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Influence of substrate and sand characteristics on Roman cement mortar performance

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HIGHLIGHTS

- Effect of coarser sand on rheological properties decreases as excess paste increases.
- Porous substrates increase mortar strength and decrease porosity, WAC and shrinkage.
- The influence of substrate on mortar strength is reduced if the substrate is wetted.
- Substrate and sand characteristics and sample thickness affect mortar properties.
- No simple correlation between properties of sampled and standard laboratory mortar.

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ABSTRACT

When formulating repair mortars standard test specimens should be used with caution as these cannot be considered representative of samples of mortars collected on site. This work reports an approach to repair mortar formulation which takes into account the influence of porous substrates, sand characteristics and mortar thickness on the properties of both fresh and hardened Roman cement mortars. It is shown that mortars cast on a dry absorbent substrate show modified properties such as increased strength and decreased water absorption coefficient, the degree of which is a function of sand grading and surface characteristics, sample thickness and substrate sorptivity.

1. Introduction

Repair mortars manufactured and tested in a laboratory are normally cast in standard 40 × 40 × 160 mm steel moulds. These standard test specimens cannot be considered representative of samples of mortars collected on site, which in most cases are applied in 10–20 mm thick layers on or between porous substrates such as brick or stone. Additionally, environmental conditions (e.g. rh, temperature, time, contaminant exposure etc.) are not replicated in the laboratory and the conservator must interpret results to maximise compatibility of the repair mortar.

It has been observed [1–5] that a porous substrate such as brick absorbs water from the fresh mortar and that this phenomenon affects the properties of both the fresh and hardened mortar. The transfer of moisture from mortar to brick leads to a shorter workable life [1–3] and a reduction in the in-situ water/binder ratio of the mortar that influences strength in the hardened mortar [1,4,5] as well as its potential for shrinkage [6]. In particular, Anderegg [1] suggested that the compressive strength of the mortar bed-joint would increase with an increase in the initial rate of suction, while Forth and Brooks [6] showed that the transfer of moisture between mortar and brick decreases the mortar potential for shrinkage. It has been shown [7–9] that moisture flow from mortar to brick is a function of the absorption characteristics of the brick, the water retention capacity of the mortar and the mortar bed thickness and that the key period is within the first few minutes of mortar application. No clear relationship between pre-wetting the brick and moisture transfer has been identified [e.g. 10].

When specifying a repair mortar based on laboratory testing it is also necessary to account for the effect that size and shape of the tested specimen have on the measured strength [11–13].

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Specifically, for a given width of the specimen, compressive strength increases as its height (thickness) decreases. A theoretical explanation of this is that the constraint of the lateral deformation of the tested specimen on the contact surface with the loading frame plate causes a tri-axial stress state in a part of the specimen. This has a greater influence on small specimens because the ratio of the contact surface to the volume of the specimen is higher and the proportion of the specimen volume occupied by the cones of constraint increases [14]. Drdacky [15] has shown that there is not a unique relationship between strength increase and sample geometry and that the relative strengths of the binder must be accounted for. He also states that the maximum sand grain size will be a factor in small samples. Thus, at its most fundamental, the strength of a mortar sample will be a complex function of substrate and mortar characteristics and sample testing regime.

The focus of this work has been to investigate the effect that different brick substrates, specimen thickness and aggregate mineralogy/grading have on strength, shrinkage, water absorption coefficient and pore structure of mortars. This way it is hoped to contribute to the correct evaluation of repair mortars produced in the laboratory under standard conditions. This work was carried out within the EU funded ROCARE project (Roman Cements for Architectural Restoration to New High Standards) and an introduction to these cements and associated mortars may be found elsewhere [16–21].

2. Materials and methods

2.1. Cement and sand

A Roman cement developed during the ROCARE project from marls sourced in Gartenau, Austria, was used throughout this work. The cement was manufactured by The Institute of Ceramics and Building Materials (MBM) in Krakow, Poland; details may be found elsewhere [22].

Two sand sources, one silica from Leighton Buzzard (UK) and one carbonate from Peggau (Austria), have been used throughout the programme. Each aggregate was supplied in single size fractions so that desired gradings could be developed. To achieve this, each individual size fraction was first dry-sieved to determine its own precise grading. This permitted the design of nearly identical gradings for the silica and carbonate sands. Four gradings (1 to 4) have been used for each sand source for the mortar mixes (Fig. 1) and for clarity only the curves for grading 1 have been shown for both sands to illustrate the minimal variability achieved.

