Acknowledgement: This paper was first presented at the 9th International Masonry Conference at Guimaraes, Portugal on 7-9 July 2014, and is published by permission of the International Masonry Society (www.masonry.org.uk)

Do binder types have influence on the interpretation of measured workability?

KOENRAAD VAN BALEN[1], ROEL HENDRICKX[2], BERNHARD MIDDENDORF[3], DEBORAH BECKER-KLEIN[4]

ABSTRACT: There is a need for an encompassing model and test procedure that is closer to the reality of workability and takes on board the required properties of fresh mortar, independently from the type of binders. Packing and rheology as well as ways in dealing with water in the matrix define workability. Parameters that define fresh mortar properties and workability are water demand, water retention, air content, cohesion, volume yield, flexibility and time of board life are described. Workability is an important measure of fresh mortar to define mortar composition made out of a granular structure with water. Using workability as defined by practitioners as a starting point, existing (standardized) tests used to define workability have been investigated. Based on a theoretical model that embeds behaviour of granular solids and water, including transfer mechanisms of water increased insight was gained and a possible alternative test has been proposed. The amount of water in fresh mortar has implications on the porosity and pore system of the hardened mortar, including all bulk mechanical properties that relate with that.

Keywords: mortar, workability, standardised test, lime

1 INTRODUCTION

One of the most important properties of plastic mortar is its workability. Workability will depend on the type of application (bedding mortar, pointing mortar, render, …) and is often adapted to the (subjective) needs of people using the mortar (masons).

The amount of water is often regulating the “workability” of the mortar, satisfying or dissatisfying masons’ expectation. Water fraction will define the properties and property changes in (short and long) term of the fresh mortar and eventually the properties and properties changes of the hardened mortar.

When the amount of mortar in mortar samples is given (e.g. in standards) through a measured “workability” test, the resulting water fraction will have an influence on the fresh and hardened mortar properties measured. This shouldn’t be a problem if a workability test exist that is able to define objectively “workability” for each type of mortar; however this is not the case. Results in the use of

[1] Professor; KU Leuven, Dept. Civil Engineering, Koenraad.vanbalen@bwk.kuleuven.be
[2] Project engineer conservation, Royal Institute for Cultural Heritage, roel.hendrickx@kikirpa.be
[3] Professor, University Kassel, Department of Construction Materials and Building Chemistry, middendorf@uni-kassel.de
[4] Technische Universität Dortmund, deborah.klein@tu-dortmund.de,

standardized tests that are related to aspects of “workability” are not independent from binder types, from mixing procedures and from application practices.

The article aims at clarifying the need for an encompassing model and test procedure that is closer to the reality of workability and takes on board the required properties of fresh mortar, independently from the type of binders. Packing and rheology as well as ways in dealing with water in the matrix define workability.

2 FRESH MORTAR PROPERTIES AND THEIR IMPACT ON RESULTING HARDENED MORTAR PROPERTIES.

Workability, water demand, water retention, air content, cohesion, volume yield, flexibility and time of board life are properties that are considered of importance for fresh mortar by applicants. These properties and the impact the use of lime as a binder is given.

2.1. Defining workability

Workability is defined by the ease of the application of fresh mortar and depends on the type of application. It is primarily defined by the craftsman, however various testing procedures have been developed to attempt quantifying this property.

The definition of workability is addressed in various texts, which are often owing to the work of standardizing institutions or specialized committees. The non-mandatory appendix to ASTM standard C 270-04a provides a good basis for a definition: “Workability is the most important property of plastic mortar. Workable mortar can be spread easily with a trowel into the separations and crevices of the masonry unit. Workable mortar also supports the weight of the masonry units when placed and facilitates alignment. It adheres to vertical masonry surfaces and readily extrudes from the mortar joints when the mason applies pressure to bring the unit into alignment. Workability is a combination of several properties, including plasticity, consistency, cohesion, and adhesion, which have defied exact laboratory measurement. The mason can best assess workability observing the response of the mortar to the trowel.” And further: “The capacity of a masonry mortar to retain satisfactory workability under the influence of masonry unit suction and evaporation rate depends on the water retentivity and setting characteristics of the mortar [1].” In the same philosophy Kampff identifies six properties controlling workability: consistency, water retention, time of set, weight, adhesion and penetrability [2]. Problems arise however when vague concepts like consistency and plasticity have to be assessed in detail.

