IV.12

Characterization of Repair Mortars for the Assessment of their Compatibility

Özlem Cizer¹, Luc Schueremans¹, Elke Janssens¹, Gerty Serré¹ and Koenraad Van Balen¹

¹ K.U.Leuven, Belgium, Ozlem.Cizer@bwk.kuleuven, Luc.Schueremans@bwk.kuleuven.be, Koenraad.VanBalen@bwk.kuleuven.be

Abstract Compatibility requirements for repair mortars used in restoration works are defined based on the original mortar characteristics, but the quality and the performance of the repair mortars after application on masonry are generally not assessed. From this perspective, original mortars and their repair mortars from three historic masonry structures were characterized to assess their compatibility in terms of chemical, mineralogical, physical and mechanical point of view. A methodology relying on a fundamental approach for a mortar analysis is adopted taking into account the added values and the basic requirements from both practical and scientific point of view. This study is aiming to contribute to the existing knowledge on mortar characterization and to provide new insights on the assessment of the compatibility of the repair mortars.

1 Introduction

In restoration works, design and application of a repair mortar that will closely match with the existing historic materials and that can replace the original mortar requires an extensive and an elaborated work to be carried out within a complete framework: on-site investigation and collecting original/historical mortar samples; characterization of the original mortar within its historical context; a damage analysis to retrieve the basic causes for which a repair mortar is to be applied; defining an optimal intervention strategy; formulation of a repair mortar composition based on above conclusions; and application of the repair mortar by suitable workmanship and technology. This concept brings together a series of interrelated performance requirements to be addressed in terms of authenticity, reversibility, compatibility, retreatability, function and technology [1-3].

One of the fundamental aspects on which the design of a repair mortar should rely is the compatibility of the new mortar with the existing historic materials,
meaning that new mortar to be used does not have negative consequences on the historic materials, and should respect heritage values and authenticity. This will direct the intervention decisions towards the concept of suitable preservation, and will define the boundaries of functional and technical requirements of the repair mortar, which will limit the impact of intervention. Within this strategy different compatibility requirements can be addressed such as aesthetical compatibility, chemical compatibility, mineralogical compatibility, physical compatibility and mechanical compatibility. These requirements will influence each other to certain extents depending on the function of the mortar and on the restoration concept.

After formulating a compatible repair mortar, the information is handed over towards the restoration engineer/architect who outlines the repair mortar recipe within the technical specifications to be used by the contractor. However, a quantitative verification of the actual composition used within the restoration work is seldom performed. The overall judgement of the mortar quality applied on masonry only relies on visual inspection. In this article, compatibility of the repair mortars proposed by laboratory/academic research with those applied subsequently on masonry is assessed. This study is the part of an extensive research on the compatibility of repair mortars used in restoration works, which was studied in a master thesis [4] and will be extended with further research.

2 Case studies

Three case studies in Belgium have been studied taking into account a detailed investigation of the original mortars performed initially by the Reyntjens Laboratory, K.U.Leuven (B). Interviews with all parties involved (contractor, architect, engineer) were performed to get full information on their experience and their opinion on the compatibility performance of the repair mortars used.

Church of Our Lady in Tongeren (B) The monument listed since 1936 is located at the centre of the town as an important landmark for the vicinity. The subsoil below and around the basilica contains traces of 20 centuries of Roman civilization (starting from the 1st century BC) and religious history of the Middle Ages. In the nave of the church an archaeological cellar was constructed in which archaeological excavations up to a depth of 3 m below the present floor level were performed. The archaeological findings were consolidated to enable the exhibition of the site to the public. Repair mortars were formulated taking into account the compositions of the original mortars and their visual aspects to achieve a good aesthetical match with the existing authentic materials. In our research [4], various original and repair mortar samples were collected. In this article, only two mortar types are presented: original brick-laying mortar (T3) dating back from the 1st century after Christ, and its repair brick-laying mortar (T4).

Abby of Herkenrode in Kuringen (B) Dating back from 1182, the abbey suffered from war and plundering in the period of 1300-1500. It is listed as an
historical building since 1974. Starting from 2003-2004, all buildings on the site underwent a stability and a historical value assessment. The old farmhouses and porter’s lodge belonging to the abbey have been restored and are refunctioned as a domain for cultural and recreation activities. In this article, results of the original mortar (H0) and its repair mortar from stables (H2) are discussed.

