The effect of aggregate composition on physical and mechanical characteristics of repair mortars

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Abstract

Mortar is an important material in old masonry. Its repair is leading to the conservation of buildings and structures of our cultural heritage. Old mortars are mainly made of pozzolan, sand, brick powder, lime and water. Repair mortars are made of the same materials whereas cement is often added in small quantities in order to improve the strength development. This paper presents preliminary results of a systematic experimental study on the effect of aggregate type and ratio on physical and mechanical characteristics of repair mortars. Four mortar mixtures were prepared with different pozzolan/brick powder/sand ratios. Compressive strength, flexural strength, weight loss and shrinkage measurements were taken for a time period up to 90 days. Different type and dosage of aggregates strongly affects the mortar’s mechanical characteristics mainly due to the different specific surface area and physical properties of sand and brick powder.

1 Introduction

Until the invention and the wide use of concrete, the most commonly used structural material was masonry. Mortars constitute the weak link in stone or
brick masonry structures, being susceptible to corrosion due to pollution, deterioration from salt crystallization and harsh weather conditions. The understanding of the nature and the deterioration mechanism of old mortars, as well as the development of compatible repair mortars is an essential element towards the objectives and needs of restoration of our architectural heritage.

The materials that constitute old mortars are lime, pozzolanic material such as natural pozzolan and/or brick powder, aggregates such as sand and/or brick and water. Sometimes the properties of ancient mortars are related to the use of organic additives, i.e. eggs, blood, milk of figs. The composition of old mortars is difficult to identify due both to the changes undergone by the components during the setting and hardening process as well as to the double function often served by the same substances. For instance, in an attempt to characterize the ceramic material, brick powder behaves as hydraulic binder material while brick fragments are considered as aggregates. Moreover the raw materials may be intentionally or unintentionally impure with substances that still perform an active function; the systems examined may have been differently disturbed by individual components. Therefore the reconstruction of the original composition is often a rather arduous task [1].

Negative results in recently restored masonries due to the use of unsuitable materials have created a growing demand for research into traditional materials. The traditional materials of brick and mortar have been proved to be long lasting and well compatible to each other. Later repair work on the repair of historical masonry with modern materials has unfortunately shown that such materials are often incompatible with the original masonry, often causing serious damage, particularly of physico-mechanical nature.

The above reasons have driven the research community towards the development of repair mortars using traditional techniques and materials characteristic of the original structure. A lot of research has been carried out in an effort to develop repair mortars compatible with the old ones and, if possible, improved regarding their strength and durability. A considerable factor, which affects the nature of mortar, is the binder to aggregates ratio. In old structural mortars, the proportion of binder to aggregates varies from 1:2.5 to 1:3 by volume and 1:4 by weight [2]. As far as aggregates are concerned, the type, gradation, proportion and density affect not only their appearance, but also their porosity and strength.

In order to study the effect of aggregates on repair mortars, four different mixtures have been designed, with main mix design variables the aggregate type and ratio. Physical properties such as drying shrinkage and weight loss, and mechanical properties such as compressive and flexural (indirect tensile) strength have been measured. The experimental data were used to document the effect provided by different binder:aggregates ratio and sand:brick fragments ratio in repair mortars.
2 Experimental procedure

Parameters of this test program were (i) the binder:aggregates ratio and (ii) the sand:brick fragments ratio. In order to estimate the relative role of the above parameters, four mortar mixtures were prepared.

The constituents of binder were hydrated lime (dry powder), natural pozzolan and cement. The pozzolan used was milled Milos earth, with maximum grain size 0.5 mm. The cement used was CEM I 42.5N according to EN 197-1 [3], i.e. ordinary Portland cement. The composition (by weight) of binder was constant, corresponding to a ratio of lime:pozzolan:cement equal to 1:0.8:0.2.

The aggregates used were natural silicate sand with maximum grain size 4 mm and crushed brick with maximum grain size 4 mm. The granulometric gradation of aggregate curves was regular.

The quantity of the water used in each mixture has been adjusted so that all mortars studied had the same workability, corresponding to a flow table measurement equal to 170 mm, measured according to EN 1015-3 [4].