A RILEM committee distinguished workability, consistence and plasticity as follows: “Consistence is that property of a mortar by virtue of which it tends to resist deformation; plasticity is that property of a mortar by virtue of which it tends to retain its deformation after the reduction of the deforming stress to its yield” [3] . And workability is defined as a combination of factors which determines the ability of the mason to do his work. An experimental program by that same RILEM committee 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 judgment and some are not suited for mortars made with specific binders.

In a recent study [4] [5] masons from Belgium, France and The Netherlands, were interviewed and were asked to define workability. According to them workability of mortar depended on:

Whether mortar sticks to the brick: the mortar should adhere well to the bricks: to the underlying brick as well as to the sides of the adjacent brick and to the brick which is put in place. The work is much easier if a mortar sticks and holds to a vertical brick face: the mortar for a vertical joint is either thrown against or smeared on the brick already in position, or smeared to the side plane of the brick which is to be put in place. A third possibility is that the new brick is used to push up the mortar against the adjacent brick which is already in place, in one single movement with the positioning of the brick. Alternatively, the vertical joint will have to be filled up from the top after placing the bricks, which takes much more work and is not always evident. This concern is included in the non-mandatory appendix to ASTM standard C 270-04a (see supra).

Whether mortar sticks to the trowel: the mason stirs the mortar in the tub and takes up an accurately estimated quantity of material with his trowel. Stirring is harder when the mortar adheres strongly to the trowel. Ideally he can make a “thick sausage” of mortar on the trowel, of appropriate size, which is cohesive on itself but does not stick to the trowel. Transfer to the masonry is generally done by throwing, or by scooping when larger quantities are necessary. It is believed that throwing with a certain speed results in good adhesion. This throwing or scooping is complicated when the mortar does not release the trowel easily. This problem also plays a role when the mortar is spread or smeared: it should remain cohesive and stick to the brick, but not to the trowel. This phenomenon is evidently related to density, as a heavier mortar will easier drop off a metal blade, while a light mousse-like paste will tend to be stickier, even when the contact surface is smaller.

Whether mortar is light or heavy: Lighter mortar makes stirring and application to the bricks easier. The energy necessary for transfer of a lower mass decreases with lower mass. Some masons experience problems of the wrist due to the heavy and recurrent loads. Other physical problems masons testified about, were injuries of back and knees, both evidently related to the position during work, but also to the density of the mortar.

Whether mortar is easy to spread on the units, shaping the bedding mortar: spreading is done with the trowel under a certain angle, either in a continuous motion (covering the whole brick with the same thickness) or in an up-and-down going motion (leaving an uneven mortar bed). The action is a combination of squeeze flow and laminar shear flow. In both cases the quantity of mortar is estimated to obtain a good filling of the bed joint when the new brick is pushed into position. The force needed is related to the yield stress and viscosity of the mixture and depends on the speed of the trowel movement. The shear resistance of the mortar is also related to the applied normal force, with the ratio between normal stress and shear stress depending on the trowel angle. This resistance should not be too high. This concern is included in the non-mandatory appendix to ASTM standard C 270-04a (see supra).

Whether mortar is easily squeezed: depending on the way of working, the brick is placed in a purely vertical motion, squeezing out the mortar laterally, or in a combined horizontal and vertical motion. The latter is the most applied technique and can be done in a continuous or a left-and-right motion. The mortar is squeezed at a speed which is usually decreasing. Resistance against squeezing increases with decreasing distance between the brick surfaces and with increasing velocity. Excess mortar can be extruded at two or more sides in an asymmetrical way, and is usually immediately removed with the trowel. The mortar’s resistance to extrusion should not be too small, to avoid instability of the next courses, but also not too large, which is hard for the mason. This concern is included in the non-mandatory appendix to ASTM standard C 270-04a (see supra).

Whether mortar stiffens (too) fast due to water loss: the porous bricks exert capillary suction on the mortar, causing a water flow from mortar to brick. The decrease of water content leads to a strong increase in the mortar’s viscosity and yield stress. This phenomenon is required to give stability to the masonry, but should not occur too fast, because it hinders the correct positioning of the brick. Placing a brick is done in a time span between 1 and 30 seconds, depending on the situation. Gaining rigidity is positive starting about 1 minute after contact with the brick. In some cases, masons prefer to apply a mortar bed for several units at once: this is only possible when the mortar does not lose too much water during 1 or more minutes. This phenomenon can be described in terms of desorption of water from the fresh mortar and concentration-dependent viscosity.

