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Assessment of the Compatibility of Repair Mortars in Restoration Projects

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Abstract In restoration works compatibility requirements of repair mortars are defined based on the original mortar characteristics, but the efficiency and the performance of the repair mortars after application on masonry are not generally evaluated. From this perspective, original mortars and repair mortars from two historic masonry structures were analyzed for their characterization. Compatibility of the repair mortars with the historic mortars is investigated in terms of chemical, mineralogical, and physical point of view. The efficiency of the analytical techniques used for the mortar characterization is discussed. A methodology relying on a basic 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 will contribute to the existing knowledge on mortar analysis and will provide new insights on the assessment of the compatibility of the repair mortars.

Keywords: Repair mortar, compatibility assessment, restoration, historic masonry

Introduction

Within the framework of a restoration project, the proposal of a compatible repair mortar often relies on an extensive on-site campaign taking mortar samples, followed by a laboratory study aiming at characterizing the original mortar composition, enabling the proposal of a compatible repair mortar recipe. These findings are 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 works is seldom performed. In addition, an overall judgement of the final result only relies on visual inspection.

This article aims at giving feedback related to the overall procedure followed to propose repair mortars by laboratory/academic research and their application in restoration practice afterwards. Two case studies have been treated at which all chains within the procedure are considered in detail. In these case studies, a thorough pre-investigation of the original mortars was performed initially by the Reyntjens Laboratory, K.U.Leuven (B) on mortar samples collected from the historical structures. Subsequently a recipe for the repair mortar(s) was prescribed within the technical specification by the restoration engineer/architect and subsequently applied on site. After application a second on-site campaign was performed within the framework of this research to collect samples of the repair mortars used and assess their compatibility. 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.

Defining the Requirements and the Methodology

In the field of conservation of architectural heritage, 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: characterization of the original/historical mortar and 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 repair mortar 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 (Bartos et al. 1999, Groot et al. 2005, Van Balen et al. 2005a).

One of the fundamental concepts on which the design of the repair mortar should rely is the compatibility of the new mortar with the existing historic materials. This will direct the intervention decisions towards the concept of suitable preservation, and will define the boundaries of functional and technical requirements that will limit the impact of intervention. Within this strategy different compatibility requirements can be searched for, which will influence each other to certain extents:

- Aesthetical compatibility: colour, texture, visual appearance;
- Chemical compatibility: chemical composition, binder/aggregate fraction, hydraulicity;
- Mineralogical compatibility: mineral phases, type of aggregate and binder,
- Physical compatibility: particle size distribution, porosity properties, physical properties,
- Mechanical compatibility: strength and stiffness properties.

Fundamental aspects of mortar characterization with respect to their repair have been defined by RILEM TC 167 COM systematically (Groot et al. 2005). This dedicated work gives important tools to identify the mortar components, nature of binder, aggregate, additives, and their relative proportions. In our study, we have adopted certain techniques to characterize repair mortars with the aim of assessing their compatibility with the original mortar and with the proposed mortar compositions.

Methodology followed is composed of dedicated site work and laboratory work. The site work includes sampling, on-site investigation and non-destructive testing of the mortar. The laboratory work covers a wide range of analytical and testing methods to characterize the mortar constituents and to define mortar properties in a comprehensive way (Cizer et al. 2007).

Visual Analysis On-site visual investigation was performed by naked eye and by documentation with colour scale using a camera to define colour, texture and surface finishing properties of the mortar. A detailed investigation was further carried out at the laboratory using stereo microscope. The amount of the mortar samples collected, ranges between 50-150 g.

Chemical and Mineralogical Characterization Chemical composition of the mortar samples was determined using wet chemical analysis according to NBN B15-250 (1991). Mineral composition of the finest fraction (<80 μm) was identified using X-ray diffraction (XRD) analysis. Thermogravimetric analysis (TGA) was performed to determine the degree of carbonation and hydration reactions. Combining these results the type of the binder, aggregate and additives could be defined and their relative ratios could be estimated.

Physical Properties This part covers the porosity properties of the mortars such as open porosity and apparent density.

Mechanical Properties This was assessed via pointing hardness. However, the research could not be extended towards the aspects of mechanical compatibility due to the lack of mortar samples in desired quantity and dimensions.

