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Original article

Characterization and compatibility assessment of commercial stone repair mortars

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ABSTRACT

Compatibility of repair materials in conservation is a widely desired goal, but difficult to achieve. In this research, the compatibility of four commercial stone repair mortars, commonly used in conservation practice in the Netherlands and neighbouring countries, is discussed. In order to do so, they have been characterized in laboratory. The composition of the repair mortars, their content of soluble salts, porosity and pore size distribution, hygric dilation and flexural and compressive strength were measured. The effect of curing was assessed by comparing specimens cured in laboratory and under outdoor conditions. The effect of 3 years outdoor exposure on the curing and weathering of the mortars was evaluated. The results show that the composition of the selected mortars varies significantly, even though, based on their technical information sheets, they appeared to be similar. Consequently, their moisture transport properties differ significantly. As expected, both the type of binder and the porosity were shown to affect the mechanical properties of the mortar: the mortar based on an inorganic polymer binder showed the highest mechanical strength; the most porous, lime- or lime-cement-based mortars, showed the lowest mechanical strength.

Based on compatibility criteria defined in literature and the results obtained in this research, an attempt was made to assess the technical compatibility of the selected mortars with building stones commonly used in the Netherlands. It was found that some requirements are hard to be fulfilled and not all requirements can be fulfilled at the same time. Besides, technical sheets of commercial mortars are often incomplete; therefore repair mortars can hardly be selected based only on the properties reported by the producers.

1. Introduction

Stone repair mortars are used in conservation practice to replace or to model missing parts in brick or stone units or decoration elements in natural stone or terracotta. The scope of the repair can be aesthetic (improvement of the appearance) and/or functional (prevention of further decay).

Next to self-made mortar recipes, very often ready-mix stone repair mortars are applied in conservation works. These mortars are generally made available by producers in a large range of colour and grain size distribution of the aggregate, with the aim of tuning the properties of the repair mortar (mainly from the aesthetic point of view) to those of the substrate on which they are applied.

Ready-mix stone repair mortars have the advantage not to require the specialized knowledge necessary for developing self-made mortars and to ensure a constant quality of the product. Besides, these mortars have generally a very good workability, which makes their application fast and easy. However, they have some major disadvantages: their detailed composition is generally not known and their properties, when reported in the information sheet, are not detailed enough [1]. This information is of crucial importance for evaluating their physical, chemical and mechanical compatibility with the substrate on which they are going to be applied. For example, knowledge about the type of binder and the presence of some additives (air entraining, water repellent, etc.) can be relevant to estimate the risk of salt efflorescence, frost decay, biological growth etc. Relevant properties, such as those related to the moisture transport behaviour of the mortars, are seldom mentioned. When values are given, these often vary within a large range and the testing procedures are not mentioned, making this information of limited value.

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This makes it necessary for the conservator to investigate the properties of the commercial repair mortars before selecting a mortar suitable for the specific substrate and application.

The choice of a repair mortar should be made taking into account, next to its performance, its compatibility with the substrate on which it is applied. Compatibility includes both aesthetic (e.g. colour and texture) and technical (mechanical, physical and chemical) compatibility [2]. A repair mortar can be considered compatible from the technical point of view if it does not lead to technical (material) damage to the original material, within the service life of the repair [3]. Therefore, compatibility criteria always relate the properties of the repair mortar with those of the original material.

In order to assess the technical compatibility of a repair mortar, technical requirements can be defined. In the literature of the last 20–25 years, requirements for a wide range of compatibility criteria are defined in more or lesser detail. WTA Merkblatt 3-11-97/D [4] is one of the first documents to propose specific requirements for repair mortars. These requirements are general and simple: the properties (elastic modulus, compressive strength, water absorption by capillarity, water vapour diffusion resistance and thermal and hygric dilation) of the repair mortar should be as much as possible similar to those of the substrate on which the mortar has to be applied. As no measure of the acceptable variation is given, these guidelines can only help ranking different repair mortars according to their compatibility.

Snethlage [5] and Siegesmund and Snethlage [6] formulate quantitative requirements for dynamic E-modulus, compressive strength, thermal dilation, water absorption coefficient (WAC), water vapour diffusion resistance and strength of adhesion of the mortar to the substrate. The requirements to the mortar are formulated as a percentage of the value measured for the substrate with respect to the considered property: for example, the compressive strength of the repair should be equal to or lower than 60% of the compressive strength of the substrate.

Delgado Rodrigues and Grossi [7] suggest an interesting, slightly different approach to conservation interventions, among which also the use of repair mortars. They propose to assess, in a semi-quantitative way, the "incompatibility risks" based on some compatibility indicators (type of binder, type of aggregate, thermal expansion, bending strength, etc.). The added value of this approach consists in giving a relative weight to each of the indicators. The sum of all scores for incompatibility risks gives an overall measure of the degree of compatibility of the repair mortar to the substrate and it facilitates the comparison between different mortars.

In 2014, Isebaert et al. [8] slightly adapt (or replace by a generic text "similar to that of the stone") the requirements previously proposed by [5,6] and add requirements related to the total porosity and pore size distribution. The grain size distribution and the mineral components of the mortar are mentioned but no requirements are defined. Isebaert and co-authors introduce some requirements related to the durability of the repair mortar with respect to biological growth: the mortar should weather in a similar way as the substrate. Besides, they propose an order according to which properties can be tested when assessing the compatibility of repair mortars. This order can also be seen as a type of ranking of the importance of different properties in determining the compatibility. In this way it should be possible to test the most important properties at an early stadium of mortar development, making it easier to adapt the mortar composition and limit further testing. Obviously, this approach is only possible in the case of self-made mortars, and when sufficient budget and time are available.