Whether mortar releases water when compressed instead of being absorbed by capillarity: Water can also be “squeezed” out of the mortar when pressure is applied. This occurs when a rather wet mortar is used for jointing and compressed with a metal tool. As long as the mixture is oversaturated with water, and water is not immediately drained, this pressure results in excess pore water pressure, driving out the water, until the solid grain skeleton can take over this stress. This effect is negative, because it complicates the correct shaping of the joint and the expelled water stains the bricks. A high permeability of the mortar makes the water seepage easier. This effect is not important when jointing is done later with another mortar.

Whether water rises in the tub: there is a water flow from the bulk of the mortar to the top, which results in a gradient in water content: liquid on top and dense, heavy mortar at the bottom. This effect is called “bleeding” in literature and it necessitates remixing by the mason, which consumes time and energy. High permeability of the mixture and high pressure gradients are the driving parameters of the problem.

Whether bricks float or swim: when shear resistance in the bulk of a bed joint is not high enough after bricklaying, bricks may slide out of position. This can happen one or several layers below the top layer and is triggered by tapping on the bricks or pressing them. High quality visible masonry is impossible when floating occurs.

Whether mortar stains the bricks: bricks are stained by a mixture of water and binder particles which runs over the surface or which permeates from the edges of the joints. The effect is worsened when the water content of the mortar is higher and the mortar has low viscosity or yield stress. The problem is prevented when the mortar is sufficiently cohesive and does not lose much liquid in contact with the brick.

Whether mortar easily fills holes or vertical joints: the mason has to be able to fill vertical joints from above, by throwing or smearing mortar, but at the same time mortar should not fall into the perforations of the bricks. Mortar is thrown into holes easier and falls easier to the bottom of the joint when it is heavier. This is more difficult to do with low density mortars. The resistance to penetrate into vertical perforations of a brick is higher when the mortar has a higher yield stress.

Whether mortar is lean or coarse versus fat, greasy or creamy: a mortar is called lean or coarse when it gives an impression of being poor in binder. The grains of sand scratch the trowel, which can be heard and felt by the mason. The opposite is a mortar which is creamy or fat, which masons relate to a higher binder content or the presence of admixtures.

Whether mortar is dry or rigid versus wet or fluid: These remarks relate to the impression of appropriate water content. Although the masons were asked to determine their ideal water content, some of the mortars gave the impression of being too rigid when used with a certain brick. This indicates that it is hard to predict the mortar’s behaviour when mixing the components.

2.2. Related fresh mortar properties.

Many of the above mentioned preferred mortar properties or behaviour related to workability also interrelate with other (standardised) fresh mortar properties as water demand, water retention, air content, cohesion, volume yield, flexibility and board life:

Water demand: Water demand for mortar is defined by the specific surface of the material and is also influenced by the mixing procedure. Longer and intense mixing procedures may result in similar workability than with short mixing procedures that are less intense with more water. When lime is added to a mortar, the fine fraction is increased and thus also the specific surface of the material.

Lime is up to four times finer than cement and fillers. This leads to a slightly increased water demand of the mortar. However the relation between that increased specific surface and fresh mortar's properties as workability is not fully understood or properly taken into account in standards.

Water retention: To avoid a too fast loss of water, which may result in poor adhesion and in the presence of insufficient water to satisfy water demand for hardening of hydraulic binders, water retention should be sufficiently high. The fine particle size, the open pore structure and high specific surface of hydrated lime improve the ability of plastic mortar to retain water. Water retention is very important when the mortar is applied to a porous material such as brick. It prevents the water to be sucked out of the mortar and the mortar being "burned". In this case, the hydraulic binder/cement has had too little water to react and has lost its binding power. Water retention enhances workability and extends board life to ensure there is enough water to fully hydrate the cement in the mortar.

Air content: Frost resistance of mortar but also workability of mortar can be increased incorporating air into the mortar matrix. Lime can deliver improved workability, thus there is less need for the use of air entrainer, which reduces the risk of over dosing air entrainer. The addition of excess air entrainer in cement mortars leads to a reduction in bond strength. Hydrated lime will give improved workability with lower air content. Giving the fact that lime hydrate has half the density of cement (500kg/m^3 versus 1000kg/m^3), at equal volumetric dosing, the weight of the mortar will reduce.