Table 1 Type and composition of the repair mortars that were prescribed and used in restoration.

<table>
<thead>
<tr>
<th>Mortar ID</th>
<th>Mortar type</th>
<th>Mortar composition</th>
<th>Used:</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>Bedding</td>
<td>Prescribed:</td>
<td>1 volume part of lime putty</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 volume parts pozzolanic red brick powder and brick parts (&lt; 6mm)</td>
<td>1 volume part Oolitic fine Bath limestone powder (&lt;1mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 parts quartz sand (&lt;0.5mm)</td>
<td>0.5 volume parts pozzolanic brick powder</td>
</tr>
<tr>
<td>H2</td>
<td>Pointing</td>
<td>Prescribed:</td>
<td>Used:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 mass parts sand</td>
<td>6 mass (3 volume) parts of white sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 mass part of binder, containing 1/3 mass parts of cement and 2/3 mass parts of lime</td>
<td>2 mass (0.5 volume) parts of yellow sand</td>
</tr>
<tr>
<td>L3 and L4</td>
<td>Bedding</td>
<td>Prescribed and used:</td>
<td>2 mass (0.75 volume) parts of lime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 volume part white sand; 2 volume parts yellow sand Cantillana; 1 volume part white cement; 1 volume part shell sand; 8 volume parts rolled gravel (&lt;0.7)</td>
<td>1 mass (0.25 volume) parts of cement</td>
</tr>
</tbody>
</table>

Castle ruins Pietersheim at Lanaken (B) This water castle dating back from the 12\textsuperscript{th} century has undergone several subsequent building periods and drastic changes. The masonry of the entrance gate is composed of three-leaf masonry with a sandstone parament and rubble infill masonry. The 16\textsuperscript{th} century defence walls (thickness: 2.0m), were made out of a thick core infill mortar and a thin outer parament of limestone (thickness: 15-30 cm). Overall the limestone parament has disappeared due to the reuse of stones, eroding, degradation by plant growth, freeze-thaw action, etc. The restoration concept was to keep the infill masonry visible and to prevent the underlying masonry from further degradation.
Two types of repair mortars (L3 and L4), which were prescribed in the same mortar composition but applied on masonry in different periods, are studied.

3 Methodology for repair mortar characterization

A systematic approach for the characterization of historic mortars with respect to their repair has been defined by RILEM TC 167 COM which offers a valuable tool to identify mortar components, nature of binder, aggregate, additives, and their relative proportions [2]. Following the same approach, we have adopted a limited set of analytical techniques to characterize the repair mortars. Dedicated site work and laboratory work were followed to achieve an effective characterization in terms of textural, physical, chemical, mineralogical and mechanical point of view. The site work includes sampling, on-site investigation and non-destructive testing of the mortars. The laboratory work covers various analytical and testing methods to characterize the mortar constituents and to define mortar properties in a comprehensive way.

Visual analysis: On-site visual investigation was performed by naked eye and by documentation with colour scale to define colour, texture and surface finishing properties of the mortars. A detailed investigation was further carried out at the laboratory using stereo microscope.

Chemical characterization: Chemical composition of the mortar samples was determined using wet chemical analysis [5] and using X-ray fluorescence (XRF) for the comparison. The latter provides only chemical composition of the mortar constituents. However, wet chemical analysis relies on acid dissolution/separation of the binder from the aggregate, and provides additional information on the chemical composition of the acid-soluble binder and the aggregate, and their relative proportions unless the aggregate is acid-soluble. After separation, particle size distribution of the aggregate fraction was determined. Interestingly, large differences were recorded between wet chemical analysis and XRF results [4].

Mineralogical characterization: Chemical characterization cannot solely yield all the information needed for a complete interpretation. Confirmation of the evidence of identification from chemical composition should be supported by combined methods including mineralogical analysis. To do so, mineral composition of the finest fraction (≤80 μm) was identified using X-ray diffraction (XRD) analysis which allows the identification of crystalline phases in the binder. Since the amorphous phases coming from hydration and pozzolanic reactions are very difficult to detect or are even not detectable, XRD was complemented with thermogravimetric analysis (TGA) which can identify these reaction products as well as the degree of carbonation and hydration reactions.