The literature on compatibility requirements makes evident the difficulties encountered by researchers when defining quantitative requirements and ranking the individual requirements in order of importance. Moreover, the requirements reported in literature have been defined by experts, based on their professional knowledge and experience of which unfortunately little has been published. At the authors' best knowledge, the proposed requirements have not been yet thoroughly assessed, neither "theoretically" (i.e. it has not yet been attempted to evaluate the compatibility of repair mortars according to the defined requirements) nor experimentally (i.e. it has not been assessed whether repair mortars which fulfil these requirements are actually not causing any damage to the substrate and vice versa). Studies on accelerated weathering tests carried out in laboratory and reports on observations in the field (e.g. [9–12]) are generally not relating the properties and the behaviour of the mortars with the compatibility requirements.

2. Research aims

The research presented in this paper has two main goals.

Firstly, it aims to get more insight in the properties of ready-mix stone repair mortars. Four commercial mortars, commonly used in conservation practice in the Netherlands (and also on the market in several other European countries), were characterized in laboratory. Their main physical, mechanical and chemical properties were assessed.

Secondly, it attempts an assessment of the technical compatibility of the investigated commercial ready-to-use repair mortars with some stone substrates, common in Dutch monumental buildings and objects. The assessment is "theoretical", i.e. based on the comparison of the properties of the repair mortars (measured in this research) with those of the natural stones (retrieved from literature).

3. Materials and methods

3.1. Materials

Four commercial ready-mix mortars were selected among those commonly used in conservation practice in the Netherlands, as resulted from an on-line questionnaire among architects, conservators and other practitioners and from inspections of case-studies [13]. The description of the products reported below is based on the information provided in the producer's technical data sheets:

- Repair mortar R: mortar with mineral binder and natural stone aggregate.
- Repair mortar J: mortar with mineral binder, especially developed for the repair of natural stone.
- Repair mortar MT: mortar with mineral binder and natural stone aggregate. The mineral binder is an inorganic polymer resulting from a reaction between the liquid and the solid components after mixing.
- Repair mortar MS: mortar with mineral binder.

These mortars are available in a range of colours and grain size distributions, in order to adapt them to different substrates. In this research we selected for all mortars a maximum size of the aggregate of 0.5 mm and a neutral (beige) colour, in order to facilitate the comparison.

3.2. Specimens preparation and curing

The mortars were prepared according to the instruction given the producers. Mortars R, J and MS were prepared adding tap water in an amount sufficient to obtain a workability between 155 and 165 mm, measured according to NEN-EN 413-2:2016 [14]. The water content varied between 16.3 wt% (mortar MS) and 26.2 wt%

Table 1
Type of specimen, size, curing conditions and investigations carried out.

Specimen	Size [mm]	Curing	Investigation
Type A	160 × 40 × 40	Few days under plastic sheets, followed by 28 days at 20 °C 95% RH	Mechanical strength
Type B	210 × 100 × 20	(1) Few days under plastic sheets, followed by 28 days at 20 °C 95% RH	Moisture transport properties, porosity & pore size distribution, microscopy study on thin sections, salt content
		(2) Additional specimens: few days under plastic sheets, followed by curing outdoors	
		Few days under plastic sheets, followed by curing outdoors	Microscopic study on thin sections
Type C	160 × 40 × 20	Few days under plastic sheets, followed by curing outdoors	Hygric dilation

(mortar J); the water content of mortar R was 21 wt%. Mortar MT was prepared using the reaction liquid provided with the dry mortar, in the amount suggested by the producer (22.6 wt%); it was not possible to measure the workability of mortar MT due to its very quick setting.

All mortar specimens, with the exception of those used for the determination of the mechanical strength, were prepared on a porous substrate; in fact, it is known that the properties of a mortar prepared in a mould of non-absorbing material (such as metal or polystyrene) may differ from those of the same mortar when applied on a porous substrate, and be therefore less representative of the properties of the mortar in the field [15]. Depending on the test to be carried out, some of the specimens were detached from the substrate after a few days, before complete hardening. In order to facilitate the detachment, a paper tissue was used between the substrate and the mortar.

After few days under plastic sheets, part of the specimens was stored in a climatic cabinet at 20 °C 95% RH for 28 days (optimal curing conditions for cement-based mortars); other specimens were stored sheltered outdoors. These two different curing conditions (laboratory and outdoor) were selected to check the effects of the curing conditions and to investigate the alteration of the mortars over time due to outdoor exposure. After 28 days, the specimens which were stored in the climatic cabinet at 20 °C 95% RH were moved to a 20 °C/65% RH room. For each type of repair mortar, specimens of different size and shape were prepared (type A, B and C) to be used in the different characterization tests (Table 1).

3.3. Characterization methods

Several mortar properties were investigated: composition (type of binder, aggregate and possible presence of additives as far as detectable by microscopy observation), porosity, pore size distribution and moisture transport properties, hygric dilation and flexural and compressive strength.