Cohesion: Cohesion of mortar facilitates the application of bedding and laying mortar; it often goes with better adhesion (in the fresh state) of the mortar to both the trowel and masonry units. Hydrated lime increases the cohesion of mortar to both the trowel and masonry units, thus reducing wastage from droppings.

Volume yield: Trials performed have shown that a lime containing mortar can lay up to 35 % more masonry units than an equivalent batch of cement sand mortar.

Flexibility: High lime content mortars are slower hardening and can be reworked over a longer time. This gives the possibility to the mason to correct for hours after the masonry has been performed.

Increased board life: Lime is improving the rheology of the mortar, the mortar stays stable without segregation and bleeding and reduces the need to remix the mortar in the tub. Lime is a natural retarder of the hydraulic binding. If no or a minor quantity of hydraulic binders are present, mortar rests of the previous working day can be remixed and reused during the next working day, reducing to a large extend the losses of mortar on the jobsite. The water fraction of mortar, independently of the way it is defined has an influence on the properties of the hardened mortar as it will define the open porosity of the mortar and all related properties. Examples of those are strength (compressive and tensile), adhesion, water uptake and durability.

3 PRINCIPLES THAT GOVERN THE WORKABILITY OF FRESH MORTAR.

A study in the nineties of the last century [7] has demonstrated that the workability of mortar is defined by the rheology and the stability of the mix containing binder, aggregates, water and possibly additives. The latter are present in minor amounts and they aim at influencing the interaction between particles in a water environment or at entraining air in the fluid mortar mixture. Therefore, the study concluded that the use of the flow-table as a measure of workability was inadequate as it neither allows a material independent evaluation of the rheological properties of mortar, nor does it take into account bleeding and water retention.

In another study on the influence of calcium hydroxide on the workability of lime based mortars [6] the tests were carried out according to ASTM [1] using the Emley plasticimeter. This test method for plasticity of lime putties takes into account the force required to lift a weight due to friction of the lime putty against a platen, reflecting the force the craftsman needs to spread the mortar. At the same time water is being sucked into a gypsum base plate, representing the surface the mortar is applied to. Furthermore, the time taken to reach failure is recorded which represents the time period of workability.

The objective plasticity values obtained in this study [6] have been verified by pilot plant experiments. The results and the rating of experienced craftsmen were in accordance with the results of the laboratory tests.

Influence of particles size:

Relative size and shape of the particles (aggregates, binder) influence the specific surface of the particles in the mixture which defines the “physical binding” (adhesion, capillary forces, …) of water to the solid mass and its stability over time. Calcium hydroxide (portlandite) is known to contribute to increasing workability of mortar mixtures. Its major contribution is defined by its high specific surface (10-50 m^2/g, and its affinity to water. Therefore the contribution of lime to workability of mortar is most pronounced when coarse types of aggregate/sand are used. The latter type of sand is often chosen in mortar depending on local availability of aggregates but also due its contribution to higher frost resistivity. Higher specific surface also leads to higher stability of the mortar mix, i.e. longer time needed to get segregation of the mix which is often named “bleeding” of mortar. Longer stability leads to higher water retention of mortar, increased board life and early deformability (or flexibility), thus leading to less losses during masonry (higher volume yield) production. Bleeding or segregation of mortar is felt as a negative factor on workability by masons as it requires them to often remix the mortar before use to overcome increase of stiffness of the mortar.

Crystal shapes and workability:

In applications of renders and finishing in which high requirements are requested on workability the flat hexagonal shape of the portlandite crystals and its easy cleavage in the packing direction shows the particular contribution of lime to workability. In that research the particular contribution of wet-slaking to workability compared to dry slaking processes has been demonstrated. Wet slaking adds to the development of a colloidal structure which is irreversible lost when the calcium hydroxide is dried as drying seems to lead to higher packing and reduces cleavage of hexagonal shape packing of the crystals. This evidences the long known understanding that slaking quick lime with more water is contributing to improving specific surface of calcium hydroxide.

