IV.03
Comparison of Different Methods to Determine the Packing Density of Fresh Mortars

Anna Arizzi\textsuperscript{1} and Giuseppe Cultrone\textsuperscript{1}

\textsuperscript{1} Department of Mineralogy and Petrology, University of Granada, Spain, arizzina@ugr.es, cultrone@ugr.es

Abstract
Packing density is considered one of the most influential factors in fresh performances of mortar and concrete. There exist standardised methods for its determination, both direct and indirect, but in most of the cases they do not give a realistic estimation of the voids content. For this reason, these methods should be substituted by the “wet packing method”, more recently developed and valid for binders, aggregates and mixtures of both. In this work, the “wet packing method” has been used to assess the optimum water/binder ratio at which the packing density is achieved in mortars of different composition and binder/aggregate proportions. To support the validity of this method, the obtained values have been compared with those obtained by measuring the bulk density of the dry granular components, with and without vibration applied, and the consistence of the pastes by means of the flowability test. This work aims to diffuse an alternative, easy and more precise method which could indirectly improve the performances of both fresh and hardened mortars, designed for restoration processes in Architectural Heritage.

1 Introduction

The packing density of a mixture ($\phi$), which represents the solid volume in a unit total volume [1], is influenced by the random arrangement of the particles and, in turn, depends on particle shape and size distribution (PSD). The dependence on particle size distribution is evident in the case of a broad PSD, in which the smaller particles fill up the voids between the coarser ones, thus increasing the value of maximum packing. The influence of particle shape is widely recognized by several studies [2-3].

In a mortar where a high density is achieved, all particles (i.e. binder plus aggregate) are densely packed, and the number of voids between them is reduced compared to less densely packed mixtures. This minimal porosity is saturated by a
The excess water, the amount of water free in the mixture, allows the mobility of particles, thus influencing the flow of the mixture. On the other hand, if the water in excess is too high, the shrinkage during drying will be too great and the strength of the hardened mortar will decrease significantly. To design good mortars and concretes, it is fundamental to determine the water/binder ratio (W/B) at which optimum workability is achieved by estimating the maximum packing density of these mixtures. Several theories and models have been created to identify the most appropriate aggregate packing for concrete [1, 4-6].

The value of packing density of individual components has been estimated in the past by measuring the bulk density of the dry materials (i.e. lime, cement, aggregates). The value of $\phi$ is determined as:

$$\phi = \frac{\rho_b}{\rho_s}$$

where $\rho_b$ and $\rho_s$ represent the bulk and the solid densities of the granular component, respectively. The voids index ($u$) of the dry component is:

$$u = \frac{\pi}{\phi}$$

in which $\pi$ is the porosity, calculated as: $1-\phi$. The dry method not only depends very much on the state of compaction, but also tends to overestimate the void content and underestimate the packing density of fine particles [7].

In the case of a mixture of cementitious material and aggregate, indirect and standardized methods exist for the determination of void content in terms of the amount of water needed to form a paste with a certain consistency (i.e. flow tests, penetration depth of a plunger). These methods assume there is a minimum amount of water for the formation of a paste in which the void content is also minimized, and the water volume can be considered as the porosity of the dry packing [1]. However, some problems are correlated with the water content needed to saturate the voids and the air content of the paste, therefore, the methods mentioned above for determining packing density of finer particles are neither precise nor realistic. To counter these inconveniences, Wong and Kwan [7] proposed another method to determine the maximum packing by estimating the solid concentration of the wet mixture instead of the packing density of the dry one. The solid concentration obviously depends on the amount of water added, and, for this reason, it does not coincide with the packing density. According to these authors [7], a minimum amount of water produces a mixture with a maximum solid concentration, which corresponds to the packing density. The wet packing method was demonstrated to be valid not only for cementitious materials, but also for fine aggregates and mixtures of both [7-9]. According to this method, the solid concentration ($\phi$) in a mortar is determined as:
where $M/V$ represents the wet bulk density of the paste; $\alpha$ and $\beta$ are two different cementitious materials; $s$ is the sand; $\rho_w$ is the density of the water; $\rho_{\alpha}$, $\rho_{\beta}$, and $\rho_s$ are the solid densities of $\alpha$, $\beta$, and $s$; $u_w$ is the W/B ratio by volume; and $R_{\alpha}$, $R_{\beta}$, and $R_s$ are the volumetric ratios to the granular material. In mortars where only a binder is present, $\rho_{\beta}$ and $R_{\beta}$ values in the equation (3) are equal to zero. By applying this equation to the suspensions prepared with different dosages of water, a maximum value of $\Phi$ is obtained, corresponding to the packing density of the mixture [10].

