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Design of quality, durable mortar for the conservation of historic masonry fabrics.

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Abstract

The last twenty years have shown a steady increase in the number of conservation works to historic structures carried out in Ireland. Much of the repair and maintenance to historic masonry buildings have required pointing, rendering, capping and grouting with mortars. Ordinary portland cement mortars can often be incompatible with historic and traditional materials and cause both structural and aesthetic damage. There has been a move in conservation work towards the use of lime mortars making allowances for the limitations of this material (eg. seasonal work, lower durability). It is the objective of this project to produce a quality, durable mortar to repair Ardamullivan Castle, a 16th century tower house in County Clare. This mortar must be compatible with the original mortars and the adjacent masonry. To this aim, the original pointing mortar and the stone masonry were studied by means of analytical techniques and laboratory testing. Porosity, densities, compressive strength, capillary suction and water absorption were tested according to relevant standards. Analytical techniques include petrographic microscopy and X-Ray diffractometry. Based on the results of this study, the components and proportions of new repair mortars were specified and the mortars fabricated and tested in the laboratory. The porosity, densities, water absorption and compressive strength of several compatible repair mortars were measured and a repair mix selected to be used in conservation works to the Castle.

Introduction

This project is part of a wide conservation programme funded by National Monuments, Irish Government. The project aims to contribute towards best building conservation practice by providing a methodology for the design of quality repair mortar compatible with existing structures.

Mortars are an essential part of a built structure and play a protective role preventing the decay of buildings. A good mortar must act as a conduit for the moisture in the wall, preserving the stone or brick from the decay induced by percolating water, moisture and salt solutions. Due to their nature and function, they are sacrificial materials with a life-span much shorter than the stone fabrics with which they are mixed. For these reasons, historical mortars often need to be replaced.

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New replacement mortars should be quality, durable materials compatible with the original fabric. The composition and mix proportions of any new mortar must take into account the physical properties and composition of the masonry to be re-pointed, as well as the composition and condition of the original mortar to be restored. Unsuitable chemical composition or physical properties of mortars can cause damage to a building fabric.

Most historic mortars are lime based. Lime mortars fell into disuse as a result of the extensive use of artificial cement mortar after 1824. Mortars made with artificial cements were faster to settle, harden and develop strength. They were mechanically stronger and more resistant to weather than lime mortars. In this context, limes began to be considered old fashioned and were superseded by artificial cements which were extensively used for both new building and repairs to historic fabrics.

Modern research and experience have demonstrated that artificial cements are not advisable for use with historical and traditional fabrics. Many masonry buildings and archaeological sites have been damaged due to the introduction of overly strong, inflexible, impermeable, salt-bearing artificial cement mortars (chiefly portland cement).

Currently, it is a common practice to use traditional raw materials and techniques in conservation works to built structures. In this context, lime is acquiring a growing importance. Mortars made with lime binders are porous, permeable and flexible. They do not contain elements capable of forming salts and are generally more compatible with historical and traditional fabrics than artificial cements.

Objective

The aim of this paper is to produce a quality pointing mortar compatible with the stone masonry of Ardamullivan Castle. The research on which this paper is based intends to contribute towards best building conservation practice by providing a methodology for the design of quality repair mortar compatible with existing structures.

Method

The composition and mix proportions of any new repair mortar must take into account the physical properties and composition of the masonry to be re-pointed, as well as the composition, proportions and current condition of the original mortar to be restored.
To this aim, both the historic mortar and the stone masonry were studied. Based on the results of the analyses and laboratory tests of the original masonry materials, four compatible mortar repairs were designed and tested in the laboratory.

The composition, grading, proportions of aggregate and binder(s) and decay of the original mortars were studied with a petrographic microscope (Charola et al. 1984). Thin sections of mortars were polished to the standard thickness of 20 microns, covered with a glass slip, and examined with a petrographic microscope using transmitted light and crossed polars.

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The mineralogy of the stone was analysed by X-ray diffraction (the powder method) with a diffractometer Philips PW 1710 using Cu α radiation with a voltage of 40 Kv. and an intensity of 40 ma. The area was scanned between 0 and 60 degrees 2θ.

Being water, generally speaking, the main weathering agent of building materials. Tests to evaluate the properties related to the presence and movement of water within the structure including real and bulk densities, total porosity, water suction and water absorption were especially considered for evaluation. Porosity, densities and water absorption were tested according to the international RILEM (1980) standards. The compressive strength of the new mortars was measured according to BS 4551: 1980 and the capillary suction according to European standard EN 480-5: 1996.