Polarizing and fluorescent microscopy (PFM) observations were carried out on thin sections of the mortars, after different periods of curing and outdoor exposure. Specimens were prepared by impregnating the mortars under vacuum with a UV-fluorescent resin and then cutting and polishing the samples to obtain thin sections of 25–30 μm thickness [16]. For each mortar type, both specimens cured under lab conditions (20 °C/95% RH) and outdoors were studied at 28 days. Those exposed outdoors were also investigated after 1 and 3 years (except mortar MT, for which not enough specimens were available).

The water-soluble salt content of the mortars was measured by Ion Chromatography (IC) on mortar samples, cured in laboratory for 3 years (type B). 0.5 g powder samples were dissolved in 30 ml deionized water (Millipore Ultrapure), the solution was further diluted 5 times and analyzed by ion chromatography (Dionex ICS 90).

The porosity and the pore size distribution of the mortars were measured in twofold with the use of Mercury Intrusion Porosimeter (Micrometrics Autopore IV9500) on samples of about 1 cm^3, collected from specimens of type B. A contact angle of 141° is assumed between pore walls and mercury; pressures between 3741 Pa and 210 MPa were applied, which allow to intrude pores with neck diameter between 7 nm and 400 μm.

The capillary water absorption of the mortars was measured in threefold on 50 × 50 × 20 mm specimens cut from mortar slabs of type B after 28 days of curing at 20 °C 95% RH. The specimens were dried at 40 °C, cooled down to room temperature and RH (20 °C/50% RH) and sealed on the lateral sides with epoxy resin. Absorption took place from the 50 × 50 mm surface originally in contact with the substrate. The weight of the dry specimens [Md] was measured before the start of the test; during the test, the weight of the specimens was recorded at regular intervals. The water absorption coefficient (WAC) was calculated as the slope of the first, linear part of the water absorption curve. After saturation with water by capillarity, the weight of the saturated specimens in air [Mw_{air}] and under water [Mw_{water}] was measured and the density D [kg/dm^3] and porosity P [vol%] were calculated as follows [17]:

$$D = Md/(Mw_{air} - Mw_{water})$$

$$P = 100 * 1 - D/2650$$

where 2650 kg/dm^3 is a reference density value for a stone-like building material without pores.

After saturation at atmospheric pressure, the bottom of the specimens was sealed with impermeable tape (in such a way that drying could only occur through their top surface) and the specimens were stored at 20 °C/50% RH to dry. The weight of the specimen was recorded at regular time intervals (every day during the first week and once a week later on) to assess their drying rate.

The hygric dilation of the mortar was measured on specimens of type C by means of a dilatometer (precision 0.001 mm). After conditioning of the specimens at 20 °C/30% RH, the RH was increased stepwise to 50, 65, 80 and 95% RH, while keeping the temperature constant; finally, the specimens were immersed in water. Each condition was kept constant for at least 24 h. At the end of each period, the length and weight of the specimens of the specimens were recorded and the hygric dilation coefficient calculated as follows:

$$eh_{h1-h0} = [1000 * (L_{h1} - L_{h0})]/L_{h0}$$

where $eh_{h1\text{-}h0}$: hygric dilation coefficient between initial condition h_0 and condition h_1, in μm mm^{-1}, L_{h1}: length of the specimen in μm at condition h_1, L_{h0}: length of the specimen in μm at condition h_0.

The flexural and compressive strength of the mortars at 28 days were determined on 5 specimens of type A for each mortar type, according to NEN-EN 196-1:2016 [18]; the specimens were saturated in water before testing. At first the flexural strength was determined; then the compressive strength was measured on the two resulting half specimens.

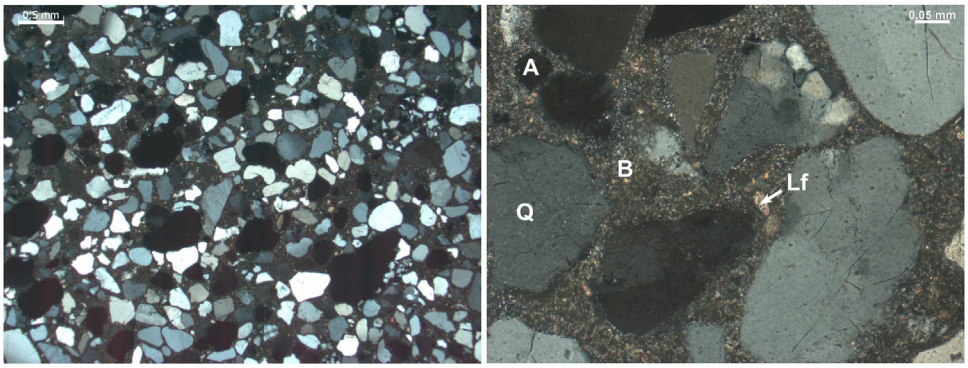

Fig. 1. Left: Microphotograph with an overview of the microstructure of repair mortar R, showing the presence of large voids (black) and locally lack of compactness (after 28 days of curing outdoors; cross polarized light. Right: Microphotograph with a detail of the binder of mortar R (after 1 year of curing outdoors; cross-polarized light). A = air void; B = binder matrix; Q = quartz sand; Lf: limestone filler.