Obviously, it is not possible to control the surface texture in the same way and microscopic examination of the sands shows the silica sand to be smooth surfaced (Fig. 2a) with the carbonate sand to be shagreened and with slightly sharper edges (Fig. 2b).

The bulk density of the sand was measured in accordance with BS EN 459-2:2010.

2.2. Substrates

Two brick sources characterised by low (4.11 $\mathrm{kg/m^2/h^{0.5}}$) and high (20.16 $\mathrm{kg/m^2/h^{0.5}}$) water absorption coefficient (WAC) have been evaluated. Fifteen millimetre thick brick slips have been carefully produced to form the sides of beam moulds and were belt-sanded to a smooth and flat finish. Special moulds have been manufactured to accommodate the slips to produce samples with brick–brick interfaces (Fig. 3a), brick–steel interfaces (Fig. 3b) and conventional steel–steel interfaces (Fig. 3c) as control samples. Beams of thickness 10, 15, 20, 25, 30 and 40 mm were produced with a common width of 40 mm and length 160 mm with 3 samples being produced for each configuration. All brick slips were oven dried at 105 °C before being used. After each batch production the slips were immersed in a 10% hydrochloric acid solution, washed and dried. This procedure was adopted after being shown not to modify the WAC of the substrate.

2.3. Mortar production and testing

Mortars, suitable for render applications, were produced at a cement:sand volume ratio of 1:2.5 and constant water/cement ratio of 0.87 (by weight) with various combinations of sand and substrate type (Table 1). The Roman cement was retarded by means of a pre-hydration (or de-activation) process, which consisted of mixing a pre-determined amount of water (7% of the cement weight) with the cement and storing for 30 min prior to subsequent formation into mortars. The retarded cement produced by this process has been termed De-Activated Roman Cement (DARC) and a detailed description of the process and mortar performance can be found elsewhere [22]. The retardation was necessary to achieve the required workable life of 1–2 h for such mortars.

Mortars were produced by mixing the products of the de-activation process with water in a Hobart mixer for 30 s at 62 rpm. At this time the mixer was stopped for 30 s and the mixer bowl scraped. The mixing was then continued for 8 min at 125 rpm. To prevent adhesion of the mortar to the brick slips they were carefully wrapped in Japanese tissue which permitted transport of water but minimised that of solid particles. Samples were cast in two layers and vibration compacted. Immediately upon floating off the fresh mortar, each mould was covered by a polythene sheet and de-moulded after 24 h. Upon de-moulding all mortars were placed in airtight boxes with wet tissues for a further 24 h prior to transfer to water curing at 20 °C. The humidity in the boxes is unknown; however, condensation was observed in the boxes and it is assumed that the rh was close to 100%.

Since the moulding process was prolonged there was insufficient time to measure the workability of the fresh mortar. However, a companion programme assessed the rheology of identical mortars. The flow was measured according to BS EN 10153:1999. The “shear strength” and “plastic viscosity” were measured using a Viskomat NT in which the torque (T) was measured at various rotational speeds (N) which are related as shown in Eq. (1). The constants are proportional to the shear stress (g) and plastic viscosity (h) (see Ref. [23]).

$$T = g + hN \quad (1)$$

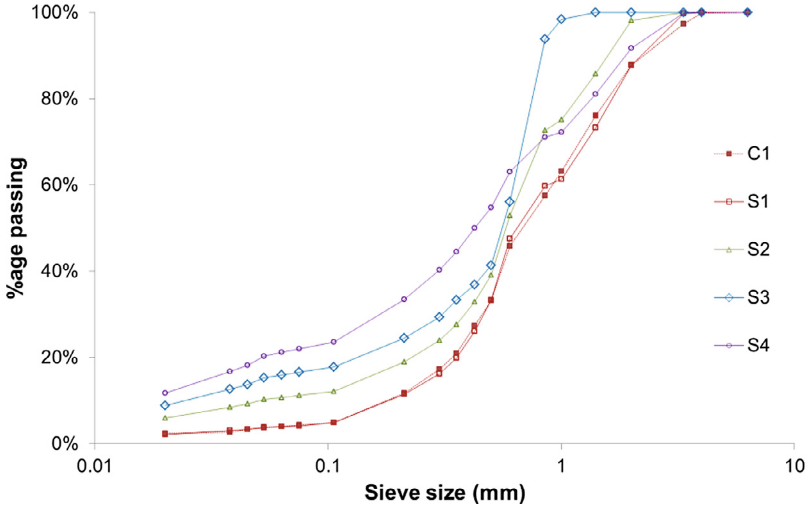

Fig. 1. Grading of sands.