Efficient prescription of mortars for durable masonry restorations: experimental study comparing the MAR with granular-based calculations.

Laurent LEOSKOOL[1], Laurent VAN PARYS[1], Thierry DESCAMPS[1], Sophie ROUGE[1], Jean-Michel RENOIRT[2]
[1]University of Mons, Faculty of Engineering, Department of Civil Engineering
Place du Parc 20, 7000 Mons
[2]University of Mons, Faculty of Engineering, Department of Materials Science
Place du Parc 20, 7000 Mons
email : laurent.leoskool@umons.ac.be, laurent.vanparys@umons.ac.be, thierry.descamps@umons.ac.be, jean-michel.renoirt@umons.ac.be

Abstract: **During numerous centuries, the European continent has been deeply involved in the recourse to masonry systems for erecting most of important structures (industry, habitation, administration or religion). Nowadays, most of these buildings are still in use, although some parts of their materials have suffered alteration induced by anthropic or natural causes. In this context, restorations have to be planned, keeping in mind a fundamental requirement related to the effective compatibility that should be achieved between the masonry parts that are kept and the ones that will come and replace altered parts. This care about compatibility is recognized to be essential in order to ensure a sufficient durability of the investments.**

In most of the cases, mortar constitutes the part of masonry systems that will be concerned by the interventions: cleaning the walls will generally imply bringing a new mortar for refilling head and bed joints. The mechanical behaviour of new mortars should be compatible with the one of the remaining mortar. In order to prevent stress concentration phenomena that could mechanically alter the masonry units, a precise care should be brought to the compressive strength and the modulus of elasticity of the new mortar. This paper focuses on the strength aspects.

Actually, developing a method allowing structural experts involved in mortar prescription to predict the compressive strength of a mortar on the basis of the relative proportion of constitutive materials (sand, binder and water) could be interesting. The Mortar Aggregate Ratio method (MAR) has not been developed for achieving such an aim although some authors have proposed a link between MAR and compressive strength.

The first part of the present paper describes the current context in which interventions on masonry structures has to take place and summarizes potential problems likely to alter the durability of proposed solutions. Then, the paper discusses the priority interest for structural experts involved in such problems to focus their attention on mechanical aspects (far before physical and esthetical ones).

In order to target the strength related objective, the paper proposes a description of the MAR measurement method and of a granular-based calculation method before illustrating their application in the framework of an experimental study carried out in the University of Mons. Finally, strong and weak points associated to the methods are discussed before outlining contemporary challenges for the near future.

Keywords: **masonry, mortar, Mortar Aggregate Ratio, compatibility, strength, rigidity, pathologies**

I. Introduction

The masonry material is a smart assembly of limited size bricks or blocks. The use of mortar is primordial for the global behavior of the structure. In fact, mortar allows joining units for giving birth to an integral structure but also helps in splitting up the stresses onto these.

In addition, the mortar is also recognized to:

- Compensate for size variations in the units by providing a bed to accommodate dimensional tolerances of units.
- Create a tight seal between units against the entry of air and moisture.
- Ensure bonding for joint reinforcement, metal ties or anchor bolts, if any, so that they may perform integrally with the masonry.
- Provide an aesthetical quality to exposed structures through color contrasts or shadow lines from various joint-tooling procedures.

II. Fundamental characters associated with mortar

In the field of masonry restoration, it is necessary to precisely know the characteristics of new mortars in order to ensure a sustainable intervention. The concept of compatibility should then be considered as a key notion for the structural engineer.

Fig. 1. Potential pathologies associated with bad compatibility

First aspect concerns mortar strength and rigidity: masonry structures must be able to bear applied loads, absorb thermal expansions, support differential settlements and so on. In this framework, the use of mortar with inappropriate compressive strength or modulus of elasticity can create stress concentration phenomena and lead to the deterioration of joints or units. Commercial mortar mixes used for new buildings are usually not suitable for old masonry structures, partly because their high Portland cement content gives them fairly high density, compressive strength and stiffness, so they cannot act as the sacrificial material of the masonry assembly. The recourse to softer mortars, with a low compressive strength, more flexibility and higher porosity, is recommended: such a mortar can better accommodate minor movements in the wall ad, if larger shifts occur, it will take the strain and "sacrifice" itself to maintain the integrity of the masonry unit [5]. Ancient walls were mostly erected with lime-based binder. Lime is well known to allow deformations of the wall with limited cracks[a]. The use of cement for pointing may constraint deformations and creates stress concentrations as consecutive problems.