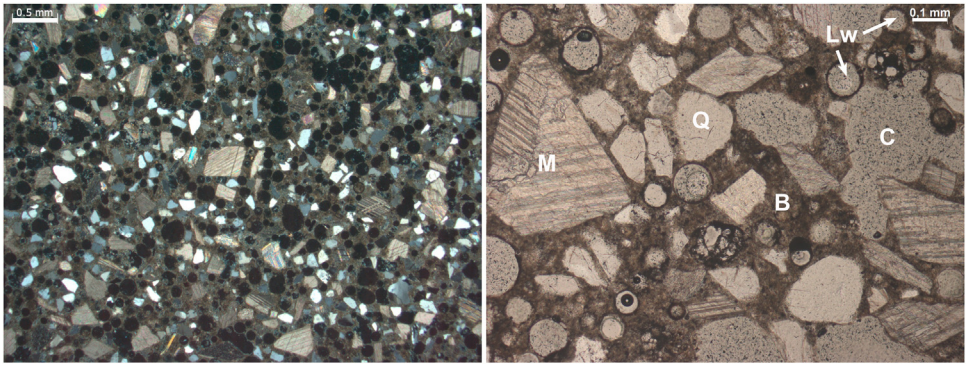

Fig. 2. Left: Microphotograph with an overview of the microstructure of mortar J (cross polarized light). Right: Microphotograph with detail of mortar J (after 1 year of curing outdoors; plain polarized light). B = binder matrix; Q = quartz sand; M = crushed marble; C = compaction void; Lw = lightweight aggregate.

4. Results

4.1. Mortar composition and microstructure

Mortar R (Fig. 1) is composed of Portland cement binder with the addition of limestone powder and well-rounded quartz sand. The porosity, as visible under microscopic observation of the thin section, is estimated to be about 15 vol%. Large voids are present, most probably due to the limited compaction during application; no air bubbles, as would have resulted from the presence of air entraining agents, are observed. After 1 year of curing outdoors, carbonation is still limited to the exterior surface (less than a few mm). After 3 years outdoors, the mortar is completely carbonated. No cracking, weathering or deterioration are observed.

Mortar J (Fig. 2) shows the presence of a lime binder with some hydraulic components, C_2S and possibly C_3S; based on these observations it can be concluded that the binder is a mix of air lime with some Portland cement or hydraulic lime. The aggregate is constituted by light-weight aggregate (expanded clay), crushed marble and well-rounded quartz sand. The mortar is fully carbonated already after 28 days of outdoor exposure. Also in this case air bubbles are scarce, but several large voids are present, due to insufficient compaction. The open porosity, visible by microscopy, can be estimated to be about 5 vol%; additionally, there is about 10 vol% of mostly closed porosity constituted by the hollow lightweight aggregate. After three years outdoors exposure, no cracking, weathering or deterioration are observed.

Mortar MT (Fig. 3) has a non-traditional binder, probably originating from the reaction between zinc oxide powder and the reaction liquid, a water solution of zinc chloride [19]. There is no experience with the microscopic investigation of this type of binder. The aggregate is (sub)rounded limestone with a small amount of fine quartz sand. The porosity of this mortar visible by microscopy is about 1 vol%. Unfortunately, no specimens of MT were available for carrying out investigation on MT mortar after 1 and 3 years outdoors exposure.

The thin section of mortar MS (Fig. 4) shows the presence of a binder containing both C_2S and C_3S, indicating Portland cement; the aggregate is constituted by well-rounded quartz sand. Large voids, due to lack of compaction, are present. The porosity visible by optical microscopy is estimated to be about 30 vol%. The mortar was already fully carbonated after 28 days of curing. After three years of outdoors exposure, no deterioration, weathering or cracking are observed.

4.2. Porosity and pore size distribution

The open porosity and pore size distribution of the repair mortars, as resulting from MIP measurements, are reported in Fig. 5.

Repair mortar J shows the highest porosity (45 vol%), with a majority of pores between 0.02 and 0.1 μm and between 1 and 2 μm diameter. The fine porosity is due to the porosity in the hydraulic binder and, most probably, to the porosity in the hollow lightweight aggregate. The latter porosity is usually closed, but may be partly accessible through cracks etc. or because the thin walls of the lightweight aggregate broke at high intruding pressures, allowing for intrusion of mercury in the (relatively large) hollow aggregate; this resulted in the large intrusion volume measured in the high pressure range. For this reason, the open porosity measured by MIP might be overestimated.

Repair mortar MS has an open porosity of 39 vol%, with pores in a wide size range and a large volume of pores larger than 10 μm.

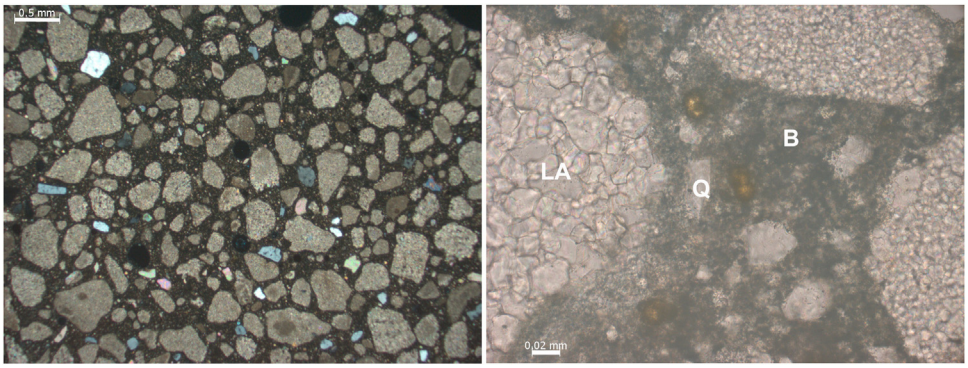

Fig. 3. Left: Microphotograph of mortar MT (after 28 days curing under laboratory conditions; cross polarized light). Right: detail of the binder matrix of the same sample (plain polarized light). B = binder matrix; Q = quartz sand; LA = limestone aggregate.