Improving workability and contributing to bond at the same time

Various alternative solutions are available to improve workability of mortar. (Super-) Plasticizers can reduce the amount of water in mortar mixtures influencing the affinity of water for solids in the mix; this reduction will reduce the risk for segregation and bleeding. Air entrainers will similarly reduce the water demand of mortar mixes but will induce an increase in porosity in the hardened mortar which results in change of mechanical and physical properties. Compared to those additives the use of lime has the advantage that lime will remain present and act as a (slow contributing) binder in the mortar, while it does not increase the porosity.

High specific surface and procedures to prepare mortar mix

Binders with a high specific surface require a proper mixing procedure to keep the amount of water minimal to obtain the workability required by the mason. The use of standard tests to measure workability often leads to excess of water in lime containing mortar resulting in exaggerated porosity in the hardened mortar. This may be avoided having more appropriate mixing procedures and a better match between workability as understood by mason and testing procedures. Materials with higher specific surface require more water but it is understood that the method and time of wetting of the solid will influence the amount of water needed to obtain a defined workability or defined rheological properties.

Mixture procedures and more particularly timing therefore influence the workability properties of mortar. It is recognized traditional knowledge in masonry practices using lime or lime-cement mortar, that long mixing or remixing after a certain resting time leads to improved workability without adding water to the mortar mix as long as the hydration process has started. This is understandable as the wetting time i.e. the distribution of water on the surface of the solids needs time and/or additional energy. Earlier mentioned research had yet demonstrated that the most used workability test, the flow table test in combination with standardized mixing procedures leads to mortar with high divergence between measured values and perceived workability by professional.

The recent PhD dissertation by dr. Roel Hendrickx [4] has contributed a lot to the understanding and the quantification of the above mentioned issues. It evaluated the perspective of mason on what they considered essential in evaluating workability. From this and testing different testing procedures a definition of workability has been drafted that should improve quantifying it. After that it looked into modelling rheology and water-retention properties of mortar. From rheological experiments and modelling, the feasibility of rheological test for mortar was defined. Eventually a new workability test was proposed that aimed at being more consistent for various types of mortar taking into account criteria used by mason. The test would allow better including physical parameters that describe workability phenomena.

This research started from the lack of adequate measuring methods for the workability of masonry mortar. The study of the state of the art came to the conclusions that many standards offer interesting test methods, with relevance for practical use, but two shortcomings appear to remain problematic: 1/ many methods are inconsistent if used for different types of mortar; 2/ almost none of the methods provides physical parameters, so that the observed phenomena are difficult to explain. In other words, the level of analysis is in the first place empirical.

The best foundation for such an investigation was found to be the assessment of the workmen who deal with the material on the site. A practical test program with 6 experienced masons from 3 different countries helped to 1/ define workability, i.e. the identification of positive and negative aspects, which could be classified and related to physical parameters; 2/ observe different working methods for bricklaying, and their relation to the water dosage of the masons; 3/ establish reference compositions of mortars for use in further experiments; 4/ assess the influence of workability-related variation in water content on the mechanical strength of masonry.

The concept of “workability” is based on a combination of rheological properties, water transport properties and density. The research demonstrated that water content has an important influence on rheology, and that density, through air content, has an important impact on rheology as well. Most of the considered properties are interrelated.

In this PhD all methods for measurement and analysis for the determination of mortar workability were either created from a combination of existing concepts, either an extension of an already used concept, or entirely new concepts.

Systematic description of the composition of mortar: an extensive set of parameters and variables for fresh mortar parameters was developed, and the relations between them and the relevance of certain variables for workability were highlighted.

Method to obtain flow curves of binder slurries and mortars: the use of a mixer-type rheometer and application of selected existing theories lead to a reliable determination of flow curves, which is rare or non-existent in literature.

Mortar and slurry viscosity as a function of particle parameters was defined. A combination of the "Krieger and Dougherty law" with the "Farris law" leads to a successful description of a mortar's viscosity as a function of particle parameters. This method can be used for optimisation of mixes.

As air also contribute to workability and to density, a description of air entrapment in mortar at high solid fraction was given. The mixing of mortar from its constituents requires the presence of some air: this can be related to dilation of granular materials under shear, and has an important effect on viscosity, through a shift in maximum packing fraction.

Rheology is defined by shear strength of fresh mortar in relation to dilation and permeability. Shear strength, or maximum shear stress in a defined process, depends on many parameters including speed of applied force or displacement and normal stress. The normal stress dependence can be related to dilation and permeability. Most of these aspects were not recognized in literature.