After several trial mixes the following four compositions were developed: two different ratios binder:aggregates and three different compositions of aggregates, as shown in Table 1.

Table 1: Composition of mortars (proportions by weight)

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Lime</th>
<th>Pozzolan</th>
<th>Cement</th>
<th>Sand</th>
<th>Brick fragment</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>2.0</td>
<td>2.0</td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>2.0</td>
<td>6.0</td>
<td>2.18</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>4.0</td>
<td>4.0</td>
<td>1.87</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>6.0</td>
<td>2.0</td>
<td>1.84</td>
</tr>
</tbody>
</table>

A total of 60 specimens were prepared, including those made for the weight loss and length change measurements. All specimens were prepared and cured according to prEN 1015-11 [5]. For all specimens the age at demoulding was two days.

The mechanical properties of mortars, namely the tensile and compressive strength, were measured according to prEN 1015-11 [5]. The tensile strength was measured at the ages of 28 and 90 days as the mean value of test results on three 160x40x40 mm prisms; the results obtained are given in Table 2. The compressive strength was measured at the ages of 7, 28 and 90 days as the mean value of test results on the six half prisms provided from flexural testing; these values are also presented in Table 2.

The development of weight loss and drying shrinkage of mortar specimens were measured in two series of three 40x40x160 mm prisms, according to ASTM C596-96 [6]. The measurements were taken every day until a stabilization of values was observed. The result reported is the mean value of the
six measurements. These values are plotted in Figures 1 and 2 for the weight loss and the drying shrinkage, respectively.

3 Discussion of test results

3.1 Tensile strength

In all mix designs the values of tensile strength are relatively low, because of the low amount of cement in the binder. However, due to the "pozzolanic reaction" (the silicate of pozzolan reacts with Ca(OH)$_2$ and hence the mortar develops further its mechanical properties), both the tensile and the compressive strength present a rate of development beyond the age of 28 days. In this experimental study, the tensile strength increases significantly until the age of 90 days in two mixtures (mixtures 1 and 2). The last two mixtures (mixtures 3 and 4) after the age of 28 days present no increase in tensile strength (in fact a slight reduction in tensile strength was recorded), which may be attributed to an effective reduction of the water available for hydration, since the increased dosage of sand provided a very large surface area available for wetting.

<table>
<thead>
<tr>
<th>Mixture No.</th>
<th>Tensile strength (MPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 days</td>
<td>90 days</td>
</tr>
<tr>
<td>1</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>3</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>4</td>
<td>0.24</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The results obtained from tensile tests at the age of 90 days are consistent with findings reported by other researchers, e.g. [7]. The experimental data report that tensile strength of old mortars ranges between <0.35 – 1.20 MPa. The values obtained in this experimental study present a tensile strength range between 0.21 – 0.30 MPa (at the age of 90 days). The above reference to the slow rate development of mechanical strength in pozzolanic mortars supports the observation that tensile strength at the age of 90 days is not the final for the mortars tested.

To evaluate the effect of sand to brick fragments ratio in tensile strength, the results of mixtures 2, 3 and 4 must be compared. In mixture 2 where brick fragments prevailed to sand, a regular rate of strength development is observed and the values of tensile strength at the ages of 28 and 90 days are sufficient. A different effect is obtained in the case of mixture 4, where the high sand dosage improved the tensile strength development until the age of 28 days. After this age an effective reduction of tensile strength was recorded. This effect diminishes if the fractions of sand and brick are equal, as in mixture 3. This finding suggests that the strength loss is a result of decreased amount of brick
fragments, which as porous aggregates absorb and retain a portion of the water, which they use as an internal water supply for continuous hydration of the pozzolanic material [8]. Between the competing actions of sand or brick fragments the one that prevails (according to the sand:brick fragments ratio), is governing the strength response of mortars.

The binder to aggregates ratio also appears to have a significant effect on later ages tensile strength. Through the comparison of mixtures 1 and 3 it appears that the increased amount of aggregates affects the tensile test response after the age of 28 days. A significant rate of strength development is observed in mixture 1 where the binder:aggregates ratio is 1:2, while a (marginal) strength loss occurred in mixture 3 where the binder:aggregates ratio is 1:4. The absence of the beneficial effect of brick is obvious in the last mixture, after the age of 28 days, because of the large dosage of aggregates used and the limited quantity of water absorbed by brick fragments.