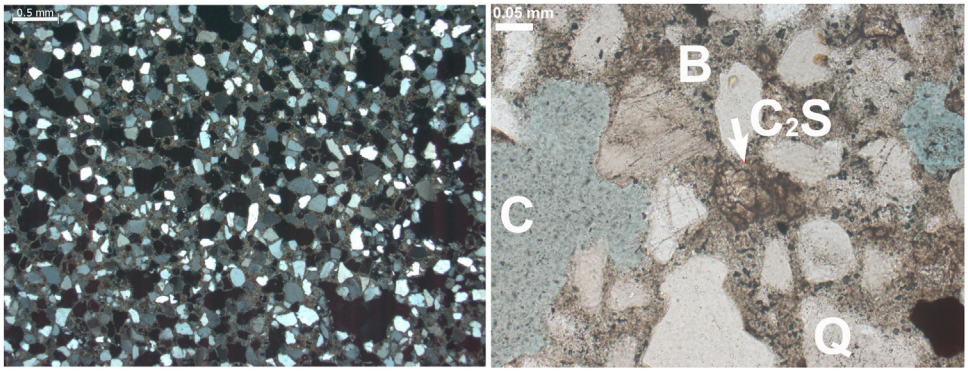

Fig. 4. Left: Microphotograph with overview of the microstructure of mortar MS with quartz sand as aggregate (after 28 days curing outdoors; plain polarized light). Right: Microphotograph of a detail of mortar MS: example of C_2S in the binder (after 28 days curing outdoors; plain polarized light). B = binder matrix; Q = quartz sand; C = compaction void.

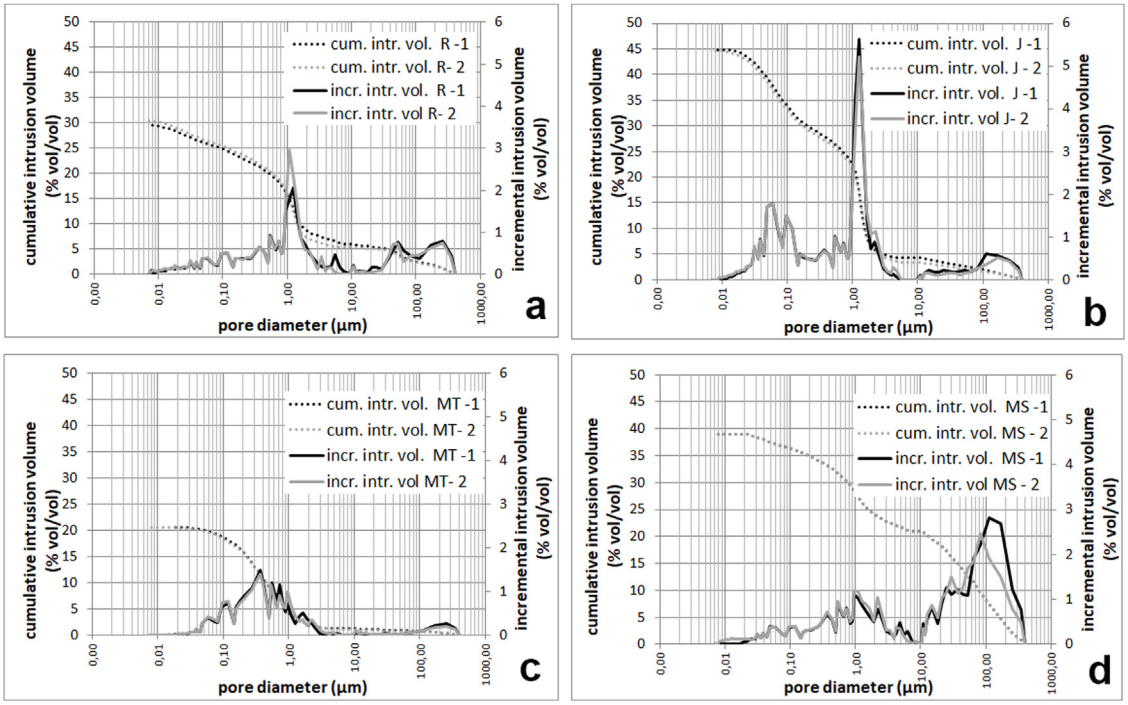

Fig. 5. Pore size distribution (continuous line) and open porosity (dotted line) of the repair mortars as measured by MIP; a: mortar R; b: mortar J; c: mortar MT; d: mortar MS. For each mortar two MIP measurements were carried out, reported with black and grey line.

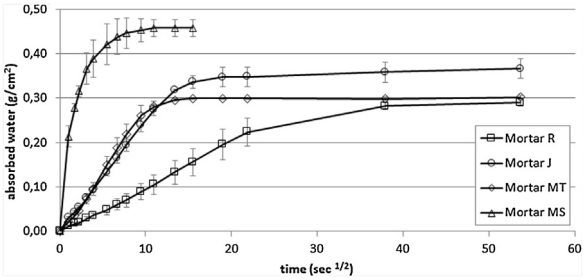

Fig. 6. Capillary water absorption of the repair mortars.