Case Studies

The church of Our Lady in Tongeren (B) is considered to be one of the most important historical buildings in the area and is listed since 1936. The subsoil below and around the basilica contains traces of 20 centuries of Roman civilization (starting from the 1st century BC) and religious history during the Middle Ages (Fig. 1). In the nave of the church an archeological cellar is constructed in which archeological excavations up to a depth of 3 m below the present floor level were performed. The archeological findings have been consolidated to enable the opening of the site towards a wide public. Mortar samples from different periods were characterized and repair mortars were proposed.

During this research, a series of samples of original and repair mortars were collected from several locations. In this article, attention will be paid on two mortar types: original brick laying mortar (T3) dating back from the 1st century after Christ, and its repair brick laying mortar (T4).

Figure 1: Archaeological cellar at church of Our Lady in Tongeren (B (left) and farm wing at the site of Abbey of Herkenrode in Kuringen (right)

The second case study is the site of Abbey of Herkenrode in Kuringen (B) dating back from 1182 when Count of Loon offers land to a monk to build an abbey. After a strong growth till 1217, the abbey started to suffer from war and plundering in the period 1300-1500. Since 1974 it is listed as an historical building. The old farmhouses belonging to the abbey are now transformed into a site which is currently used as a domain for cultural and recreation activities. Starting from 2003-2004, all buildings on the site underwent a stability and a historical value assessment.

Repointing repair mortars were collected from the abbey barn, stables and porter's lodge. These three repair mortars were treated with the same mortar composition prescribed. However, our results indicate that the compositions of these repair mortars differ slightly from each other due to the different contractors dealing with the restoration work (Janssens and Serré 2010). In this article, results of the original mortar (H0) and its repair mortar from stables (H2) will be discussed.

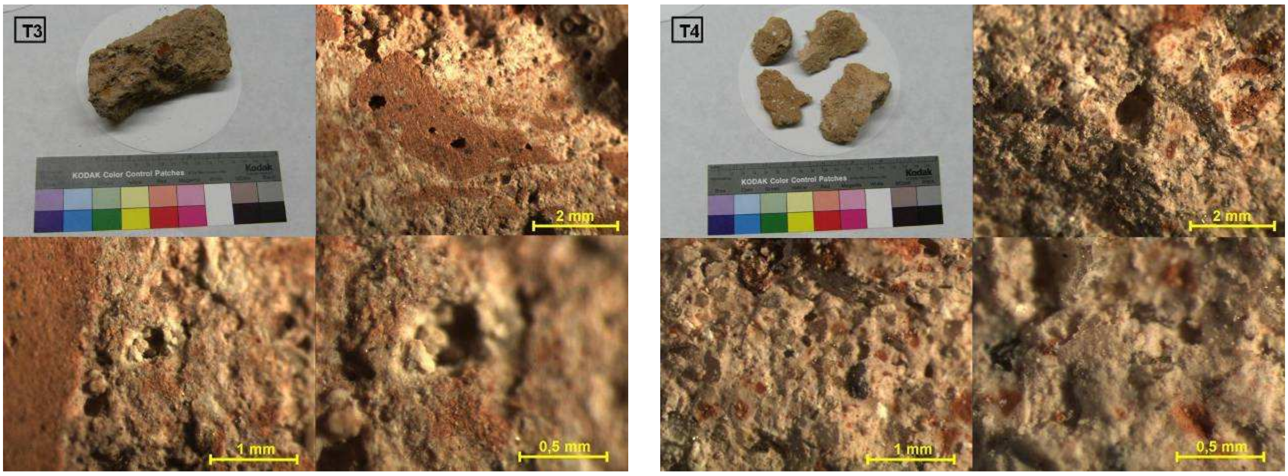

Figure 2: Original brick laying mortar (T3) (left) and repair brick laying mortar (T4) (right)

From Characterization towards Compatibility

From visual layout of the existing original mortar T3 and executed repair mortar T4 nearly a perfect match is realized (Fig. 2). Both mortars include brick particles and white inclusions related to the binder part. On the other hand, a large difference is recognized in their chemical compositions with the insoluble part referring to the aggregate fraction, the amount of soluble SiO_2 originating from hydration products and the amount of CO_2 related to the calcium carbonate phases (Table 1). The insoluble part in T4 is considerably low because of presence of chalk and limestone powder which dissolve in HCl during wet chemical analysis. This gives higher fractions of CaO and CO_2. Higher content of soluble SiO_2 in T4 repair mortar indicates higher degree of hydration reactions indicating pozzolanic reaction between brick particles and lime. This large compositional difference between T3 and T4 mortars is also observed in their XRD patterns with varying intensities of calcite and quartz minerals (Fig. 3). TGA results support these findings with large differences in $CaCO_3$ and CO_2

fractions, the latter being very similar to the values obtained from wet chemical analysis (Table 2). Additionally, these two analytical techniques give information on the presence of calcium hydroxide in T4 repair mortar, which cannot be determined by wet chemical analysis.