The decrease of tensile strength, during hydration, is consistent with reported data [9]. This trend is observed in repair mortars with small amounts of cement or brick fragments; the addition of the above components leads to strength stabilization after the age of 28 days. A slight reduction in tensile strength is also reported at the age of 28 days, when the sand volume increased; the aggregate stiffness does not contribute to strength development rate, whereas the mortar–aggregate transition zone has a significant effect on tensile strength.

3.2 Compressive strength

As mentioned in the case of tensile strength, in all mix designs the values of compressive strength are relatively low, because of the low amount of cement in the binder. Note again that consistently with their "pozzolanic property", mortars presented a slow rate of compressive strength development, as it was the case with the tensile strength. In this experimental study, the compressive strength increased significantly after the age of 28 days in three mixtures (mixtures 1, 2 & 3). The last mixture (mixture 4) after the age of 28 days presents a dramatically slow rate of strength gain; there is no difference in the values of compressive strength measured at the ages of 28 and 90 days.

The results provided from compressive tests at the age of 90 days are in agreement with those measured by other researchers in a wide range of old mortars, e.g. [2]. As reported in the literature, compressive strength of old mortars ranges between 2.5 – 5.0 MPa. The values obtained in this experimental study present a compressive strength range between 2.3 – 2.8 MPa (at the age of 90 days). As mentioned above, the slow rate of strength development in pozzolanic mortars outlines that compressive strength at the age of 90 days is not the final for the mortars tested.

The binder to aggregates ratio affected profoundly the value of compressive strength. Mixture 1 had a binder:aggregates ratio equal to 1:2, whereas mixture 3 had a binder:aggregates ratio equal to 1:4 (all other parameters were constant). In mixture 1, the dosage of aggregates used led to increased values of compressive strength and a fast rate of strength development. When a significant increase in
the dosage of aggregates was applied, a slower rate of strength gain and an effective reduction of early and later ages compressive strength was recorded. This effect was moderated at the age of 90 days, probably due to the fact that brick fragments behave as porous aggregates.

The aggregate type also appears to have a significant effect, as it is concluded from mixtures 2, 3 and 4. The beneficial effect of brick fragments as aggregates on compressive strength was apparent in those mixtures. Mixture 2, which had the highest amount of brick fragments, presents a satisfactory strength development. This advantage is attributed to the above mentioned property of brick as porous aggregate; and, most likely, to the favourable bond conditions at the paste-aggregate interface. From a comparison of mixtures 3 and 4 it is clear that sand addition in larger amounts counteracts the benefit of brick fragments due to increased porosity resulting from the inadequate compaction.

Through the comparison of mixtures 2, 3 and 4, it appears that the ratio of aggregates used affected the compressive strength. The increased amount of sand instead of brick fragments provoked a slow rate of strength development and a low early age strength. This was caused by an effective reduction of the water available for hydration, since sand had a very large surface area for wetting. For this reason the mortar mixture with the larger amount of sand was not as adequately compacted as that containing the smaller sand content, leading to a less satisfactory response. Note that, whereas the sand:brick ratio is equal in mixtures 1 and 3, the variation in binder:aggregates ratio led to considerably different compressive strength results because of the increased specific surface area. This trend became less pronounced in mixture 2, where the increased dosage of brick fragments had a beneficial effect in the rate of strength development. This is due to the high water absorption capacity of brick aggregate and its property to render water during hydration.

3.3 Weight loss

Weight loss is owing to water evaporation and affects profoundly physical and mechanical properties of mortars. Drying shrinkage, due to water loss, significantly increases the deformation of mortar by invariably reducing its original dimensions. Tensile and compressive strength are also affected by water loss because of the weakness induced in the specimen. A large amount of water loss diminishes the amount of water stored in the mortar and leads to strength reduction and deficient durability.

The weight loss curves plotted in Figure 1 are the results of weight loss measurements on the 40x40x160 mm prisms (each curve represents one mixture). The coordinates represent, in percentage, the mean value of weight loss in the mixture as a function of age. A stabilization of results was observed after an age of about 7 days.