Also in this case, pores in the range 0.02 and 1 μm are present, due to the porosity in the hydraulic binder and to interstitial porosity.

Repair mortar R has an open porosity of 30.5 vol%, with most pores in the range between 1 and 2 μm; smaller and coarser (between 50 and 300 μm) pores are present as well. The coarser pores are probably the voids observed in the thin section and can be attributed to the scarce compaction of the mortar during preparation; the smaller pores constitute the porosity in the hydraulic binder.

Repair mortar MT shows the lowest open porosity among the investigated mortars (20.5 vol%). Its pore size is unimodal, with most pores between 0.1 and 1 μm. In this case, the voids larger than 100 μm observed in the thin sections were not measured by MIP: this can be due to the fact that the small samples used for the MIP measurements (about 1 cm^3) and these might not contain voids or have voids of sizes exceeding the range measurable by this technique.

4.3. Moisture transport properties

The capillary water absorption of the repair mortars is shown in Fig. 6. The water absorption coefficient (WAC), density and porosity as measured by immersion are reported in Table 2.

Repair mortar MS shows the fastest capillary absorption (WAC 1412 g m^{-2} $s^{-0.5}$). This behaviour can be explained by its high proportion of pores with radius between 10 and 100 μm which contributes to quick and high water suction by capillarity. Repair mortars MT and J have a comparable WAC (275 and 217 g m^{-2} $s^{-0.5}$ respectively). Based on porosity results, a lower water absorption rate would have been expected for mortar MT than measured, as this mortar has the lowest open porosity among all tested mortar and relatively small pores. The reason of this behaviour is not clear; it might be related to a different contact angle between water and the binder of this mortar or to the specific connectivity of the pore system. Mortar R has the slowest capillary absorption (WAC = 102 g m^{-2} $s^{-0.5}$) among the investigated mortars. The reason for the slower capillary absorption of mortar R cannot be directly deduced based on the MIP results. The connectivity and tortuosity of the pore network, or the possible use of additives (not detectable with the used investigation methods) might be the reasons of these differences.

The density of the mortars varies between 1350 kg/m^3 (mortar J, with lightweight aggregate) and 2303 kg/m^3 (mortar MT).

The porosity measured by immersion is, with the exception of mortar MT, always higher than the porosity measured by MIP. This is probably due to the presence of large voids, which are visible in the thin sections, but fall often outside the measuring range of the MIP. These large voids are absent in mortar MT. The porosity assessed on thin sections includes air and compaction voids, but not the smaller pores below the resolution of light microscopy; a consequently, the porosity assessed on thin sections is lower than that measured by immersion and MIP. Differences are the smallest in the case of MS mortar, which has a large volume of coarse pores, and the highest in the case of MT mortar, which has mainly fine pores.

The drying curves of the mortars are reported in Fig. 7. Repair mortar MS and J show a similar drying rate: both have an initially almost linear drying phase (liquid moisture transport) followed by a slower drying phase (water vapour transport). In repair mortars R and MT, which dry slower, this difference is less evident.

When comparing the capillary absorption and the drying curves, it can be concluded that mortar MT absorbs relatively fast but dries slowly. This might have negative consequences for its durability.

4.4. Water soluble salt content

The results of the ion chromatography are reported in Fig. 8. It is possible to observe that all mortars except MT have similar type and content of soluble ions. The mortars J, R, MS have a high calcium content, most probably deriving from the dissolution of calcium compounds present in the mortar itself. Next to Ca^{2+} ions, SO_4^{2-} ions have been detected in mortars J, R and MS, most probably present in the form of gypsum ($Ca_2SO_4{\cdot}2H_2O$). Gypsums was possibly used as setting agent in the Portland cement present in these mortars. Some minor amounts of potassium ions are present as well.

The ion chromatography results for MT mortar are diverging from this general trend. Mortar MT has a lower Ca content, whereas it shows a high content of chloride ions. This is related to the composition of this mortar. The fact that chloride ions have been dissolved in water suggests that dissolution can occur also in the field, and possibly lead to formation of chloride salts. Additionally, low amounts of sodium and potassium ions have been detected.

4.5. Mechanical properties

The average flexural and compressive strength values of the mortars (in saturated conditions) are reported in Table 3. Mortar MT shows the highest strength: its compressive strength is up to 4 times higher that of the other mortars. Repair mortars J and MS have the lowest mechanical strength.

4.6. Hygric dilation

The hygric dilation of the repair mortars is reported in Fig. 9. There is a large scattering of the data; as expected, the dilation increased with increasing RH and, even more, after saturation in water.

Table 2
WAC, capillary water content, density and porosity of the repair mortars (each value is the average of 3 specimens; standard deviations are reported in italics). The porosity, as estimated by microscopy observations on thin sections, is reported for comparison.

