WORKABILITY OF MORTARS WITH BUILDING LIME:

ASSESSMENT BY A PANEL OF MASONS VERSUS LAB TESTING

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SUMMARY

The workability of mortar is best assessed by the mason's feeling when using a trowel or his hands. As a first step towards quantifying workability, a panel of masons was invited to the lab to assess mortars with 7 different types of binder. Their findings allow to identify the most important aspects of workability: yield stress, water retention, density and adhesion to bricks. The results of the masons were compared to lab results on reference composition with a water content equal to the average of the practical tests. Each mortar was tested using procedures based on European standards and with a vane apparatus measuring yield stress.

INTRODUCTION

Workability of fresh mortar is the sum of the application properties which provide its suitability, whether for masonry purposes, plastering or jointing. Several authors and normalising institutions published lists of these properties in varying order of importance (ASTM 2004, Kampff 1961 and RILEM 1978). Recent literature about the rheology of mortar has focused mainly on concrete mortar, which is much more fluid than masonry mortar. The methods used are rotational rheometry, compressive rheometry (squeeze tests), slump tests and alternative methods like the rotating ball method or a trowel-imitating method (Banfill 2006). Standardised methods are available to measure consistence, plasticity, water retention, air content, etc.. Most of the consistence tests provide a measure of spread or slump, or penetration depth of a falling object. Their drawback when compared to the rheological tests is that they are not directly related to the fundamental physical properties of the material. The practical difficulties in designing suitable measuring methods for masonry mortar are: poor reproducibility due to variations in components

and preparation, important sensitivity to deformation history (thixotropy), and slip and plug flow in standard test geometries. The method with the lab vane apparatus used here to measure yield stress, has recently been demonstrated to be fit for use on mortars (Bauer et al. 2007) and pastes (Hendrickx et al. 2006), although some drawbacks and difficulties in interpretation of the results remain.

Assessing measuring methods is possible by comparing results to the findings of experienced practitioners. An experimental programme in the framework of a RILEM committee TC13-MR on mortars involving 5 masons led to the conclusion that (1) all craftsmen were able to attain the desired consistence independently of the (dry) mix composition, (2) each craftsman has an individual ideal consistence, (3) all known test methods are inferior to the craftsmen's judgement and some are not suited for mortars made with specific binders (RILEM 1978). It has been shown that the often used flow table test yields contradictory results for cement mortars and lime mortars (Van Balen and Van Gemert 1991). The addition of lime is reported to have an important influence on workability (Van Balen and Van Gemert 1990).

MATERIALS AND METHODS

The selected binders include a wide variety of lime-based binders and an ordinary Portland cement (Table 1). The units are fired clay bricks of three different sizes, two of which are perforated (Table 2). Binder 7 is used in 2 subsets of mortars with a different dosage of the air entrainer: 0.4% of the binder weight in 7a and 0.1% of the binder weight in 7b. The plasticizer is added at 0.5% of the binder weight. The chemical analysis (XRF) the specific surface area (B.E.T.) and porosity (B.J.H.) are listed in Table 3. The particle size distribution was measured by laser granulometry (Coulter LS230) (Figure 1).

Table 1. Description of binders

N°	Description	Binder dosage (kg/m³)
1	calcic lime CL90S (EN 459-1:2001)	180
2	calcic lime CL90S (75%) with hydraulic binder (15%) and pozzolana (10%)	280
3	calcic lime CL90S (EN 459-1:2001) with air entraining agent	180
4	calcic lime CL90S (EN 459-1:2001) (66.7%) and ordinary Portland cement CEM I 42.5 R (33.3%)	300
5	natural hydraulic lime NHL 5 (EN 459-1:2001)	300
6	ordinary Portland cement CEM I 42.5 R	350
7	ordinary Portland cement CEM I 42.5 R with commercial additives: plasticizer Rheomix 359 and air entraining agent Micro-air 100 (BASF)	350

Table 2. Dimensions of masonry units

Unit type	L (cm)	D (cm)	H (cm)	Commercial name and producer
Facing brick	19	9	5	Mono 3009, Vandemoortel (B)
Small perforated brick	29	14	19	Porotherm, Wienerberger (B)
Large perforated brick	37.3	30	24	Poroton Plan-T 14-30,0; Wienerberger (G)