Second aspect concerns mortar physics, namely the permeability to the water vapour. Lime-based mortars allow the wall to dry faster thanks to their permeability. Consequently, a repointing joint that is dense and slightly permeable will resist less to the frost-defrost cycle and lead to unsticking (see figure 1-yellow).

Third aspect concerns mortar aesthetics. Without tackling precise problems of historic monuments, UNESCO or ICOMOS guidelines (Venice Charter), the colour and the texture of mortar should also be considered before the restoration of buildings in order to conserve and reveal the esthetical value of heritage architecture.

III. Mechanical strength of the mortar

A. Challenges concerning the strength

In practice, mortars are established with only three ingredients: binder (cement or lime), sand and water. It is recognized that the water–cement ratio has an important influence on the quality and performances of all cement based products. We also know that the most important quality for a mortar is its workability in such a way that water is most of the time adjusted with every batch to meet job site conditions. In this case, prescribing a mortar composition consists in accurately and consistently proportioning the amount of sand relative to cement. That sounds simple, but actually is not once strength criteria have to be fulfilled. For qualifying a mortar, its compressive and/or flexural strength as well as its modulus of elasticity may be used since they are relatively easy to measure with lab equipment. The compressive strength commonly relates to other properties, such as tensile strength or absorption of the mortar.

Several non- or less-destructive testing techniques have also been developed for field-collecting of mechanical or physical information. It should be reminded that lab-qualified mortars and effective field-tested mortar are not expected to exhibit strictly identical properties, what complicates matters. In fact, the aspect ratio (height to thickness) of mortar specimens used in lab tests clearly influences the apparent measured strength even when made from the exact same material. Moreover, mortar used in the actual project being placed between potentially absorbent units will draw some water out of the mortar, lowering its water content and increasing its strength. Finally, field-tested mortars potentially exhibit a larger variability of their quality, forasmuch as they are produced on site with water contents depending most of the time on a biased judgment concerning their workability.

[a] The use of lime mortar will also produce low shrinkage mortar limiting corresponding cracks and water infiltrations.

B. Conventional measurements of strength with lab tests

The guidelines for strength measurements with lab tests on hardened mortar are expressed in EN 1015-11. The flexural strength is determined, after 28 days of underwater curing, by three points loading of a prism specimen, subsequent to the failure and breakage of this specimen the compressive strength is determined on each half of the prism.