Physical properties: In our study, attention goes to the porosity properties of the mortars such as total porosity, open porosity and apparent density.
Mechanical properties: This was assessed via pointing hardness by pendulum hammer performed as a non-destructive testing at site [6]. Due to the lack of mortar samples in desired quantity and dimensions, mechanical strength via direct testing methods could not be performed.

Table 2 Chemical composition (by wet chemical analysis), physical properties and binder/sand fractions of the original and repair mortars.

<table>
<thead>
<tr>
<th></th>
<th>T3</th>
<th>T4</th>
<th>H0</th>
<th>H2</th>
<th>L0</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>original</td>
<td>repair</td>
<td>original</td>
<td>repair</td>
<td>original</td>
<td>repair</td>
<td></td>
</tr>
<tr>
<td>L.O.I at 540°C (m.%)</td>
<td>3.53</td>
<td>3.58</td>
<td>3.48</td>
<td>4.07</td>
<td>/</td>
<td>2.10</td>
<td>2.87</td>
</tr>
<tr>
<td>L.O.I at 1050°C (m.%)</td>
<td>11.92</td>
<td>25.82</td>
<td>17.70</td>
<td>9.61</td>
<td>5.94</td>
<td>10.01</td>
<td>7.92</td>
</tr>
<tr>
<td>Insoluble part (m.%)</td>
<td>72.40</td>
<td>27.46</td>
<td>59.61</td>
<td>75.88</td>
<td>86.42</td>
<td>75.12</td>
<td>73.46</td>
</tr>
<tr>
<td>Soluble SiO₂ (m.%)</td>
<td>1.50</td>
<td>5.24</td>
<td>1.18</td>
<td>1.86</td>
<td>1.01</td>
<td>1.25</td>
<td>2.59</td>
</tr>
<tr>
<td>CaO (m.%)</td>
<td>10.65</td>
<td>38.57</td>
<td>19.41</td>
<td>10.77</td>
<td>5.78</td>
<td>12.03</td>
<td>13.67</td>
</tr>
<tr>
<td>MgO (m.%)</td>
<td>0.27</td>
<td>0.06</td>
<td>/</td>
<td>0.12</td>
<td>0.00</td>
<td>0.30</td>
<td>0.24</td>
</tr>
<tr>
<td>Fe₂O₃ (m.%)</td>
<td>0.06</td>
<td>0.24</td>
<td>/</td>
<td>0.15</td>
<td>0.15</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃ (m.%)</td>
<td>0.60</td>
<td>0.62</td>
<td>/</td>
<td>0.40</td>
<td>/</td>
<td>0.32</td>
<td>0.50</td>
</tr>
<tr>
<td>SO₃ (m.%)</td>
<td>0.48</td>
<td>0.98</td>
<td>/</td>
<td>0.70</td>
<td>/</td>
<td>0.56</td>
<td>1.06</td>
</tr>
<tr>
<td>Sum (m.%)</td>
<td>97.05</td>
<td>98.99</td>
<td>97.90</td>
<td>99.49</td>
<td>99.15</td>
<td>99.18</td>
<td>98.50</td>
</tr>
<tr>
<td>CO₂ (m.%)</td>
<td>9.49</td>
<td>21.89</td>
<td>14.29</td>
<td>7.29</td>
<td>4.09</td>
<td>7.61</td>
<td>4.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>T3</th>
<th>T4</th>
<th>H0</th>
<th>H2</th>
<th>L0</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>original</td>
<td>repair</td>
<td>original</td>
<td>repair</td>
<td>original</td>
<td>repair</td>
<td></td>
</tr>
<tr>
<td>Hydraulicity index</td>
<td>0.20</td>
<td>0.15</td>
<td>/</td>
<td>0.21</td>
<td>/</td>
<td>0.13</td>
<td>0.23</td>
</tr>
<tr>
<td>Cementation index</td>
<td>0.44</td>
<td>0.40</td>
<td>/</td>
<td>0.53</td>
<td>/</td>
<td>0.32</td>
<td>0.56</td>
</tr>
<tr>
<td>App. density (kg/dm³)</td>
<td>1.428</td>
<td>1.503</td>
<td>1.608</td>
<td>1.861</td>
<td>2.077</td>
<td>1.899</td>
<td>1.953</td>
</tr>
<tr>
<td>Open porosity (v.%)</td>
<td>45</td>
<td>42</td>
<td>31</td>
<td>27</td>
<td>21</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>Binder/sand-ratio</td>
<td>0.38</td>
<td>2.64</td>
<td>0.43</td>
<td>0.32</td>
<td>0.15</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>Sand (m.%)</td>
<td>72.40</td>
<td>27.46</td>
<td>59.61</td>
<td>75.88</td>
<td>86.42</td>
<td>76.37</td>
<td>73.46</td>
</tr>
<tr>
<td>Lime (m.%)</td>
<td>15.20</td>
<td>*</td>
<td>25.6</td>
<td>7.13</td>
<td>11.00</td>
<td>17.28</td>
<td>8.02</td>
</tr>
<tr>
<td>Pozzolan (m.%)</td>
<td>2.66</td>
<td>*</td>
<td>/</td>
<td>2.00</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Cement (m.%)</td>
<td>/</td>
<td>*</td>
<td>/</td>
<td>7.02</td>
<td>/</td>
<td>/</td>
<td>12.33</td>
</tr>
</tbody>
</table>