Table 3. Chemical and physical properties of binders (binder 7 = identical to 6)

	1	2	3	4	5	6
	CL90S	CL90S + PZ + HB +AEA	CL90S + AEA	CL90S + CEM I 42.5 R	NHL 5	CEM I 42.5 R
CaO (%)	96.6	75.1	96.3	75.6	51.2	63
MgO (%)	0.94	1.88	1.05	1.49	1.68	1.74
Al_2O_3 (%)	0.059	1.640	0.072	2.6	4.9	4.6
SiO_2	0.144	6.2	0.19	9.6	16.6	16.7
Fe_2O_3 (%)	0.048	1.55	0.063	2.7	2.1	3.6
CO_2 (%)	2.0	10.6	2.0	3.0	19.8	2.9
SO_3 (%)	0.10	1.84	0.18	2.80	2.10	4.50
SSA (BET) (m^2/g)	12.0	5.7	11.9	4.5	3.5	1.3
Porous volume between 100 and 300 A° (cm^3/g)	0.025	0.008	0.024	0.008	0.005	0.004
Porous volume between 17 and 100 nm (cm^3/g)	0.063	0.025	0.065	0.023	0.015	0.001
Av. pore diameter (A°)	177	156	189	172	142	124

Two types of aggregate are used: a standardised (EN 196-1) sand 0/2 and a siliceous quarry sand 0/0.5 (0/1) (EN 13139:2002), a so-called “Lommel” type of sand from a quarry in Zutendaal, Belgium (Figure 2).

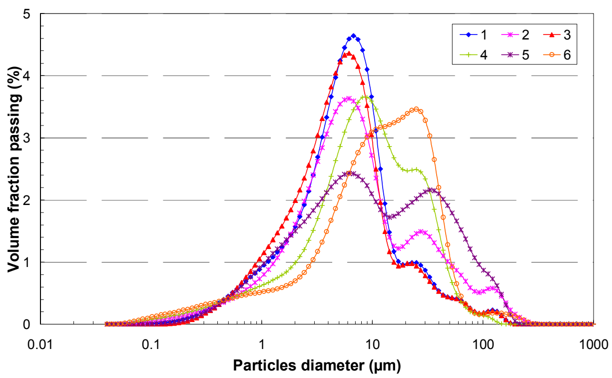

Figure 1. Particle size distribution of binders measured by Coulter counter

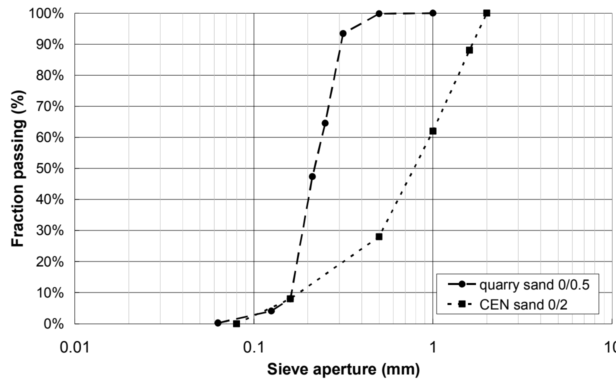

Figure 2. Grain size distribution of aggregate (EN 933-1:1997)

The masons in the panel all have at least 5 years of experience with mortars containing lime. The panel is composed of three nationalities: Dutch (1), French (1) and Belgian (4).

In the first section of the programme, with quarry sand, the binder to aggregate ratios (B:A) are fixed, and the water to binder ratios (W:B) are left free for the masons. All ratios are given in mass proportions. The B:A are derived from a practice-based reference for amounts of binder weight for 1m³ of dry aggregate and the measured bulk densities (Table 1 and 5). Batches of approximately 35 litres are mixed in a floor-model Hobart mixer type M80. Approximately 75% of the estimated needed water quantity is poured in the bowl, then half of the aggregate, the binder, and the other half of the aggregate are added. Mixing is done at low speed, while water is added by the mason, until the water content and homogeneity are optimal. The amount of added water is weighed and the consistence of each composition is measured immediately by plunger penetration (EN 459-2:2001). Each batch is tested on all three brick types: both types of perforated bricks are used to add three bricks to a single-leaf wallet, and the facing brick is used

to produce small columns of eight layers of three bricks in alternating bond. The masons are continuously interviewed and filmed during the procedure.