As expected, mixture 1 has experienced the largest amount of weight loss, because of the high content of brick fragments which favour the water retainment and consequently the water loss due to evaporation. The amount of
mixing water physically bound in the pores of brick material decreases dramatically as hydration progresses.

Figure 1: Weight loss of mortars

Through the comparison of mixtures 1 and 3, where the binder:aggregates ratio changes, it appears that the rate and the quantity of weight loss diminish as the sand dosage increases in the mixture and the brick content reduces, respectively. For the same level of hydration, sand needs a smaller amount of physically bound water (compared with brick), which results in a smaller quantity of evaporated water.

The different sand:brick fragments ratio used in mixtures 2, 3 and 4 led to different rates of weight loss, supporting the observation that water loss in mortar is intimately related to the type of aggregates used. It is evident that mixture 2 presented the greater percentage and the faster rate of weight loss because of the increased amount of brick fragments. The above mentioned property of brick, i.e. to maintain a quantity of mixing water physically bound in its pores, leads to a very fast rate of change of weight due to evaporation. A lower percentage of weight loss was presented in mixtures 3 and 4 where the sand content was 50% or 75%, respectively, of aggregate content.

From the above it becomes evident that the type of aggregates and their content controlled the weight loss of mortar.

3.4 Drying shrinkage

Drying shrinkage was monitored by performing length change measurements on prismatic specimens 40x40x160 mm up to the age of 15 days where a stabilization of the values was observed clearly. The results are illustrated
collectively in Figure 2, in order to compare the strain caused in each mixture due to water loss and hydration of the components.

**Drying Shrinkage**

Whereas the shrinkage in all mixtures did not vary considerably until the 4\textsuperscript{th} day after demoulding, the slope thereafter was reduced when the sand and brick fragments were of unequal contents, as in mixtures 2 and 4. For an equal sand:brick ratio, mixtures 1 and 3 developed an increased shrinkage rate, which led to higher strain values. From the curves corresponding to mixtures 1 and 3, it is observed that the shrinkage of mortars was not affected by the binder:aggregates ratio. Through this comparison it appears that the magnitude of shrinkage is not affected in a clear manner by the type or the dosage of aggregates or by the water:binder ratio.

This behavior during mortar shrinkage was reported by other researchers too [10]. It may be seen that mortar (as concrete) containing large amounts of brick aggregate, in general, shrunk less than the corresponding silicate-aggregate mortar, at all ages. The rate of shrinkage of mixtures 2 and 4 as compared to mixture 3 supports the observation of other researchers. It was noted that the reduced shrinkage of brick-aggregate mixture contradicts the expectation that brick aggregates offer less deformation resistance to the shrinkage of paste due to their lower modulus of elasticity [11]. Also, there is a possibility that the aggregate itself is subjected to shrinkage. This effect is explained because drying shrinkage in brick-aggregate mixtures is delayed by continued hydration due to the presence of internal moisture in the aggregate; an experimental period of more than a year would be necessary to eliminate this effect. It was concluded that the normal assumption of shrinkage being dependent on total moisture content does not apply to brick mixtures [10].
4 Conclusions

The mix designs employed in this study were developed in order to estimate the effect of binder:aggregates ratio and the effect of aggregate type and ratio in repair mortars of equal workability. The main physical and mechanical properties investigated were: weight loss, drying shrinkage, tensile and compressive strength.

The lower binder:aggregates ratio (1:2) gives the highest strength (both compressive and tensile) due to the low amount of mixing water required, but leads to an increased weight loss and drying shrinkage.

The results of this experimental study illustrate that the use of brick fragments (as compared to sand) as aggregates in mortars improves the early age strength development; but after the age of 28 days, the strength development rate is delayed. There is a greater degree of strength development when sand is used, but after the age of 28 days, strength values did not increase. The addition of large quantities of brick fragments in the mixture also increases the weight loss values. The greater dosage of sand in aggregate content corresponds to a less precipitous water loss and a lower deformation.

From the above preliminary test results, it is clear that the type and ratio of aggregates used in repair mortars for historical structures plays a major role (which reached a degree of quantification in this study) in physico-mechanical properties.

References