*: could not be quantified due to the limestone aggregate fraction

4 From characterization towards compatibility

Original brick-laying mortar T3 is a typical Roman mortar composed of brick dust, brick particles and white inclusions of lime giving crucial information on how the binder was prepared such as the way the lime was slaked. After analyses of this type of mortar by K.U.Leuven, a mortar recipe (T4) was prescribed with a composition of lime putty, brick particles/dust and quartz sand which are compatible with the original materials (Table 1). However, the executed mortar composition of T4 was altered in proportions and in components by the restoration
architect. The fractions of lime putty and sand were kept the same but that of brick particles/dust was replaced by chalk and by limestone powder to duplicate white lime inclusions present in the original mortar. These materials are not compatible with the original materials used and cannot be treated as the part of the binder. The mortar composition of T4 was optimized by the restoration architect for visual reasons to achieve an aesthetical match with the original mortar in terms of colour, texture and structure (Fig. 1). Therefore, a large difference is realized in the chemical compositions of T3 and T4 with the insoluble part referring to the aggregate fraction, the amount of soluble SiO₂ originating from hydration products and the amount of CO₂ related to the calcium carbonate phases (Table 2). The insoluble part in T4 is considerably low because of the presence of chalk and limestone powder being soluble in acid, making the retrieval of the relative proportions of binder and aggregate quite difficult. Higher content of soluble SiO₂ in T4 repair mortar indicates higher degree of hydration reactions due to the pozzolanic reaction between brick particles and lime. This large compositional difference between T3 and T4 is also observed in their mineral compositions (Table 3). TGA results support these findings with different CaCO₃ and CO₂ fractions, the latter being very similar to the values obtained from wet chemical analysis (Table 4). Additionally, the presence of Ca(OH)₂ in T4 repair mortar is recorded in the XRD and TGA results.

No visual comparison could be made between the original mortars and the repair mortars from the other two case studies of Abbey of Herkenrode and Castle ruins Pietersheim due to the lack of access to the original mortars in masonry. Similar to the first case study, visual aspect was one of the major concerns for the restoration architect. Sand fraction in the prescribed mortar composition of H2 was replaced with white and yellow sand during restoration to duplicate the visual aspects of the original mortar (Table 1). Although the original mortar H0 is a pure lime mortar, the repair mortar contains a small fraction of cement together with lime to get a faster hardening and initial strength. This has resulted in differences in terms of chemical composition and porosity between H0 and H2 (Table 2),
altering compatibility and authenticity aspects defined initially. Traces of bassanite are found in H2 due to the use of cement (Table 3).

Regarding the third case study of Castle ruins Pietersheim, L3 is the repair mortar applied on masonry during the first phase of restoration of the defence wall. Second phase started after two years when L4 repair mortar was applied. According to the information taken from the restoration architect, in the first phase of restoration the recipe of the repair mortar was altered to get a better aesthetic match with the original mortar as well as a better workability on site. For that purpose, several test areas were mutually assessed both by the contractor and by the restoration architect. The optimal composition was then prescribed in the second phase. An important aspect in this case is the change in function of the repair mortar from bedding to infill mortar which has a protective function for the underlying masonry. Also in this case study, visual aspect was one of the major concerns for the restoration architect. White cement and white sand were used to duplicate the visual aspect of the original lime mortar while achieving faster hardening with cement, which is similar to the previous case study.