Reference compositions for lab experiments with the quarry sand are calculated by taking the average of the W:B chosen by the masons. They are tested for flow (prEN 1015-3:1998), plunger penetration (prEN 1015-4:1998), bulk density and air content (EN 459-2:2001). The mixing procedure is not standardised, but attempts to approximate the procedure from the masons' programme (see above), using a table model Hobart mixer: 1.5 min mixing, 0.5 min scraping and homogenising, 2 min mixing. All mixing is done at low speed.

In the second section, with standardised sand, W:B and B:A are free to choose for the mason for composition of small batches (1.2 liter). Lab experiments with average values for W:B and B:A from these tests sometimes yield visibly unworkable mortars. Hence it was decided to discard them from the lab experimental programme described below.

Yield stress is measured with a vane apparatus for clayey soil according to ASTM D 4648-87 (ASTM 1987). It measures the torque necessary for a cross-shaped vane (DxH), immersed in a sample container with mortar, to initiate rotation. Shearing is assumed to occur in the cylindrical surface surrounding the vane (Lidell and Boger 1996). All mortars are measured with a spring with spring constant B=380°/Nm, except binder 4, for which a vane with B=260°/Nm is used. The vane has dimensions D=H=4.5cm. Rotation speed ω is constant and equal to 9.2°/min. The test is done at 3 min, 26 min and 56 min after the end of the mixing procedure (which takes 4 min). A reasonable reproducibility is reached (variation within 5%) when the procedure is kept constant. The reversibility of the thickening or stiffening is measured by remixing the mortar after each test for 2 min at low speed and then doing a second test. This procedure gives two results for each couple of tests: an unsheared and a pre-sheared yield stress value. The results for mortar with binder 2 were not reliable because the time-dependent effect of the of the air entraining agent complicates the measurement, and are not reported. For binder 7, only the lower dosage of air entraining agent (binder 7b) is tested.

Water retention is tested in three different procedures: using filter plates (EN 459-2:2001), filter paper (EN 413-2:2005) and an adapted method with vacuum suction of the specimen. The latter method uses the setup of ASTM C91 in an alternative procedure: a vacuum of 61+/-8 mbar is applied to the mortar during 15 minutes and the water retention value is the percentage of water in the mortar that is not lost by suction. This procedure is comparable – apart from a different pressure – to a directive of the french institution CSTB (Sébaïbi 2003).

EXPERIMENTAL RESULTS

Composition and workability appreciation

In the first section of the programme (fixed B:A), the selected W:B values for mortars with each binder have a coefficient of variation of 3% to 10% between the different masons for one specific binder (Figure 3). A systematic difference between some of the masons is observed. A correlation

between W:B and the specific surface area of the binder is found. Air entrained mortars have lower values than non air entrained mortars (Figure 4).

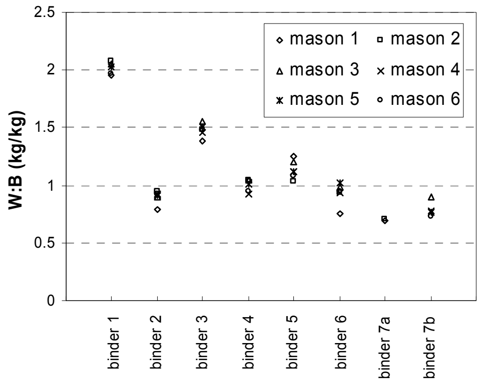

Figure 3. W:B selected by masons for fixed B:A (section 1)