The Castle

Ardamullivan Castle is a tower house built of coursed limestone rubble with abundant punch-dressed limestone work including quoins, pointed-arch doorways, jambs and window elements (slit loops, flat headded and double-light ogee-headed windows). The Castle holds valuable medieval paintings on lime plaster and was probably built in the 16th century.

The building stone

According to the petrographic and X-Ray diffraction analysis, the Ardamullivan stone is a pure Carbonifeous limestone of local origin consisting of calcite (95%) and quartz (5%). Under the microscope, the stone is compact and sound and has virtually no porosity.

According to the results from laboratory testing, the limestone is a dense material. The density values are high when compared with those of other building stones, e.g. typical bulk and real densities of calcareous sandstone are 1.57 (g/cm^3) and 2.47 (g/cm^3) respectively (Pavía, 1994). The bulk and real densities of the Ardamullivan Limestone are similar suggesting that the stone contains a small amount of empty spaces.

As expected from the petrographic analysis and the similar bulk and real densities, the limestone's porosity is low. The porosity is extremely low when compared with that of other sedimentary rocks such us calcareous sandstone, usually ranging from 12 to 24 %, and certain limestones which can reach up to 34 % pore volume (Pavía, 1994).

The water absorption of the limestone is also very low. The limestone's porosity and water absorption compare well to those of granite and other impermeable igneous rocks rather than to the typical values for other limestones and sandstones (3-17% and higher).

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Table 1: Limestone: Real and bulk densities, total porosity, water absorption and compressive strength.

Sample	Real density (g/cm^3)	Bulk density (g/cm^3)	Total porosity (%)	Water absorption (%)	Compressive strength (N/mm^2)
Ar 1	2.71	2.70	0.36	0.12	112.3
Ar 2	2.70	2.70	0.26	0.12	101.4
Ar 3	2.70	2.69	0.37	0.11	108.9
Ar 4	2.29	2.29	0.27	0.19	143.6
Ar 5	2.72	2.70	0.73	0.21	149.7
Ar 6	2.45	2.44	0.40	0.19	159.5
Ar 7	2.73	2.70	1.09	0.29	132.2
Ar 8	2.73	2.71	0.73	0.26	115.3
Ar 9	2.74	2.72	0.73	0.27	133.0

The capillary suction is extremely low. The water raised to 5-6 mm after a 24 hours period, remaining stable for a 48 hours period. For all specimens tested, the amount water suctioned remained stationary after 48 hours. This behavior again compares to that of granite and other impermeable rocks rather than to that of sedimentary building material (where water can rise by capillary action up to 7 m. (Pavía, 1994)).

The compressive strength of the limestone is similar to that of the Leinster Granite (102.0 - 139.0 N/mm^2). The limestone's compressive strength is much greater than the typical strength of sedimentary stones such as Portland limestone or Baumberger sandstone (27.8 - 42.2 N/mm^2 and 30.5 - 44.6 N/mm^2 respectively) (Pavía et al. 1997).

The original mortars

According to the petrographic analysis, the mortars are hydraulic. Hydraulicity is partially due the lime itself being hydraulic. Further hydraulicity arises from the presence of reactive aggregate of microcrystalline silica and pozzolanic additions (brick dust, burned coal and charcoal particles). The mortars were fabricated with a sharp, limestone aggregate including a significant siliceous fraction mixed with lime in approximate proportions 2:1 (aggregate:binder in % by volume). According to the petrographic analysis a magnesian limestone was calcinated to obtain the lime.