As water transfer plays a role in stability of fresh mortar properties, diffusivity of water has been studied applying the cake filtration theory to mortar, using newly developed test methods. Cake filtration theory was used as fresh mortar behaves as oversaturated, compacted granular materials. Theoretical concepts derived in filtration literature were applied to calculate the diffusivity curve of mortars. This information was inputted in the developed "Control Volume method" including measured mortar parameters for a numerical calculation of moisture transport giving more insight than existing publications that relied on general assumptions about the mortar's properties.

Finally a prototype of a new test method with pocket vane and vacuum suction was developed and tested (see Figure 1). This new method to test workability of fresh mortar combines yield stress measurement with a (pocket) vane and desorption of mortar with a vacuum pump. It has some similarities with the Emley plasticimeter test described in the ASTM. While the Emley test is conducted on lime putties, this prototype is also applicable to testing mortars.

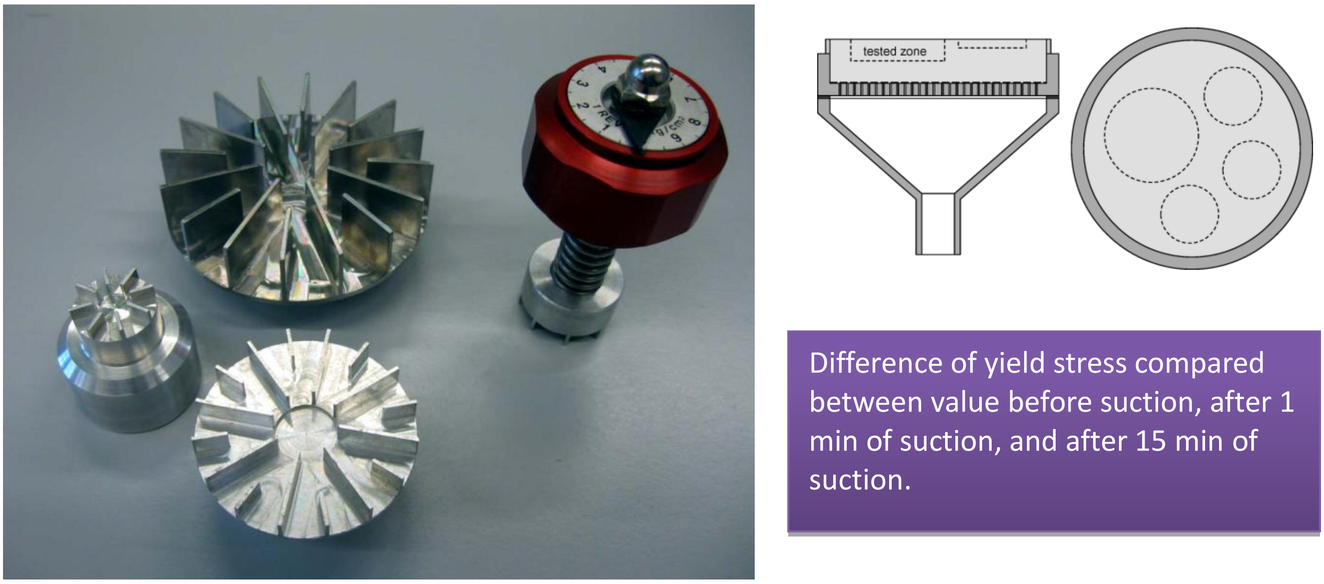

Figure 1. New test method with pocket vane and vacuum suction [4]

4 EFFECT OF LIME ON WORKABILITY.

Lime is the primary contributor to workability of cement-lime mortars. It is known from practice that hydrated lime provides good workability without the addition of excessive amounts of air entrainment additives that could negatively impact bond strength Lime preparation has an influence on the contribution of lime to the workability of mortar. However standardized workability tests that are used to define the necessary amount of water (or additives) to mortar do not reliably measure workability as it is understood by practitioners in the field, as masons.

Several authors investigated the influence of lime as a binder on the workability of mortar. Van Balen and Van Gemert [7] demonstrated the advantages of the addition of lime hydrate in cement mortars for water retention and the prevention of segregation and bleeding. A general appreciation of workability of mortar with natural hydraulic lime as a binder is given by Hanley and Pavía [8], but their measuring method is limited to the flow table. Thomson [9] and Godbey and Thomson [10] investigated different workability aspects for lime hydrate mortars: plasticity, water retention, soundness and sand carrying capacity. Green studied the effect of addition of lime specifically for water retention [11].