Repair mortar	WAC [g/(m^2 $s^{0.5}$)]	Capillary water content [% of dry weight]	Density [kg/m^3]	Porosity by immersion [vol%]	Porosity by MIP [vol%]	Porosity assessed optically by PFM [vol%]
	102 ± *15*	8.9 ± *0.3*	1714 ± *11*	35.3 ± *0.4*	30.1	15
J	217 ± *9*	13.7 ± *0.1*	1350 ± *10*	49.1 ± *0.4*	44.7	5 (+10% closed)
MT	275 ± *23*	6.3 ± *0.1*	2303 ± *3*	13.1 ± *0.1*	20.6	1
MS	1412 ± *55*	16.2 ± *0.4*	1407 ± *6*	46.9 ± *1.4*	39.6 ± *0.1*	30

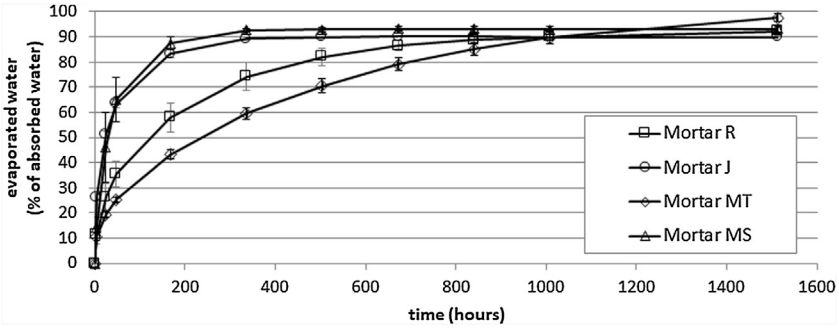

Fig. 7. Drying curves of the repair mortars.

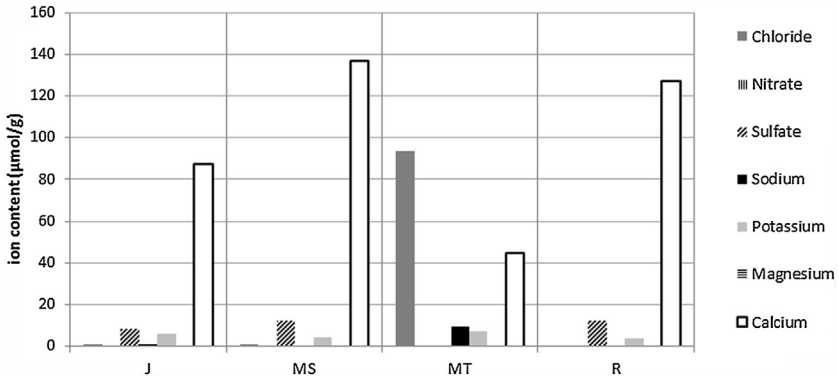

Fig. 8. Water soluble salt content.

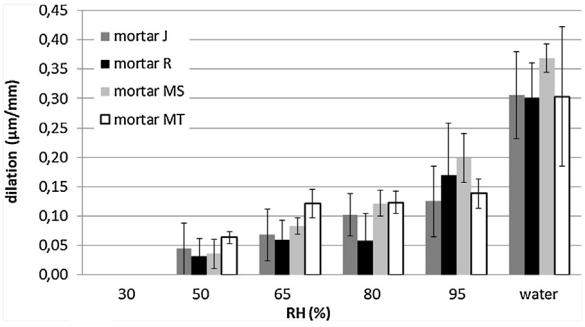

Fig. 9. Hygric dilation of repair mortars (average of 6 specimens).

Table 3
Flexural and compressive strength of the mortars.

Mortar	Flexural strength *(standard deviation)* [N/mm²]	Compressive strength *(standard deviation)* [N/mm²]
J	2.30 *(0.15)*	5.45 *(0.04)*
R	3.38 *(0.08)*	7.37 *(0.15)*
MT	5.56 *(0.52)*	19.54 *(1.05)*
MS	2.49 *(0.24)*	4.67 *(0.64)*

5. Discussion

The characterization tests show that the studied repair mortars have quite different compositions although their description in the technical sheets is very similar (all mortars are described by the producer as containing a mineral binder, some of them with natural stone aggregate). The studied mortars are made with (a mix of) different binders and aggregates, probably in order to obtain certain aesthetic properties (in this case the light colour). The studied mortars show significantly different moisture transport related properties (water absorption and drying behaviour, porosity and pore size distribution). When considering the expected effect of these physical properties of the mortar on its durability, it can be supposed that repair mortars having a high water absorption and a slow drying, such as mortar MT, may remain wet for a longer period and therefore may run a higher risk of frost decay and biological growth; also in the case of the presence of salts in the substrate, these properties would be undesirable. All mortars have a sufficient mechanical strength, but mortars with not traditional binder and those with larger percentage of cement might be stiffer than others [3]. Measurements of the E-modulus could confirm this hypothesis.

An attempt has been made to evaluate the compatibility of these repair mortars with different stone substrates commonly used in the Netherlands and neighbouring countries, based on compatibility requirements established in literature.

These substrates include: Sandy limestones (Lede, Gobertange) from Belgium, widely used in Dutch Gothic architecture, Bentheim and Obernkirchen sandstones from Germany, common all over the Netherlands since the mid-15th century, French Euville and Savonnières limestone, often used for both restorations and new buildings since the middle of the 19th century and native Maastricht limestone, used especially in the south of the Netherlands. Together, they make up quite a significant amount of the (natural stone) building mass in Dutch built cultural heritage. Evidently, they have also been used in their countries of origin.

In the process of compatibility assessment, some difficulties became immediately clear. Some properties, such as the pore size distribution cannot be easily expressed by one single value; therefore, it is not always easy to define what is more or less similar. Moreover, the test methods used and the size of the specimens used for the determination of some properties (such as the WAC and the compressive strength) on the mortar and the stones, when not explicitly specified, might be different and the results not easily comparable.

