Flow Test: Particle-Level and Macroscale Analyses

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The physical interpretation of the flow test is investigated by conducting image-monitored flow tests on mortars prepared with mixtures of natural round sand and crushed angular sand to evaluate the progression of flow and the effect of aggregate shape characteristics on cement mortar rheology. The evolution of flow with the number of drops follows a hyperbolic trend. When analyzed within an energy-based framework, it is found that both the base shear at the mortar-plate interface and the internal energy loss in shear deformation are functions of the shear resistance within the mortar. This is further confirmed with mortars prepared with varying quantities of round particles. It is also shown that particle shape affects packing density and the mobilized friction between aggregates; therefore, particle shape defines the amount of paste required to reduce grain interaction to attain adequate flow.

Keywords: aggregate; flow; hydraulic cement; manufactured sand; rheology.

INTRODUCTION

Various tests employ vibration to measure the rheological properties or to evaluate the workability of cement mixtures quantitatively. These include: compaction test (Walz test), Vebe consistometer, Powers remolding test, Thaulow tester, flow table test (DIN flow table), Angels flow box test, LCL flow test, Wigmore consistometer, vibropenetrator, inverted slump cone test, vertical pipe apparatus, vibrating slope apparatus, settlement column segregation test, and vibratory flow meter (Koehler and Fowler 2003).

The flow table test (DIN flow table [DIN 1048 1972; BS EN 12350-5]) and the flow test (ASTM C 1437 2001) are similar: a cone-shaped mold is used to give the initial shape of the specimen, multiple jolts (drops) are applied to spread the specimen, and the horizontal spread of the specimen is measured. Previous studies with the DIN flow table test have shown that (Diamond and Bloomer 1977, Mor and Ravina 1986, Tattersall 1991, Bartos 1992, and Koehler and Fowler 2003):

- The DIN flow table test is simple, inexpensive, and can be readily used in the field.
- Test results are difficult to analyze and are not necessarily adequate to investigate shear rate effects.
- The specimen spread becomes homogenized as the number of jolts increases.
- The initial spread and the final spread after 15 jolts are linearly correlated.
- The spread is nonlinearly related to the number of jolts.
- Specimen slump and spread correlate linearly when the slump is greater than 177.8 mm (7 in.).

In the context of workability assessment tests, the flow test (ASTM C 124 1971) is a quantitative, yet empirical, single-point test (Tattersall and Banfill 1983). It was withdrawn in 1973 because its use in the field was deemed cumbersome compared with the slump test (ASTM C 143; Roy and Idorn [1993]—A detailed analysis of the slump test can be found in Murata [1984] and Schowalter and Christensen [1998]).

The flow test was later reinstated in 2001 for its unique advantages, including reproducibility and standardization (ASTM C 1437 2001). Still, the significance of flow test results remains unclear.

RESEARCH SIGNIFICANCE

The purposes of this study are to gain new insight into the underlying physical processes involved in the flow test (ASTM C 1437 2001), to assess its ability to capture fresh mortar rheology, and to address the effects of particle shape on mortar workability. The methodology consists of recording the evolution of flow and developing complementary mathematical analyses.

EXPERIMENTAL INVESTIGATION

Materials

Natural Ottawa sand (OS) and crushed granite sand (CS) of the same particle size \( D (0.85 \text{ mm} > D > 0.60 \text{ mm} [0.03 \text{ in.} > D > 0.02 \text{ in.}]) \) are selected to prepare mixtures with different mass fractions. OS is round, semi-spherical, and smooth quartzite aggregate, while CS is angular, platy, and rough. Surface characteristics can be inferred from Fig. 1 (optical

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Fig. 1—Microscopic images of natural Ottawa sand and crushed granite sand. (Note: 1 mm = 1000 μm = 0.039 in.)
stereomicroscope and scanning electron microscope). Clear differences in angularity are observed in the mm-scale. Roughness and indentations on the surface of crushed granite are seen at a scale of approximately 100 µm. However, differences vanish at the 10 µm scale. Therefore, crushing defines shape and contributes to surface roughness at a scale of approximately 10% of the particle diameter.