Table 1: Chemical characterization and composition of original and repair mortars.

	Tongeren		*Herkenrode*	
	T3	*T4*	*H0*	*H2*
	original	*repair*	*original*	*repair*
Loss at ignition 540°C (m%)	3.53	3.58	3.48	4.07
Loss at ignition 1050°C (m%)	11.92	25.82	17.70	9.61
Insoluble part (m%)	72.40 (73.8)	27.46	59.61	75.88
Soluble SiO_2 (m%)	1.50 (1.5)	5.24	1.18	1.86
CaO (m%)	10.65 (15.8)	38.57	19.41	10.77
MgO (m%)	0.27	0.06	/	0.12
Fe_2O_3 (m%)	0.06	0.24	/	0.15
Al_2O_3 (m%)	0.60	0.62	/	0.40
SO_3 (m%)	0.48 (0.2)	0.98	/	0.70
Sum (%)	97.05	98.99	97.90	99.49
CO_2 (m%)	9.49	21.89	14.29	7.29
Hydraulicity index	0.20	0.15	/	0.21
Cementation index	0.44	0.40	/	0.53
App. density (kg/dm³)	1.428	1.503	1.608	1.861
Open porosity (v%)	45	42	31	27
Mortar composition				
Binder/sand-ratio	0.38	2.64	0.43	0.32
Sand (m%)	72.40	27.46	59.61	75.88
Lime (m%)	15.20	*	25.6	7.13
Pozzolan	2.66	*	/	/
Cement (m%)	/	*	/	7.02

*: could not be quantified due to limestone aggregate fraction

Intentional use of pozzolanic brick powder in T4 repair mortar for visual concerns has improved the mortar quality with a high structural integrity. However, together with the addition of limestone powder and chalk, this complex composition leads to vast different conclusions, as can be seen from the binder to sand ratio (Table 1). The low amount of soluble part together with the high amount of soluble CaO warns for partial soluble aggregates in the mixture that are wrongly interpreted as part of the binder fraction based on a wet chemical analysis solely. This has been verified by the particle size distribution before and after HCl attack on the aggregate fraction (Janssens and Serré 2010). Besides wet chemical analysis, XRD and TGA cannot retrieve actual composition of this type of T4 mortar without having information on the exact fractions of the components within the mix.

T4 is the prescribed repair mortar composed of lime putty, brick particles/dust and quartz sand (Fig. 4). However, the executed mortar composition was altered in fractions 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 limestone powder to duplicate white lime inclusions present in the original mortar T3, giving crucial information on how the binder was prepared such as the way lime was slaked (Fig. 4). These materials are not compatible with the original materials used and cannot be treated as the part of binder. These results clearly indicate that mortar composition of T4 was optimized by the restoration architect for aesthetical reasons to reach compatibility with the original mortar in terms of colour, texture and structure.

Similar conclusions are also drawn from the second case study. Chemical composition of H2 repair mortar differs from H0 original mortar composition with insoluble part, CaO content and CO_2 content. Although the original mortar is pure lime mortar, the repair mortar contains a small fraction (1/3rd of binder fraction) of cement together with lime to get a faster hardening and initial strength. Also in this case study the visual aspect was one of the major concerns for the restoration architect.

Sand fraction in the prescribed mortar composition was replaced with white and yellow sand to duplicate the visual aspects of the original mortar (Fig. 5).

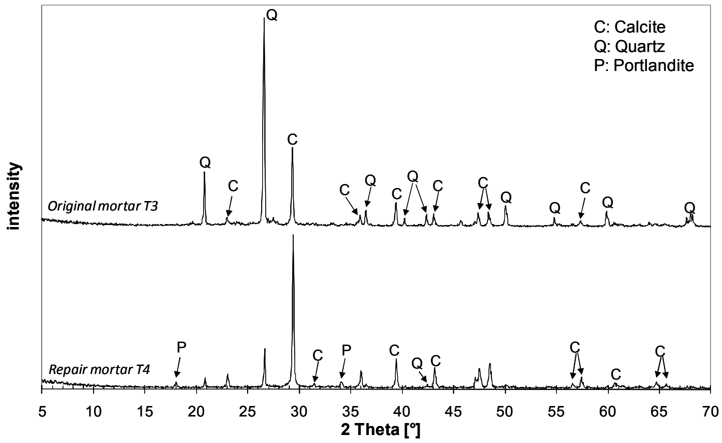

Figure 3: XRD patterns of original mortar T3 (top) and repair mortar T4 (bottom).