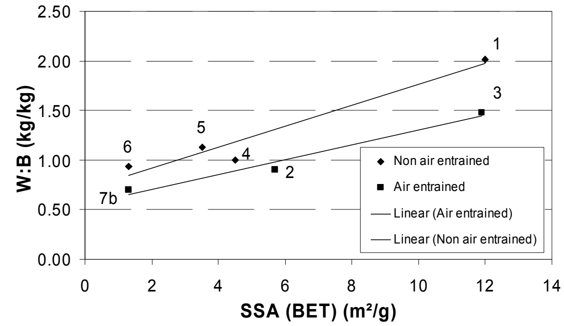

Figure 4. average W:B (section 1) as a function of SSA of binder

The same trend in W:B is found in the second section of the programme, although with larger variation due to the varying B:A for each composition. The average selected B:A are between 0.15 and 0.2 for binders 1, 2 and 3; between 0.2 and 0.3 for binders 4, 5, 7a and 7b, and 0.4 for binder 6. The latter value is very high: it appears that the test persons added a high quantity of the ordinary Portland cement because a normal dosage gives an impression of being poor in binder.

The qualitative judgement of different mortars is similar for all the masons and is summarised in Table 4. Comments on the mortar with binders 7a and 7b are comparable and are taken together. Binder 7a and 7b come out of the test as the best for workability, followed by binder 3, 1 and 4 in varying order. Binder 5 and 6 were unacceptable because of poor water retention. Binder 2 has an important problem with the air entraining agent, which causes swelling and subsequent shrinkage of the mortar during mixing and in the first 10 minutes after mixing. The same problem is present in binder 3 to a lesser extent. The remarks depend on the type of brick used. For the small and large perforated bricks, it is judged important that the mortar adheres well to the vertical sides, that it does not fall into the perforations and that it allows a large unit to be manipulated in the mortar bed without too much force. For the small facing bricks, staining and floating of bricks are more important criteria. Floating must be understood as instability due to lack of stiffening of the mortar, which should occur upon dewatering in contact with the porous brick.

An inquiry about the relative importance that the masons of the test panel attribute to different properties of mortar (in fresh and hardened state), reveals three major concerns: workable time, adhesion to brick and workability. Mechanical resistance and yield are also considered important. Cost, thermal insulation, frost resistance and environmental nuisance have low appreciation.

Table 4. Mortar assessment by masons from questioning during work

Binder	Positive remarks	Negative remarks
1 CL 90	stable – doesn't stain brick – workable, even when a bit harsh – sticks well to brick – no quick stiffening	heavy – hard for wrist
2 CL90 + PZ + HB + AEA	light – easy to manipulate	doesn't stick to brick – sticks to trowel – bricks floating – stains the brick – dries fast – falls in voids of perforated bricks – hard to throw into joints – bleeds during pointing
3 CL 90 + AEA	smooth – light – spreads easily – stable	doesn't stick to brick – sticks to trowel (but less than binder 2) – bricks floating – stains the brick – hard to throw into joints – stays too soft after application
4 CL 90 + CEM I 42.5 R	sticks quite well to brick – quite stable	heavy for wrist – works slower than binder 2 and 3 – bricks floating – bleeds while pointing
5 NHL 5	no staining – correct for use with facing brick (less absorbing)	strong bleeding – not stable – stiffens too fast (water sucked out) – harsh – heavy – doesn't stick to brick –poor in binder – bleeds while pointing
6 CEM I 42.5 R	correct for use with facing brick (less absorbing) – gives stable masonry	strong bleeding – not stable – stiffens too fast (water sucked out) – harsh – bleeds while pointing
7a - 7b CEM I 42.5 R + SP + AEA	sticks to brick – spreads easily – easy to position brick – stable	not ideal for pointing – slight bleeding

Scientific assessment of workability

The results of the vane test are represented as a function of the actual time when yielding occurs, to take into account the duration of the test, which is often 10 min or more. The values range from 20 tot 80 Pa shortly after mixing, and rise above 100 Pa after 1 hour (Figure 5 and 6). A different behaviour is again observed for air entrained mortars (15 to 30 % air content) and non air entrained mortars (3 to 7 % air content) (Table 5). In the first group the increase of yield stress is limited during the first half hour of resting time, and becomes more important during the second half hour. The second group shows an adverse effect, with a large increase in the early stage and a smaller increase after 40 min. In both groups a large drop of yield stress is obtained by pre-shearing the mortar. This means that only a fraction of the stiffening is irreversible. For comparison of the different mortars, yield stress values at 30 and 60 min of resting time were calculated by linear interpolation (Table 5). It has to be stressed that these values are valid only for the (relatively low) rotation rate in this setup. Strictly speaking, this method is neither rate controlled, nor exactly stress controlled. Important theoretical and practical considerations on this subject are published elsewhere (Lidell and Boger 1996).