Mixtures are prepared with different mass fractions of OS: 0% (this is the pure CS), 10, 20, 30, 40, 50, 70, and 100% (this is the pure OS). Gravimetric mixing ratios are kept constant; in particular, the fine aggregate-to-cement ratio (FA/C) is 2.0, and the water-to-cement ratio ($w/c$) is 0.46 in all cases. Mixing is implemented in a standard laboratory mixer. Angular CS produces mixtures with lower workability than spherical OS for a given water and paste content (Quiroga and Fowler 2003).

The maximum void ratio $e_{\text{max}}$ is measured for all sand mixtures following ASTM D 4254 (2000). Figure 2 shows that the CS packs in a looser state ($e_{\text{CS}} = 1.1$) than the OS ($e_{\text{OS}} = 0.74$). The maximum void ratio for all mixtures can be estimated in terms of mass fraction of OS $M_{\text{OS}}$ as follows: $e_{\text{mix}} = 1.1 - 0.38M_{\text{OS}}$. Despite the higher maximum void ratio, the angular CS exhibits a higher angle of repose or critical state friction angle ($\phi' = 36$ degrees) than the round CS ($\phi' = 34$ degrees) because of enhanced interlocking between angular particles.

### Test procedure

The flow test is performed following ASTM C 1437 (2001). Freshly mixed hydraulic cement mortar is placed inside the cone-shaped mold in two layers. Then the mold is removed and the vibrating table is dropped 25 times in 15 seconds. Flow $F$ is defined as $F = (R_{25} - R_0)/R_0 \times 100\%$, where $R_{25}$ is the radius of the mortar pile after the 25th drop and $R_0$ is the initial radius of the mortar pile (ASTM C 1437 2001). In this study, the incremental spread of the mortar pile is recorded using digital photography after each drop, therefore $F_i = (R_i - R_0)/R_0 \times 100\%$, where $i$ is the drop number (refer to Fig. 3). Figure 4 shows the evolution of the pile during the first 25 drops for the 100% OS mortar.

### Segregation

Segregation can occur between cement paste and aggregates (refer to DIN flow table [Bartos 1992]). The development of segregation is explored in this study using a mixture of 50% natural OS and 50% CS. After 25 drops, the pile is divided into eight sectors, and the sand content in each sector is determined by washing away the paste. Results show that vibrations in the flow test cause no clearly detectable segregation between paste and fine aggregates.
EXPERIMENTAL RESULTS AND ANALYSIS

The measured horizontal spread in terms of flow at each i-th drop $F_i$ for all mortars is shown in Fig. 5. There are two salient observations. First, flowability increases as the mass fraction of OS increases. OS begins exerting a strong effect on flow when the mass fraction of OS is $M_{Ott} \geq 0.3$; therefore, the presence of OS is more effective in promoting flow than the CS in hindering it. Mixtures can be classified into round-like, crushed-like, and transitional mixtures. The transition range in this study is observed between $M_{Ott} = 0.3$ and 0.5.

Second, there is a nonlinear relationship between the mortar spread $F_i$ and the drop number $i$. As the height of the mortar pile decreases with increasing spread, the driver for spreading decreases while the resistance to flow at the mortar-surface interface increases. Hence, the incremental spread decreases with the number of drops. This suggests a nonlinear hyperbolic trend between flow, $F_i = (R_i - R_0)/R_0$, and drop number $i$

$$F_i = \frac{i}{a \cdot i + b} \tag{1}$$

The two independent parameters $a$ and $b$ can be replaced by the flow value $A$ at 25 drops and the initial flow rate $B$ at the beginning of the test

$$A = F_{i=25} = \frac{25}{25a + b} \tag{2}$$

$$B = \left[ \frac{dF}{dt} \right]_{t=0} = \left[ \frac{b}{(ai + b)^2} \right]_{t=0} = \frac{1}{b} \tag{3}$$