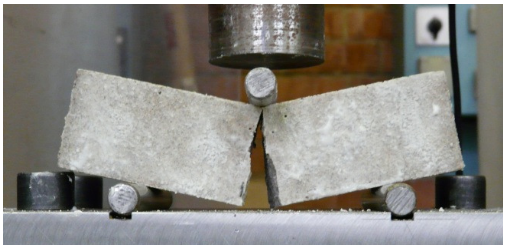

Fig. 2. Bending test of Rhine sand and white cement

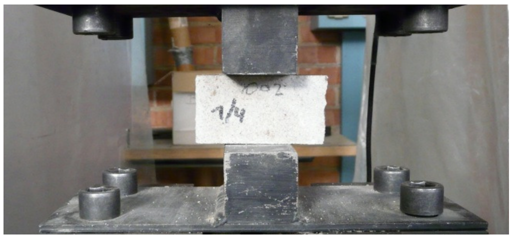

Fig. 3. Compressive test of Rhine sand and white cement

IV. Mortar aggregate ratio approach

A. Context, initial and extended usage of such measurement

Masonry walls are designed and built every day around the world. Although masonry is a proven construction method, and one of the oldest, the structural engineers are still faced with the same challenge: how to prescribe a mortar and then verify that you are getting what you asked for. For documenting this problem, American researchers have developed a method called 'mortar aggregate ratio' (MAR) which normally allows controlling the quantities of mortar constituents. This technique is integrated in the ASTM C780 standard (American Society for Testing and Materials). In its original purpose, the MAR method was essentially developed for verifying the adequation between the mortar prescribed by structural engineers and the one that is effectively used on the building site. Nevertheless, a research team from University of Florida proposed to establish correlations between MAR and the average compressive strength of the mortar tested at the age of 28 days [1]. Indeed, as the compressive strength of mortar depends largely upon the cement content, the MAR method would potentially constitute a good starting point to control the strength properties based on fresh mortars. Despite the limited size of the database considered by this research and further than important dispersions noticed in the experimental results they proposed, the present paper initiates further investigations carried out at University of Mons.

B.Method description

The MAR test is based on the study of fresh mortar. Two samples of mortar and one of sand have to be taken. Both are placed into methyl alcohol jars (their weight are known) to stop the hydration of binder. One is wet weighed and a surplus of methanol is added. After that, combustion is activated to evaporate the main part of the water and to calculate the water content. A passage in an oven is also needed to improve the results. The second sample of mortar is wet sieved to separate binder from the sand (fine particles lower than 150µm being considered as binder). Sand sample is also wet sieved in order to apply a correction factor to fine particles. Thanks to this process, it is possible to calculate the mortar aggregate ratio and the water content, which permit to control the good consistency of the mixture:

Water content:

$$\textit{Mortar water content, wet basis, \%} = \frac{(b-a-d)}{(b-a)} . 100$$

where: a = weight of the container and alcohol [g],
b = weight of the container, alcohol and mortar [g],
d = weight of oven-dry mortar sample [g].

MAR:

$$\textit{Weight of mortar } (> 150\mu m), \textit{dry, corrected} = Q = Y . \frac{R}{W}$$

$$\textit{Weight of mortar } (< 150\mu m), \textit{dry, corrected} = P = K - Q$$

$$\textit{M.A.R. (Sand -- to -- binder ratio), by wt} = {}^{Q}/_{P} \textit{ to } 1$$

where: Y = weight of mortar (>150µm), non-corrected,
R = weight of sand, oven dry,
W = weight of sand (>150µm), oven dry,
K = weight of dry mortar.

V.GRANULAR-BASED PREDICTION APPROACH

A.Context, initial and extended usage of such calculation

Mathematically establishing a relationship between a relative proportion of ingredients and key properties of the associated mortar represents another challenge for structural engineers. Such a mathematical prediction has been investigated for concrete by several researchers for decades and the granular-based approaches appear like the most advanced development stage of available theories [4]. As such philosophies mainly rely on the properties of the granular skeleton, a granular-based method could potentially constitute a good starting point to predict the strength properties based on fresh mortars. The present paper initiates some investigations carried out at University of Mons.

B.Method description

The granular-based method proposed by a LCPC team (Laboratoire Central des Ponts et Chaussées) allows predicting several parameters both for the fresh and the 28-days hardened mortar: like strength, workability, shrinkage or even porosity. The present paper will focus on the compressive strength. The method takes aggregate, binder and water into account. For the aggregate, physical properties are considered like grain density, granular repartition and compacity. For the cement, similar physical information is required, completed by the conventional strength value. Granular mixing laws are used in conjunction with cement, water and air volumes for expressing information concerning the matrix compacity and then correlating them with a value for the compressive strength.

Compressive strength:

$$fc = \frac{p \ fc_m}{q \ fc_m + 1}$$

where p, q = parameters associated with aggregate type
f_{cm} = matrix strength

$$fc_m = 13{,}4 \ Rc_{28} \left(\frac{V_c}{V_c + V_e + V_a} \right)^{2{,}85} EMP^{-0{,}13}$$

where R_{c28} = conventional strength value for the cement
Vc = volume of cement
Ve = volume of water
Va = volume of air
EMP = parameter associated with compacity

VI.CONVENTIONAL STRENGTH, PREDICTION AND MAR

A.Experimental program

Disposing of a short term method likely to predict long term values of strength could reveal interesting. The present study initiates a wide-scale investigation campaign carried out at the University of Mons to complete the MAR approach (as a quality tool) by adding information about compressive strength and to combine it with ex-ante predictions by granular-based approach.