Table 2: Calcium hydroxide, calcium carbonate, carbon dioxide and hydration degree determined using TGA.

	$Ca(OH)_2$ (%)	$CaCO_3$ (%)	CO_2 (%)	Hydration degree (%)
T3	0.00	21.65	9.52	4.39
T4	2.07	60.99	26.83	5.58
H2	0.00	30.27	13.32	19.45

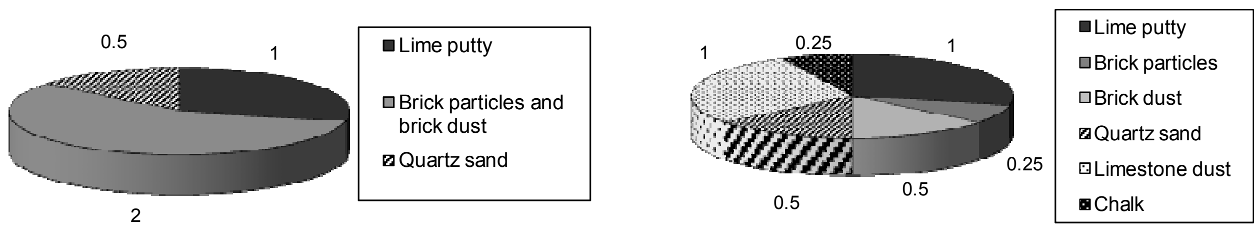

Figure 4: Compositions of the prescribed repair mortar (left) and executed repair mortar (right) of T4 (in volume fractions).

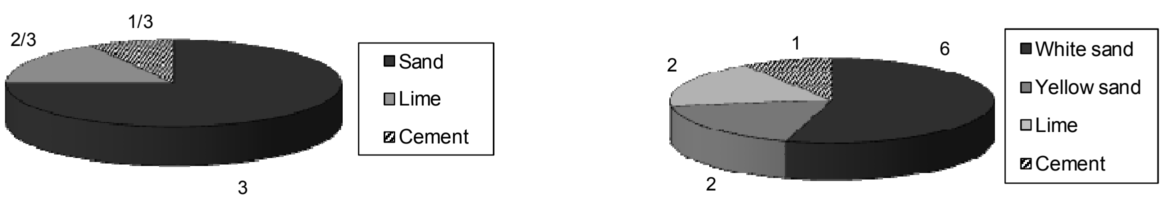

Figure 5: Compositions of the prescribed repair mortar (left) and executed repair mortar (right) of H2 (in mass fractions)

Synthesis and Conclusions

From a dedicated comparison between original and repair mortars from two case studies, some clear differences were evidenced between laboratory/academic research and restoration practice:

- Useful information related to the mortar components and their relative ratios can be extracted from wet chemical analysis unless limestone aggregates are used. Analytical techniques such as XRD and TGA can give additional information on the crystalline mineral phases, and on the degree of hydration and carbonation reactions giving evidence on the type of binder.
- Chemical characterization provides quantitative comparison between the actual composition used and the prescribed composition. This method gives results in mass ratios. However, in practice preferably volume parts are used, which was the case in church of Our Lady in Tongeren. Therefore, transition from mass to volume parts based on overall bulk densities of the raw materials should be counted for actual consultancy.
- It has been confirmed that what is executed by the contractor does not always correspond with what is prescribed by the laboratory/academic research for the repair mortar. Aesthetical concerns can forge ahead other aspects of compatibility such as chemical and mineralogical compatibility. This raises the question to what extent compatibility in one aspect is to be merged or sacrificed with/by other compatibility/authenticity requirements.
- Strength-stiffness requirement is an important parameter for compatibility but its priority may be less depending on the function of the mortar such as repointing mortar. However, it will gain an important status in case of bedding mortar and therefore must be considered in such cases.
- Ultimately, an important parameter which will affect the final performance of the repair mortar must be taken into account: skilled workmanship as a technical input which is not considered but is essential in the formulation and execution of repair mortars (Van Balen and Hendrickx 2008). As water content is not given in the prescribed mortar composition, the judgement of the craftsman will have a crucial impact on the final state of the fresh mortar mix and therefore on the ultimate state of the hardened mortar and of the masonry. This must be considered and integrated into the design of the repair mortar together with the envisaged compatibility requirements.

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