Table 4
Open porosity, WAC and compressive strength of some stones commonly used in the Netherlands and neighbouring countries [13].

	Open porosity [vol%]	WAC [kg/m² h½]	Compressive strength [N/mm²]
Lede and Gobertange sandy limestone	6–15	4–6	65–75
Bentheim sandstone	20–26	9–16	47–79
Obernkirchen sandstone	16–21	0.5–1	70–94
Euville limestone	7–18	3	12–43
Savonnières limestone	23–40	0.5–2.5	9–30
Maastricht limestone	50	200	5–35

Table 5
Recommended values for some of the properties of repair mortars with respect to those of the stone on which the mortars are applied (based on [8]).

Property	Recommended value (as % of the value measured on the stone)
Open porosity	>80%
Water absorption coefficient (WAC)	50–100%
Compressive strength	20–100%

The values of the properties of these stones, derived from literature [13], are reported in Table 4. In Table 5 the recommended values for the selected properties of the repair mortars, defined in [8], are reported. Finally, in Table 6, an attempt is made to check to which extent the studied mortars would fulfil these recommendations. In order to facilitate the comparison, average values have been used for the stone properties, together with the values assessed in this study. Besides, it should be mentioned that test methods used in the determination of these properties from literature might slightly differ from the methods used in this study. Therefore, the assessment reported in Table 6 should be considered only as indicative.

Despite these limitations, from Table 6 it becomes clear that some requirements might be hard to be fulfilled and that generally not all requirements can be satisfied at the same time. Furthermore, in order to carry out all laboratory tests and measurements, considerable time and budget are needed, which are often not available in conservation practice. Some questions left for future research are how to define a limited number of essential properties for assessing compatibility requirement show to assess these properties by simple tests, preferably applicable on site and if (all) the recommended values (Table 5) are actually feasible.

6. Conclusions

Compatibility of repair materials is a widely desired aim in conservation, though difficult to achieve. In this paper, this is illustrated by four different commercial ready-mix stone repair mortars, widely used in the Netherlands. These mortars may appear very similar from the description reported in their technical data sheets. However, characterization in the laboratory shows them to have a large variation in types of binder and aggregate. This confirms that technical sheets of commercial mortars are often incomplete, cannot be mutually compared and, consequently, that the compatibility of repair mortars can hardly be selected based only on the properties reported by the producers.

Three out of four studied mortars contain a hydraulic binder, sometimes in combination with air lime; one mortar, MT, has a non-traditional binder. The aggregate is often a mixture of different components: rounded limestone and/or quartz sand, light weight aggregate and crushed marble pieces. As a consequence of their diverse composition, the moisture transport properties of the studied mortars differ significantly: mortar MS has the fastest capillary water absorption and drying, due to its high porosity with pores in a range (10–100 μm) which provides a fast capillary transport. Mortar MT has a slow drying, despite its high and relatively fast capillary water absorption. This might be related to the type of binder and/or to the connectivity between the pores.

As expected, both the type of binder and the porosity were shown to affect the mechanical properties of the mortar. The low porous MT mortar, containing an inorganic polymer binder, showed the highest mechanical strength; the highly porous mortars,

Table 6
Assessment of the compatibility of the studied repair mortars with natural stone types commonly used in the Netherlands, based on some of the criteria proposed by [8].

		Measured value (this study)	**Lede/Gobertange sandy limestone**	**Bentheim sandstone**	**Obernkirchen sandstone**	**Euville limestone**	**Savonnières limestone**	**Maastricht limestone**
Open porosity (vol%)		*10.5*	*23*	*18.5*	*12.5*	*31.5*	*50*	
	mortar J	*44.7*						
	mortar R	*30.1*						
	mortar MT	*20.6*						
	mortar MS	*39.6*						
WAC (kg/m²h½)								
	mortar J	*13.0*						
	mortar R	*6.1*						
	mortar MT	*16.5*						
	mortar MS	*84.7*						
Compressive strength (N/mm²)								
	mortar J	*5.45*						
	mortar R	*7.37*						
	mortar MT	*19.64*						
	mortar MS	*4.67*						

Mortar and stone average values are reported in italics. By comparing these values with the requirements reported in Table 5, it is assessed whether the requirement is satisfied (green), at the limit value (orange) or not satisfied (red).

J (containing a mix of lime and cement binder) and MS (based on Portland cement), showed the lowest mechanical strength.

No significant alteration was observed in the mortars after 3 years of outdoor exposure.

The results of the characterization were used to evaluate the compatibility of these mortars with natural stone substrates commonly used in the Netherlands and in neighbouring countries. This evaluation underlined first of all the difficulties of assessing the requirements: some properties, such as the pore size distribution, cannot be easily expressed in one single value; therefore, it is not easy to define which mortar is more or less similar to the substrate with respect to pore size distribution. Moreover, it became clear that some requirements are hard to be fulfilled and not all requirements can be fulfilled at the same time.

Last but not least, it is evident that in order to carry out all laboratory tests and measurements, considerable time and budget is needed, which are often not available in conservation practice.

This suggests that, for making feasible the application of these requirements to the practice of conservation, the selection of a limited number of essential properties and the development of simple tests, preferably applicable on site, to assess these properties would be desirable.

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