B.Preliminary strength-MAR study

A preliminary study has been carried out with different mortars covering a wide range of recipes: various kinds of sands (Rhine, white, yellow) and binders (white cement, grey cement and lime-cement combinations), water being adjusted to meet a fine workability target. For each mortar, the MAR has been lab-measured on the fresh mortar directly following the mixing operation. After 28 days of underwater curing, mortar samples have been tested for determining both the conventional flexural and compressive strengths (fig 2 and 3). The obtained results are illustrated on Figure 4, expressing the evolution of compressive strength with respect to the MAR. For mortars made with a lime-cement combination as binder, the MAR ratio has been calculated by taking their sum into account. Hydrated lime reacts with carbon dioxide in the atmosphere to form limestone. This provides the mechanism for long-term strength development of the mortar. Due to such different time dependent behaviours, samples of mortar (with and without lime) have been separated in two groups.

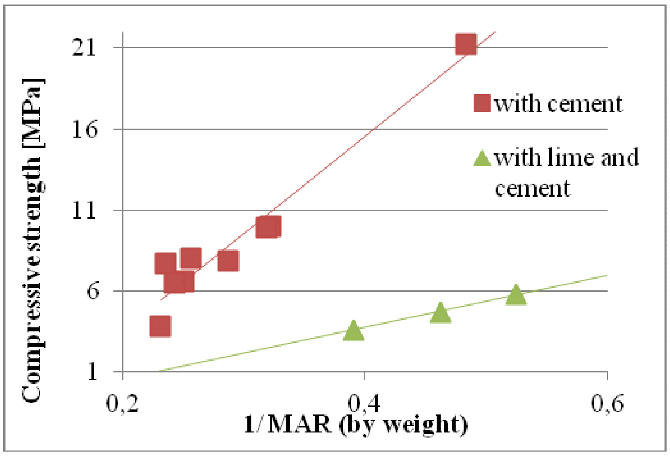

Fig. 4.Measured MAR versus compressive strength

For each group, we clearly observe the logical increasing strength of mortars with the cement content and the weaker strength properties of mortars (measured at 28 days) made with a lime-cement combination. Aware of such encouraging results confirming general trends outlined by researcher from the University of Florida, a more detailed study has been initiated, focussing on one single type of binder.

C.Further strength-MAR study

The main process is similar to that just described but here the material composition has been sharply controlled by precise weight and water content of each constitutive material before batching mortars. Allowing a computed version of the MAR to be outlined from the recipe, such ingredient quantification avoids taking the experimental dispersion associated with MAR measurement into account. Once again different types of sands have been considered (Rhine, yellow and green) but only one cement (White 42.5R) has been chosen like binder, water being adjusted to meet correct workability. For each sort of mortar, the flexural and compressive strength have been measured. Results are screened on figure 5 for different proportions of binder and sand.

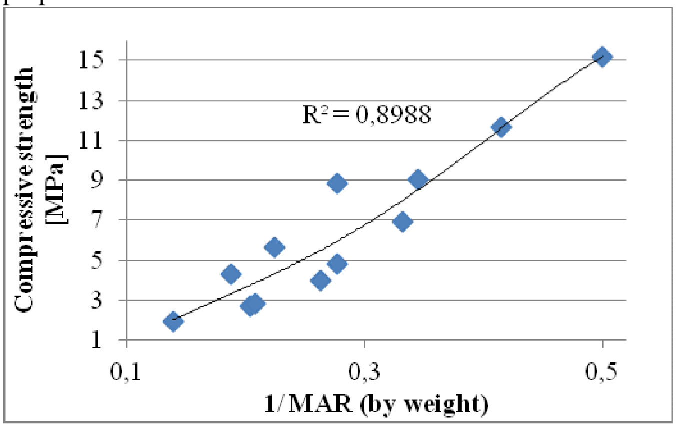

Fig. 5. Computed MAR versus compressive strength

Sand type non differenciated.