The flow and plunger penetration value of the lab mortars are listed together with other properties in Table 5. The difference in flow can be explained by the different densities, because gravity is the driving force in the flow table test. If we assume that masons prefer mortars with a specific yield stress, this implies that a heavier mortar will have a higher flow value. The plunger penetration value is equal to 2.0 +/- 0.2 cm, except for the mortar with binder 2. This value is

clearly more independent of the density and may therefore be a more suitable reference measuring method. The water retention measured with filter plates (WRV 1) and measured with vacuum suction (WRV 3) have a reasonable correlation (Table 5). Both methods discriminate the mortars in a way that corresponds to the findings of the test panel (Table 4). The method with filter paper (WRV 2) yields very different results. During these tests problems were observed of poor contact between the 9 individual sheets of absorbing paper used. The water retention shows an increasing trend as a function of the specific surface area of the binder (Table 3 and 5). The air entrained mortars yield higher values than the corresponding non air entrained mortars.

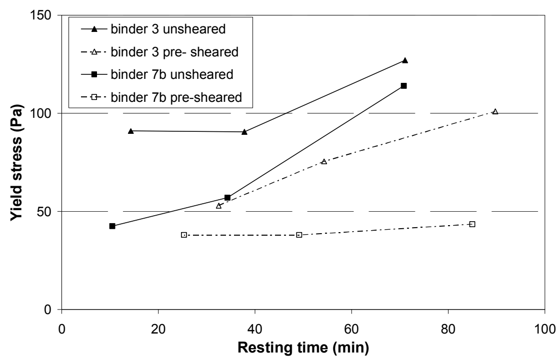

Figure 5. Yield stress unsheared and pre-sheared for air entrained mortars

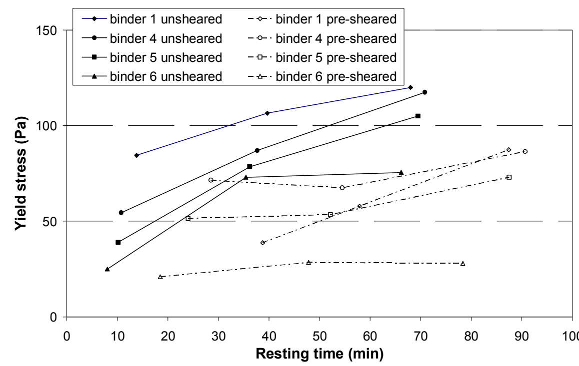

Figure 6. Yield stress unsheared and pre-sheared for non air entrained mortars

Table 5. Results of laboratory experiments on mortars

	1	2	3	4	5	6	7a	7b
	CL 90	CL90 + PZ + HB	CL 90 + AEA	CL 90 + CEM I 42.5 R	NHL 5	CEM I 42.5 R	CEM I 42.5 R + SP + AEA	CEM I 42.5 R + SP + AEA
W:B (kg/kg)	2.02	0.90	1.48	1.00	1.13	0.93	0.70	0.79
B:A (kg/kg)	0.13	0.20	0.13	0.21	0.21	0.25	0.25	0.25
Flow (mm)	139	128	130	134	147	143	-	149
Plunger pen. (cm)	1.8	1.3	2.2	1.9	2.1	2.0	-	2.2
Bulk density (kg/m³)	1908	1383	1519	1966	1971	2009	1741	1746
Air content (%)	3.5	27.8	21.0	6.4	6.0	6.6	16.3	15.8
WRV 1 (%)	83	93	92	81	66	63	-	78
WRV 2 (%)	93	94	95	93	85	87	-	88
WRV 3 (%)	85	82	88	86	66	66	-	75
$\tau_{0\ vane}$, t=30 (Pa)	98	-	91	78	69	64	-	54
$\tau_{0\ vane}$, t=60 (Pa)	116	-	115	108	97	75	-	97