The voids content, indicating the porosity ($\varepsilon$) of the wet mixture, is calculated as:

$$\varepsilon = \frac{u}{1+u}$$

(4)

where $u$ is the void ratio, estimated by means of the following formula:

$$\varphi = 1 - \varepsilon = \frac{1}{1 + u}$$

(5)

A minimum value of voids ratio is obtained by plotting $u$ against $u_w$, and it corresponds to the basic water ratio [7], that is, the water content necessary to fill up the voids.

The objective of this work is to establish the optimum W/B ratio at which the packing density is achieved in mixtures of different composition and binder/aggregate ratios, in order to achieve mortars with good workability, without the use of any superplasticizers. Since other authors [8-9] have already adopted the wet packing method as a successful way to fix the packing density of granular mixtures, its validity has been proved in this work and compared with other methods, including the determination of the bulk density of the dry granular components and of the consistency of the fresh mixtures by means of the flow test.

2 Materials and methods

Components used in this study were a calcitic aggregate (CA), with a continuous grading between 0.063 and 1.5 mm in size, and a calcitic lime (CL), which is a standardized CL90-S [11].

Packing density of single components was measured by means of the dry method (Eq. 1). Pycnometer analysis was performed to measure the solid (or particle) density ($\rho_s$, gr/cm$^3$) of lime and sands. Measurements have been carried out following the ASTM, D 854-92 standard [12]; pycnometers have been calibrated and filled with white spirit. Dry bulk density ($\rho_{bw}$, gr/cm$^3$) of components
was determined by simple pouring, with and without vibration applied. The vibration was led at an amplitude of 0.3 mm during 300 s; the value of dry bulk density obtained after vibrating was indicated as $\rho_b^*$ (gr/cm$^3$).

Regarding the determination of mortars packing density, four types of mortars were obtained, differentiated according to their binder/sand ratio by volume (B/S): CC1:1, CC1:2, CC1:3, and CC1:4. Six mixtures of each mortar were prepared, maintaining the fixed B/S ratio and changing the water content. Solid concentration and the void ratio of every mixture were calculated by applying Eqs. 3, 4, and 5. Values of minimum water content (or basic water), corresponding to the maximum solid concentration and to the minimum void ratio, were used for the preparation of mortars whose flow was determined with the flow test [13].

### 3 Results and discussion

As shown in Table 1, values of packing density obtained for the dry materials change depending on their preparation procedure. When the powder is simply poured into the container without any forces applied to it, the quantity of voids (indicated in Table 1 as porosity, $\pi$) is bigger because particles cannot arrange in a more dense system. The reduction of porosity due to vibration, with the consequent increase of packing, is much bigger in the case of CA, characterized by a continuous grading in which the smaller particles can easily move and set between the coarser particles.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\rho_s$</th>
<th>$\rho_b$</th>
<th>$\rho_b^*$</th>
<th>$\phi$</th>
<th>$\phi^*$</th>
<th>$\pi$</th>
<th>$\pi^*$</th>
<th>$u$</th>
<th>$u^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL – lime</td>
<td>2.421</td>
<td>0.496</td>
<td>0.611</td>
<td>0.205</td>
<td>0.253</td>
<td>0.795</td>
<td>0.747</td>
<td>3.877</td>
<td>2.959</td>
</tr>
<tr>
<td>CA- aggregate</td>
<td>2.550</td>
<td>1.514</td>
<td>1.831</td>
<td>0.594</td>
<td>0.719</td>
<td>0.406</td>
<td>0.281</td>
<td>0.682</td>
<td>0.390</td>
</tr>
</tbody>
</table>

Another factor causes an error in the estimation of the packing density of dry fine powders. Lime is formed by micro- and nanoparticles (under 50 µm), which agglomerate due to the inter-particle forces acting on them [14]. When water is added, repulsion forces between charged portlandite crystals cause the agglomerates to disperse [15], and particles rearrange into a denser system, achieving a higher packing density in suspension. As shown in Table 2, $\phi_{\text{max}}$ of CL suspensions is about three times higher than the value of packing density found in the dry powder. In the case of the calcitic aggregate, a similar increase of packing density was registered, although the value was only 1.5 times higher than that measured for the dry aggregate. This is because in CA only 19% of the total aggregate is formed by particles smaller than 100 µm in size, which disagglomerate in water.
Of the four mortar mixtures, CC1:3 demonstrated the best packing (Table 2). The basic water content ($u_{w_{\text{min}}}$) corresponding to this packing was also optimal for achieving good workability (flow).