The obtained results are illustrated on Figure 5, expressing the evolution of compressive strength with respect to the MAR. Once again, we clearly observe a trend of correlation between compressive strength and the binder quantity. Nevertheless, the dispersion of results remains wide. The reason of this is that the direct proportion analysis method that we have applied does not take care of the water-to-cement ratio although it is well-known that it significantly influences the results (water was added to meet workability). In the same way, the particle size distribution of sand is not used to characterize the method although, for example, Rhine sand has particle sizes bigger than yellow sand. This property largely influences the porosity and the amount of water needed to reach the workability target and so, its strength. In order to remove this last hypothesis, all types of sand used have been dry sieved, weighted and the determined passer-by is presented in Figure 6.

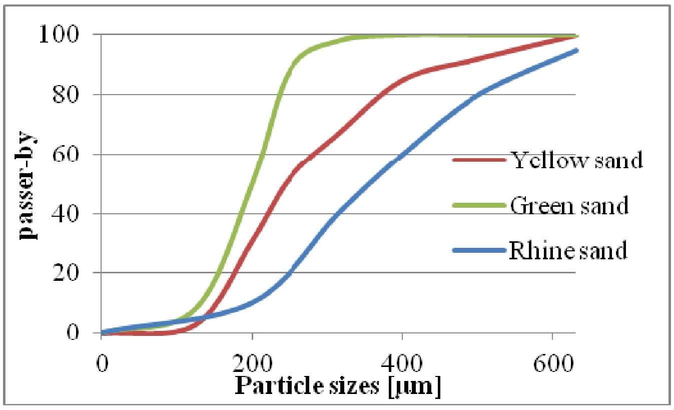

Fig. 6. Graph of passer-by according to particle sizes of sand

The results presented on Figure 7 taking care of the sand type present better correlations. They show that mortars made with Rhine sand tends to have better resistances than other types of sand, as normally expected. The difference between yellow sand and green sand is practically zero. Added to water content, these characteristics could make it possible to reduce considerably the variability of results without wasting too much time of processing.

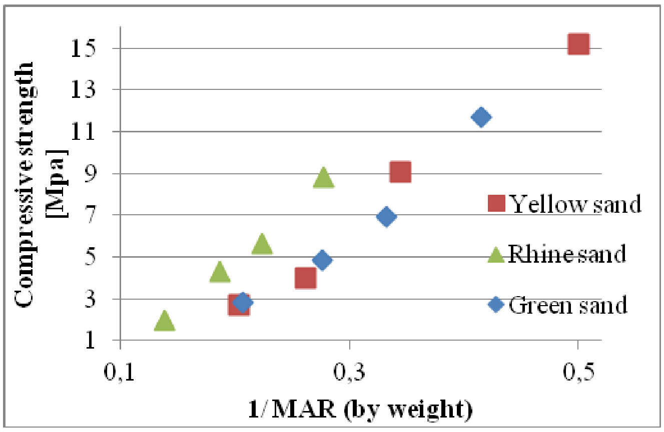

Fig. 7. Computed MAR versus compressive strength

Sand type diffrenciated.

D.Complementary information obtained by calculation

As previously expressed, the considered granular-based calculation approach is likely to take sand type and water content into account. In this framework, our precise knowledge of weight and water content for each constitutive material allows a sharp calculation of predicted value for compressive strength. The obtained results are illustrated on Figure 8, expressing the evolution of measured compressive strength (experimental) and calculated compressive strength (theoretical) with respect to the MAR. We observe that the results are clearly encouraging.

