscosity can only be the result of too little plasticiser in the product. Preliminary work on the product enables the magnitude of the various effects to be established. In addition, the sensitivity of instruments such as the Viskomat, combined with their ability to provide an estimate of experimental error with each test performed, enables greater and more reliable discrimination between test results. Therefore it is easier to decide whether two test results are significantly different than it would be with less precise tests, and quality control decisions are more easily made.

6. CONCLUSIONS

Rheology is important because of the scope it offers for characterising fresh mortar and understanding how it performs in practical applications. Without satisfactory fresh properties it is unlikely that the desirable properties of the hardened materials can be achieved. The rheology is dominated by the structure that exists in the binder paste, but in mortar that structure has been partially or fully broken down during mixing. As a result it conforms closely to the Bingham model and its behaviour can be explained by reference to that model.

Sufficient information about the effects of the types and relative proportions of constituent materials is available to demonstrate the feasibility of discriminating between different materials and mixes using rheological methods. It is possible to understand the behaviour of mortar in practical situations by reference to its rheology and this enables practical details of handling and conditions of use to be optimised.

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