The contribution of lime to workability has been demonstrated. Workability improvement can be achieved while limiting the amount of air in the fresh and hardened mortar which has a positive impact on addition between hardened mortar and units.

The testing method proposed by R. Hendrickx [4] [5] is more reliable and encompassing to measure and compare workability and to demonstrate the specific contribution of lime to workability of mortar.

Water demand and water retention are related to the specific surface of the solids in the mix. The fine particle size, the open pore structure and high specific surface of hydrated lime improve the ability of plastic mortar to retain water.

This characteristic is very important when the mortar is applied to a porous material such as brick. It increases the water retention of the mortar, preventing the water to be sucked out of the mortar and the mortar being “burned”, i.e. the hydraulic binder has too little water to react and loses its binding power.

Water retention enhances workability and extends board life to ensure there is enough water to fully hydrate the cement in the mortar. Hygric properties of the material in combination with workability requirements have been investigated.

Air content plays part in understanding the workability of the mortar. The mixing of mortar from its constituents requires the presence of some air: this can be related to dilation of granular materials under shear, and has an important effect on viscosity, through a shift in maximum packing fraction.

Masons experience that adhesion of mortar with lime, considering the water amount is properly defined, to both the trowel and masonry units is higher than in case of cement mortar, which reduces unwanted loss of material in the process.

5 RECOMMENDATIONS FOR FURTHER RESEARCH AND IMPLEMENTATION.

From previous research the international community is invited to further improve research in this field. The authors see two paths to improve scientific knowledge on the influence of lime on fresh mortar properties.

Firstly, more insight should be gained to validate some of the above mentioned recent findings, which include validation of alternative testing procedures.

The needs for further research based on the study made by R. Hendrickx are manifold: newly proposed techniques should undergo a process of validation on a broader basis, and some new techniques and methods of analysis follow logically from what is presented in this thesis.

1. Determination of particle parameters for rheology can be done in solvents other than water. This should allow enhancing the stability and having more reliable results. Use with different binders and different combinations of binders may extend and correct the hypotheses.

2. A measuring method for shear stress and normal stress combined with monitoring of pore water pressure should be developed. Existing tri-axial test setups may be useful, at least as an inspiration. So far there are only hypotheses about the interaction of these parameters. Nonetheless theoretical concepts are readily available in geotechnical engineering.

3. The hypothesis of saturation of mortar throughout the process of dewatering should be checked. Probably at some point air does intrude in the mortar, and capillary effects start to work. From that moment unsaturated transport parameters should be used.

4. The interface resistance between fresh mortar and brick should be investigated more in depth. Ideally it should be linked to material parameters and implemented as an extension in the existing model code.

5. The Control Volume Method (CVM) model for water transport from mortar to brick should be refined and used to assess the consequences of different initial situations of moisture content of the materials. It could lead to important recommendations about custom mortar design for specific types of brick, or about pre-wetting of bricks. Another possible extension is to incorporate evaporation at the edges, and to extend the code to 2 dimensions.

6. The feasibility of discrete element methods (DEM) for analysis of mortars has to be explored. The importance of granular behaviour is obvious from the phenomena discussed in this thesis. As a consequence it can be possible to make meaningful models based on the different large sand grains as discrete units with some pre-defined way of interacting. Mortars with sieved sands or uni-modal glass beads can be produced to simplify the situation.

7. A suitable framework to account for the changes in the solid network, liquid flow and the relation of those phenomena to stress and deformation may be found in poro-mechanics. The feasibility of a poro-mechanical approach can be checked by making a number of assumptions, write a set of governing equations, and apply them to simple tests like the vane test or direct shear test. As it is essentially a Lagrangian coordinate system, large deformations may be difficult to treat.

In a more ambitious scope, and reasonably speaking on longer term, one can imagine more developed models. Two tracks are given as an example.

8. A numerical (poro-mechanical?) model could combine the effects of stress and deformation with the effects of water transport. CVM analysis is appropriate for liquid transport, Finite Element Model (FEM) for the deformation. In each time step an interface potential and liquid fluxes between the control volumes are determined. The local mechanical parameters are derived from the resulting moisture content, and deformation follows from those parameters and the stress tensor. It should be checked if commercial packages for soil mechanics offer good possibilities.