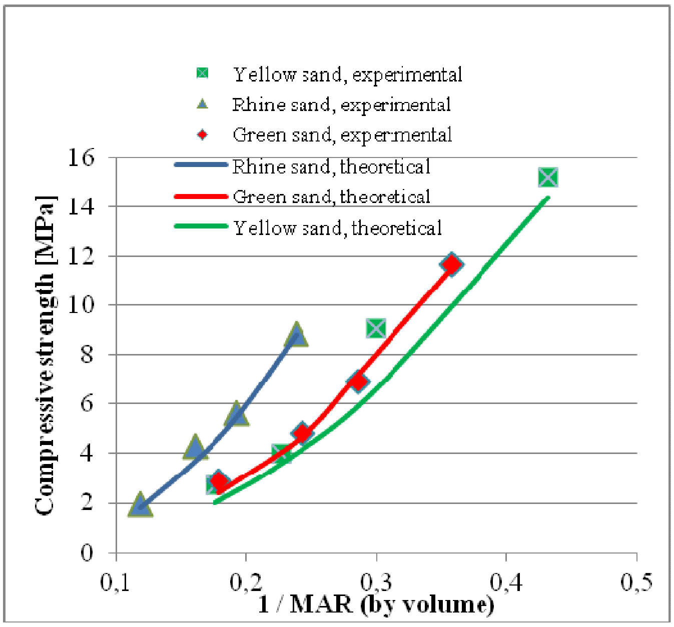

Fig. 8. measured and calculated values of strength

VII. Conclusions

The present paper has proposed a double approach of the compressive strength for the mortars as a complement to the conventional approach based on tests carried out on hardened mortar specimens but intervenes after a 28 day delay.

The MAR method has initially been developed for on-site controlling of mortar compositions (quantity of sand, binder and water used to batch). In that respect, this technique is very useful compared to number of other methods. By comparing the values of the aggregate ratio from samples taken during construction, engineers have a good quality control tool and can evaluate if a particular mortar sample has been properly mixed by comparing test results to the ratio of the mortar's approved mix design. By reviewing the results from a number of different samples over a period, they can also determine if the batching process has been consistent.

Further than these considerations, some researches have shown this short term measurement (on fresh mortar) should probably be correlated with the compressive strength (on hardened mortar). The preliminary part of our study has confirmed such interesting trends on a varied range of mortars. A more detailed study has allowed clearly outlining some limitations associated with such a relationship between MAR and compressive strength. It is difficult to take the water content effect into account[b], impossible to take the effect of air content or to differentiate different types of sand or binder (which can raise problems when lime and cement are mixed).

So, we can say that the MAR method is very attractive to control the quality of mortars rapidly. The experimental process is easy to apply and it does not need much equipment. Nevertheless, the application of the method may reveal delicate for complex mortar (varied sand type or binder). As the compressive strength of mortar depends largely upon the cement content (what can be measured for a fresh mortar with MAR tests), the MAR method is a good starting point to control and predict the strength properties of fresh mortars. Our first attempt to complete MAR tests to predict compressive strength gives encouraging results, however, a huge number of parameters (water-to-binder ratio, particle size distribution of sands, porosity, water-reducing admixture and plasticizers …) are not integrated in the process and limit the accuracy of the results. In the future, a detailed analysis of water-content will be carried out.

The LCPC granular-based calculation approach proposed for concrete strength calculation could reveal interesting for a transposition to mortars. Such a complement has been proposed in our detailed study, outlining very encouraging results and showing the mathematical prediction makes sense to experimental results.

The present study is not yet really extended and more experimentation is required for improving the techniques. It should allow integrating other parameters in the reflection like porosity or module of elasticity for achieving a mortar exactly similar to another one, which is helpful for restoration studies.

References

[1] J.A. Farny, J.M. Melander and J.H. Greewald, *Mortar quality assurance: a review of North American practices,* 10th Canadian Masonry Symposium, Banff, Alberta, June 8-12, 2005.

[2] A.H.P. Maurenbrechern, K. Trischuk, M.Z. Rousseau, M.I. Subercaseaux, *Les mortiers de rejointoiement pour la conservation des maçonneries anciennes (Rapport de recherche 225),* National Research Council Canada, Ottawa, Canada, March 2007.

[3] ASTM Standards, *Standard test method for preconstruction and construction evaluation of mortars for plain and reinforced unit masonry (C780-10)*, ASTM International, United States of America, December 2010

[4] F. De Larrard, *Concrete Mixture-Proportioning – A Scientific Approach*, Modern Concrete Technology Series (No. 9), E & FN SPON, London, 1999

[5] M.Z. Rousseau and P. Maurenbrecher, *Mortar for pointing old masonry buildings*, Columns, The Newsletter of the Alberta, Saskatchewan, and Manitoba Associations of Architects, V. 6 No. 1, October, 1998

[b] at the time of MAR measurement, the hydration of binder has already begun and the time is then determining.