Either set of model parameters, $(A, B)$ or $(a, b)$, can be extracted from the data by fitting the hyperbolic model using least squares. The $L_2$ norm is

$$L_2 = \left[ \sum_i \left[ F_i^{(measured)} - F_i^{(estimated)} \right]^2 \right]^{1/2} \tag{4}$$

Fitted lines are shown together with the measured data in Fig. 5. Both the $A$ parameter (flow at 25 drops) and the $B$ parameter (initial flow rate) increase with the mass fraction of OS. Furthermore, there is a positive correlation between $A$ and $B$, as shown in Fig. 6.

The $A-B$ correlation suggests the possibility of a single-parameter hyperbolic model. Furthermore, note that the height of mortar piles converges towards a low asymptotic value as the drop number increases. The associated flow value is extracted from a formal inversion analysis based on the $L_2$ norm. The computed value is $\approx 200\%$ (Fig. 7). Then, the hyperbolic model can be written as a function of a single parameter, the initial flow rate $B = 1/b$, and Eq. (1) becomes

$$F_i = \frac{i}{0.5i + b} \tag{5}$$

When this equation is fitted to the data, the trends are indistinguishable from those shown in Fig. 5.

ANALYTICAL INVESTIGATION

As the number of drops increases, the height of the pile decreases; therefore, the potential energy $E_p$ decreases as well. The potential energy lost at the i-th drop $(E_p)_i$ is spent in deforming the mortar pile $E_{deform}$ and spreading it against
the interfacial shear at the base $E_{\text{base shear}}$. The energy balance for the $i$-th drop is

$$ (E_p)_i = (E_{\text{deform}})_i + (E_{\text{base shear}})_i $$ \hspace{1cm} (6) $$

It is assumed herein that: 1) wet mixtures preserve volume; 2) the energy spent in deforming the mortar pile $E_{\text{deform}}$ is linearly proportional to the incremental global deviatoric strain; and 3) the interfacial shear energy $E_{\text{base shear}}$ between a unit area of the deformed mortar pile and the flow table surface is linearly proportional to the incremental radial spread (refer to Fig. 8). Then, each energy component becomes

$$ (E_p)_i = w(h_d + \frac{h_{i-1} - h_i}{2}) = V_0 \gamma \int_0^R \left[ h_d + \frac{V_0}{2\pi} \left( \frac{1}{R_{i-1}^2} - \frac{1}{R_i^2} \right) \right] V_0 $$ \hspace{1cm} (7) $$

$$ (E_{\text{deform}})_i = \int_0 V_0 \left[ \tau_0 \cdot \frac{2}{3} (v_h - \epsilon_r) \right] dV = \tau_0 \cdot \left( \frac{R_i^2 - R_{i-1}^2}{R_i^2} \right) V_0 $$ \hspace{1cm} (8) $$

(for $\epsilon_{\text{vol}} = 0$, $\epsilon_r = -0.5 \epsilon_h$)

where $w$ is the weight of the cement mortar pile, $h_d$ is the drop height of the flow table, $h_i$ and $R_i$ are the height and radius of the mortar pile after the $i$-th drop, $\gamma$ is the unit weight of the mortar, $V_0$ is the volume of the mortar pile, $\tau_0$ is the shear resistance of the mortar, $\tau_{bs}$ is the base shear resistance between the mortar pile and the flow table, and $\delta_i(r)$ is the incremental spread of the mortar pile at a radial distance $r$ during the $i$-th drop. The implicit solution of the mortar spread $R_i$ in terms of parameters $\tau_0$ and $\tau_{bs}$ is obtained by substituting Eq. (7) through (9) into Eq. (6)

$$ (E_{\text{base shear}})_i = \int \tau_{bs} \delta_i(r) dA $$

$$ = \tau_{bs} \int_0^R \int_0^{2\pi} \left[ \left( \frac{R_i}{R_{i-1}} - 1 \right) \cdot r \right] d\theta \cdot dr $$

$$ = \frac{2}{3} \pi \cdot \tau_{bs} \cdot \left( \frac{R_i}{R_{i-1}} - 1 \right) \cdot R_i^3 $$ \hspace{1cm} (9) $$

Fig. 8—Schematic diagram of mortar pile flow between two consecutive drops $i - 1$ and $i$.