9. A microstructural model could go beyond the time restrictions of the research carried out and take into account that hydration and carbonation change the microstructure of the mortar. This change in the structure of the porosity causes a change in the hygric properties. The quality of hardened masonry depends on these processes. Much work has been done on the reaction

kinetics and microstructure formation at early age of hydraulic and air-hardening mortars. There is also substantial information about the development of early strength in mortars with hydraulic binders. Interesting perspectives can be opened by linking this knowledge to the knowledge of the processes in the first two hours.

Secondly, standards and standardized tests should be proposed and validated that properly reflect workability and fresh mortar properties in a similar and reliable way for different binder types and combinations of them, reflecting the point of view of the applicant. The proposed vane test in combination with a suction test is probably a good starting point as it covers the main principles that govern workability and is easy in application.

6 CONCLUSIONS

An overview has been given of the parameters that define fresh mortar properties. Workability is an important measure of fresh mortar to define mortar composition made out of a granular structure with water. Using workability as defined by practitioners as a starting point, existing (standardized) tests used to define workability have been investigated. Based on a theoretical model that embeds behaviour of granular solids and water, including transfer mechanisms of water increased insight was gained and a possible alternative test has been proposed. The amount of water in fresh mortar has implications on the porosity and pore system of the hardened mortar, including all bulk mechanical properties that relate with that. Lime with its fine granular structure and its high specific surface plays an important stabilizing role on the fresh mortar suspension, improving most of the fresh mortar properties. The same stabilising effect however complicates the correct interpretation of some of the workability tests used in standards compared to mortar containing cement.

Further research is proposed to complete past research as well as to validate and normalize the proposed test using a pocket vane in combination with a suction table.

ACKNOWLEDGEMENTS

LHOIST group is thanked for the support given to the research carried out by dr. R. Hendrickx;

REFERENCES

[1] ASTM C 270-04a Standard specification for mortar for unit masonry. West Conshohocken, 2004

[2] Kampff, L.; Workability of masonry mortars. Materials research and standards, 1.1(1961):7–8.

[3] TC MR-13 on mortars and rendering. Tentative recommendation. Materials and structures, RILEM 11(63) (1978): 207-216.

[4] Hendrickx, R., Van Balen, K. (sup.), Van Gemert, D. (sup.). The Adequate Measurement of the Workability of Masonry Mortar. Unpublished dissertation, Civil Engineering department, KU Leuven, (2009) 231 p.

[5] Hendrickx, R., Van Balen, K., Van Gemert, D. The workability of masonry mortar assessed by masons. International, Journal for Restoration of Buildings and Monuments, 15(1) (2009): 39-50.

[6] Klein, D., Haas, S., Schmidt, S-O. & Middendorf, B. Morphological and Chemical Influence of Calcium Hydroxide on the Plasticity of Lime Based Mortars in Historic Mortars: Characterisation, Assessment and Repair, RILEM Bookseries 7, RILEM (2012): 319-328

[7] Van Balen, K. & Van Gemert, D. Kalk in metselmortel. over het meten van verwerkbaarheid en hechting en over de invloed van luchtbelvormers en superplastifieerders [Lime in masonry mortar, on measuring workability and adhesion and on the influence of air entrainers and superplastifiers]. Unpublished Technical report, Katholieke universiteit Leuven (1991).

[8] Hanley, R. & Pavía, S. A study of the workability of natural hydraulic lime mortars and its influence on strength. Materials and structures, 41 (2008):373–381.

[9] Thomson, M. Plasticity, water retention, soundness and sand carrying capacity: what a mortar needs. In Bartos, P., Groot, C., and Hughes, J., editors, International RILEM workshop on historic mortars: characterisation and tests, RILEM, Paisley, Scotland (2000):163–172.

[10] Godbey, R. & Thomson, M. Emley plasticity testing: first steps to a precision and bias statement. In Throop, D. and Klingner, R., editors, Masonry: opportunities for the 21st century, ASTM, West Conshohocken (2002): 61–72..

[11] Green, K., Carter, M., Hoff, W.& Wilson, M. The effects of lime and admixtures on the water-retaining properties of cement mortars. Cement and concrete research, 29 (1999): 1743–1747.