DISCUSSION

From the results presented in Table 4 and 5, we can identify the most important aspects of workability. The two major groups of properties are the rheological properties and the water retention properties. Rheology embraces ease of spreading, flow ability, plasticity, stiffening or thickening, etc.. Water retention is the governing mechanism for bleeding, inhomogeneity and

water loss in contact with the brick. The other important properties are density and adhesion to bricks.

Masonry mortar is a plastic material and is often described rheologically by the well-known Bingham model, which uses two parameters to express shear stress (and thus, the viscosity) as a function of shear rate: yield stress τ_0 and plastic viscosity μ.

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

Literature gives values for mortar from 80 to 400 Pa for τ_0 and from 1 to 3 Pa·s for μ (Banfill 2006). Apart from the practical difficulties to realise a laminar flow in order to measure these parameters, equation 1 is not sufficient to describe the clearly time-dependent behaviour. At most, it can be used to describe the behaviour at constant structure in the framework of a model which involves also an expression for the evolution of that structure as a function of time and shear history, e.g. a structural kinetics model, as has been used successfully for sludge (Toorman 1997).

Our approach is to focus on the static yield stress, i.e. the stress which has to be overcome to initiate flow, as the most important parameter for practice, and to evaluate its evolution as a function of resting time. Yield stress quantifies the ease to spread and shape the mortar bed, the pressure needed to push the brick in place and the ability of the joint to remain stable under working pressure. With measures at different times after mixing, we also obtain an indication on stiffening behaviour and thus on the workable time. This static yield stress is opposed to the dynamic yield stress, which is a measure for the stress when flow stops, and which is not considered here (Wallevik 2003).

From the practical point of view, the observed stiffening is a negative effect and the mortar with the most constant yield stress over the workable time or board life, is preferable. The different behaviour of the air entrained mortar can maybe partly be explained by the phenomenon of bleeding. The non air entrained mortars have in general a lower water retention capacity (Table 5), which caused significant bleeding. This bleeding has typically a large increase in the first half hour, and then tends towards an equilibrium (Van Balen and Van Gemert 1991). This may indicate that the larger initial increase in yield stress of these mortars is due to a densification of the bulk material around the vane. The mortar with binder 1 is an exception to this principle, with a high water retention even without entrained air.

SYNTHESIS AND CONCLUSIONS

The variance in chosen W:B between the different masons in practical tests is small. This indicates that a marked transition in the mortar's behaviour takes place around a specific water content: from a granular material to a liquid material, from a frictional regime to a viscous regime. Small variations of water content around this transition point, give a very different mortar for the user.

This article proposes a combination of yield stress measurement with a vane apparatus, water retention tests with vacuum suction or filter plates, and density and air content tests to

characterise the workability of a mortar in detail. It has been shown that entrained air has an important positive influence on the necessary water content and on the water retention, although an air entrainer with a variable effect in time can also cause problems. The specific surface area is an important characteristic of the binder: a higher value gives higher W:B, water retention and yield stress. The important differences between lime-based and cement-based mortars can be explained by this relation. The natural hydraulic lime (binder 5) used in this programme does not overcome the problems of the Portland cement (binder 6) with regard to water retention. The performance of the cement is improved by replacing 1/3 of the weight by lime (binder 4) or by adding admixtures (binder 7a and 7b). Another problem of ordinary Portland cement, is that the subjective optimum B:A for masons is clearly too high, which may have consequences for the final mechanical properties as well as for cost.

The yield stress measurements with the vane allow to compare the differences between the mortars for the chosen test conditions. The influence of the different test parameters remains to be quantified. All mortars are thickening in time. Their yield stress increases due to flocculation of the binder particles. This thickening, which occurs before the second stage of hydration of the hydraulic binders, is mostly reversible but partly also irreversible. Further rheological research is needed to provide the basis for modelling this behaviour.

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