Fig. 9—Flow versus drop number—energy-based model predictions. Points are measured data. Lines show fitted energy model. Numbers indicate mass ratio between Ottawa sand and crushed granite sand.

Fig. 10—Energy-based model—fitted model parameters $\tau_0$ and $\tau_{bs}$. (Note: 1 kPa = 0.145 psi.)

Fig. 11—Correlation between yield stress $\tau_0$ and base shear resistance $\tau_{bs}$. (Note: 1 kPa = 0.145 psi.)
Figure 9 shows the flow-versus-drop trends of all mixtures and the fitted energy model. The fitted model parameters in each case, $\tau_0$ and $\tau_{bs}$, are plotted versus the mass fraction of round particles (that is, OS) in Fig. 10. The two parameters are affected by the mass fraction of round particles $M_{OS}$ as discussed previously: the presence of round particles decreases the resistance to flow when $M_{OS} < 0.5$ and determines flow when $M_{OS} > 0.5$. The apparent correlation between $\tau_0$ and $\tau_{bs}$ observed in Fig. 10 is confirmed in Fig. 11. The fitted trend is

$$
\tau_{bs} = 5.16 \left( \frac{\tau_0}{1 \text{kPa}} \right)^{0.44} \text{[kPa]}
$$

Once again, a single controlling parameter becomes apparent; in this case it is the mortar shear resistance $\tau_0$. The flowability of mortar is controlled by its shear resistance at the given shear rate. Data presented herein show that shear resistance is in part due to frictional losses at particle contacts. Viscous losses may be involved as well; however, the relative contributions cannot be inferred from flow test data alone. It has been shown that the interaction between cement paste and aggregates governs the rate-dependent viscous dissipation (Larrard 1999; Tattersall and Banfill 1983): the presence of rigid particles produces higher shear rate within the cement paste, and increases the viscous dissipation. From this perspective, angular sands have higher specific surface and promote greater interfacial resistance.

On the other hand, angular particles yield a looser packing density (that is, higher $e_{max}$) and higher frictional resistance (Fig. 2). Both packing and frictional effects lead to lower flow for the same volume ratio of $V_{aggregate}$ to $V_{paste}$ as particle angularity increases (Fig. 5). This contributes to the strong effect of particle shape on the rheology of mortar (Tattersall 1991). Conversely, more paste is required to keep angular particles apart to decrease their interaction and increase flow.

**CONCLUSIONS**

The detailed experimental and analytical study of the flow test permits extracting the following conclusions:

- There is a nonlinear relationship between flow $F_i$ and drop number $i$. A single parameter hyperbolic equation adequately fits measured data;
- An energy-based physical model explains the relative contribution of internal energy loss in shear and base shear along the mortar-surface interface. The two model parameters, mortar shear resistance $\tau_0$, and mortar-to-base shear resistance $\tau_{bs}$, are correlated suggesting internal shear as a single loss mechanism;
- Flow reflects the packing characteristics and the frictional resistance of the fine aggregate. Both are affected by particle shape. In particular, crushed angular aggregates yield loose packing density and high friction. Hence, more paste is required to keep angular particles apart and to attain adequate flow;
- The presence of round particles controls flow when the mass fraction of round particles exceeds 30 to 50%.

**ACKNOWLEDGMENTS**

This research is supported by a grant from the Georgia Department of Transportation and Georgia Crushed Stone Association. Additional support was provided by the Goizueta Foundation.

**REFERENCES**