<table>
<thead>
<tr>
<th>Mortar name</th>
<th>$u_{w_{\text{min}}}$</th>
<th>$\phi_{\text{max}}$</th>
<th>% water</th>
<th>Flow (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>1.950</td>
<td>0.77</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA</td>
<td>0.838</td>
<td>0.98</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC1:1</td>
<td>0.813</td>
<td>0.59</td>
<td>32.30</td>
<td>172</td>
</tr>
<tr>
<td>CC1:2</td>
<td>0.808</td>
<td>0.62</td>
<td>31.94</td>
<td>&gt;180</td>
</tr>
<tr>
<td>CC1:3</td>
<td>0.491</td>
<td>0.74</td>
<td>20</td>
<td>143</td>
</tr>
<tr>
<td>CC1:4</td>
<td>0.576</td>
<td>0.73</td>
<td>22.68</td>
<td>&gt;180</td>
</tr>
</tbody>
</table>

In the other mortars, the water content (corresponding to the maximum solid concentration) used for the preparation of mixtures was too high, creating quite fluid pastes. It is interesting to note that in all the cases, the value of flow is within the range established for a plastic mortar (140-200 mm of flow) [16]. Nevertheless, according to the consistence appreciated during the manual mixing, the limit of plasticity of mortars corresponded to a maximum of 170 mm of flow. However, we must consider that the flow test is not a precise method for the determination of the optimal amount of water, especially because of the low adaptability of existent standards [13, 16] to lime mortars.

In general, it has been observed that the value of $\phi_{\text{max}}$ increases with increasing S/B ratio, except in the case of the highest proportion of sand. The basic amount of water, represented by the value $u_{w_{\text{min}}}$, does not present the same linear trend, because there is a sharp decrease in this value from the 1:2 to the 1:3 B/S ratio. This can be explained by considering the decrease in the amount of lime. In CC1:2, the packing is a bit higher than in CC1:1, but the minimum void ratio ($u_{\text{mind}}$) is almost the same (Fig. 1), as is the basic amount of water ($u_{w_{\text{min}}}$), which is only slightly reduced. The most influential difference is the amount of lime present in the two mortars, considering that CC1:2 contains half the amount lime as CC1:1. This means that water is not entirely absorbed by the lime but is free in the mixture, producing a much more liquid mortar.

On the other hand, we obtained for CC1:4 a packing density a bit lower than that of CC1:3 with bigger water content, which produced a mixture with high flow. In this mortar, the high packing density is produced quite exclusively by the continuous grading of the aggregate, because the lime content is very low and insufficient to fill the voids while absorbing the excess water present in the mixture. The flow is, however, a bit lower with respect to that of CC1:2 because of reduced quantity of water.
Fig. 1 Curves representing the water ratio ($u_w$) versus the solid concentration ($\phi$) (black lines) and the void ratio ($u$) (gray lines) for the calcitic lime (CL), the calcitic aggregate (CA) and the four mortar mixtures. Maximum solid concentration ($\phi_{\text{max}}$), basic water content ($u_{\text{w min}}$) and minimum voids ratio ($u_{\text{min}}$) are indicated in each graphic with a $\times$. 

868
4 Conclusions

The determination of the packing density of the dry granular materials used for the production of mortars (calcitic aggregate and lime) was proven to be strongly dependent on the procedure used for the preparation, being always higher in the vibrated powders compared with the non-vibrated ones. The measurement of solid concentration in fresh pastes by means of the wet packing method has found to be more realistic with respect to the dry method, but also with respect to the flow test, which is imprecise, especially when lime mortars are studied. Among the four types of mortars, the best values of $\phi_{\text{max}}$ and $u_w$ were found in CC1:3. The binder/sand ratio used in this mortar produces the most packed mixture, in which the quantity of voids and the amount of water necessary for their saturation are minimal. These important characteristics produce a mortar with optimal workability.

5 Acknowledgments

This study was financially supported by Research Group RNM 179 of the Junta de Andalucía and by Research Project MAT 2008-06799-C03-03.

6 References