Table 3 Mineral composition of the binder fraction of the mortars.

<table>
<thead>
<tr>
<th></th>
<th>Calcite [CaCO3]</th>
<th>Quartz [SiO2]</th>
<th>Portlandite [Ca(OH)2]</th>
<th>Bassanite [CaSO4.1/2 H2O]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>++</td>
<td>+++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T4</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>H2</td>
<td>+++</td>
<td>++</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>L3</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>L4</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

+++ : dominantly present; ++ : present; + : traces; - : not detected

Table 4 Ca(OH)2, CaCO3, CO2 and hydration degree determined using TGA.

<table>
<thead>
<tr>
<th></th>
<th>Ca(OH)2 (%)</th>
<th>CaCO3 (%)</th>
<th>CO2 (%)</th>
<th>Hydration degree (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>0.00</td>
<td>21.65</td>
<td>9.52</td>
<td>4.39</td>
</tr>
<tr>
<td>T4</td>
<td>2.07</td>
<td>60.99</td>
<td>26.83</td>
<td>5.58</td>
</tr>
<tr>
<td>H2</td>
<td>0.00</td>
<td>30.27</td>
<td>13.32</td>
<td>19.45</td>
</tr>
<tr>
<td>L3</td>
<td>0.00</td>
<td>57.71</td>
<td>25.39</td>
<td>9.29</td>
</tr>
<tr>
<td>L4</td>
<td>5.60</td>
<td>35.86</td>
<td>15.78</td>
<td>9.04</td>
</tr>
</tbody>
</table>

Mechanical properties of the mortars were estimated via pointing hardness that measures the quality of the pointing work done [6]. The results are given in Table 5. Repair mortars L3 and L4 indicate relatively similar values. A large difference is recorded between T3 and T4 mortars. Relatively low rebound value of T3, despite its currently sound state, is related to the lack of uniform surface on which the test was performed. It is worth to note that the use of pointing hardness test is limited for the application to lime mortars which can give low rebound values.
This does not mean that the mortar is in a bad condition. The measurements are in fact affected by a number of variables, such as surface roughness, subsurface anomalies (voids, near-surface cracks, or incipient spalls), specimen geometry, vicinity of nearby edges and hammer orientation. Despite this, pointing hardness is a useful means to assess the mortar quality in cases where mortar samples cannot be collected for direct mechanical testing.

Table 5  Pointing hardness of the mortars by pendulum hammer.

<table>
<thead>
<tr>
<th>Mortar ID</th>
<th>Pointing hardness</th>
<th>Class</th>
<th>Range</th>
<th>Indicated quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>16.00</td>
<td>A</td>
<td>15-25</td>
<td>Soft</td>
</tr>
<tr>
<td>T4</td>
<td>51.33</td>
<td>D</td>
<td>45-55</td>
<td>Hard</td>
</tr>
<tr>
<td>H2</td>
<td>37.75</td>
<td>C</td>
<td>35-44</td>
<td>Normal</td>
</tr>
<tr>
<td>L3</td>
<td>26.20</td>
<td>B</td>
<td>25-34</td>
<td>Moderate</td>
</tr>
<tr>
<td>L4</td>
<td>27.50</td>
<td>B</td>
<td>25-34</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

5  Conclusions and final remarks

- Some clear differences are evidenced between laboratory/academic research and restoration practice. Aesthetical/chemical/mineralogical compatibility is the main aspect for the laboratory/academic research while formulating a repair mortar composition. On the other hand, restoration architects seem to be interested mainly in the aesthetical aspects of the repair mortar. This raises the question to what extent compatibility in one aspect is to be merged or sacrificed with/by other compatibility/authenticity requirements.
- Compatibility and authenticity aspects defined for the repair mortar are often compromised by the restoration architect with the concern of achieving faster hardening by introducing cement into the binder composition.
- Assessment of a compatibility of repair mortar via analytical methods is a useful tool but is not always possible in practice. Application of a compatible repair mortar can be ensured by a continuous communication and collaboration among laboratory/academia, restoration architect and contractor.
- Skilled workmanship as a technical input is not considered in restoration works but is essential in the formulation and application of repair mortars [7].

6  References