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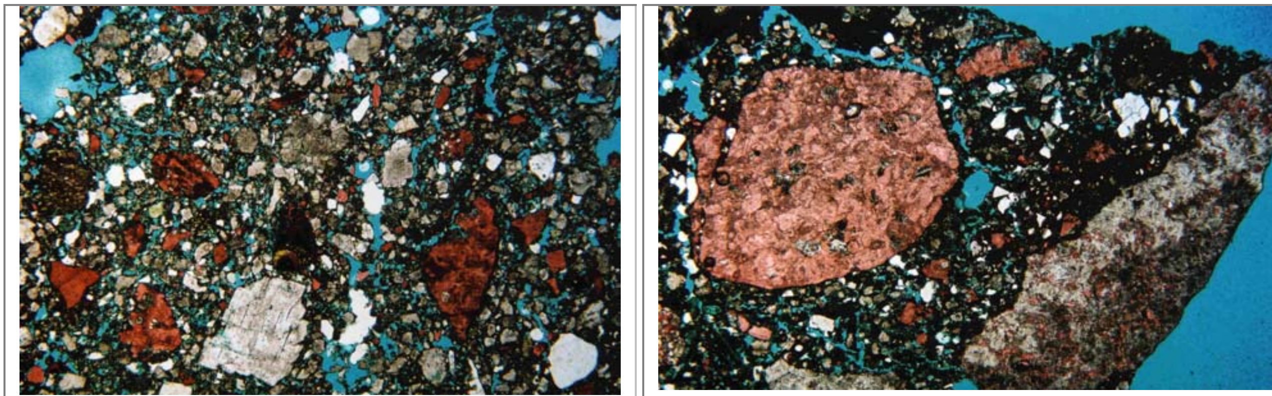

Petrographic microscope images of the original pointing mortar including sharp limestone and siliceous sand and reactive microcrystalline silica. Parallel polars 2X.

The porosity of the original pointing mortars ranges between 17.17 and 25.65 % and the water absorption varies between 7.92 and 12.77 %. See table 2. These values are high, falling within the normal range for historical, lime-based, pointing mortars and renders.

Table 2 - Real and bulk densities, total porosity and water absorption of original lime mortars.

Mortar	**Real density (g/cm^3)**	**Bulk density (g/cm^3)**	**Total porosity (%)**	**Water absorption (%)**
Arda 1	2.94	2.39	18.70	9.31
Arda 2	2.66	2.06	22.55	10.40
Arda 5	2.75	2.19	20.36	9.40
Arda 8	2.62	2.17	17.17	7.92
Arda 12	2.69	2.00	25.65	12.77

Microscopic examination evidenced the presence of retraction fractures and dissolution of carbonated lime binder. Failure includes intense microcracking. A number of fractures are due to the natural retraction of lime however, some of these have been further enhanced through dissolution causing loss of adhesion between aggregate and binder. These are common weathering processes affecting historic lime-based mortars (Pavía et al. 2000).

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Specification for repair mortar

Three practical problems arose from the results of testing and analysis, and decisions were made as follows:

1- The original mortars were made with a magnesian lime which is not commercially available. To overcome this problem, lime was obtained by calcinating the local limestone in a lime kiln. Kilkenny dolomite was also calcinated in the kiln and mixed with the local lime in order to fabricate the repair mortars.

Lime kiln used to calcinate the limestones. National Monuments Depot, Athenry, Co. Galway.

The local lime is a lime putty with no hydraulic properties. This material was gauged with magnesium hydroxide (mix 1.9 in table 3) or Kilkenny dolomite lime (mix 1.13) in order to match the original pointing mortars by rendering the lime magnesian. Two control mixes, without magnesian lime, were also prepared for testing: control mixes 1.15 and 1.17 were designed in order to compare the properties of magnesian lime to those of lime putty and commercially available, moderately-hydraulic lime 3.5.

2- A pointing mortar made with an eminently hydraulic lime binder would be compatible with the low porosity and permeability as well as the high density and compressive strength of the Carboniferous limestone masonry. However, according to the petrographic analysis, the physical properties and composition of an eminently hydraulic mortar would be substantially different to those of the original,

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feebly hydraulic, mortar. It was therefore decided to fabricate two feebly hydraulic pointing mixes based on the results of petrographic analysis (mixes 1.9 and 1.13 below). These mortars are compatible in composition, porosity/permeability and mechanical strength with the limestone masonry and similar in mineral composition and physical properties to the original pointing.

3- The aggregate proportion in the repair mortars was raised from 2:1 (in the original mortars) to 3:1 to minimize risk of microfracturing by shrinkage (recorded under the microscope in the original mortars). In all cases, the aggregate is local limestone sand with a significant siliceous fraction matching the original in composition and grading.

Table 3 - Specification for new repair mortars and control mixes.*

Mortar	Mix proportions (% by volume)	Binder	Pozzolanic additions (brick dust)
1.9	3:1	75% local limestone lime 25% magnesium hydroxide	5%
1.13	3:1	75% local limestone lime 25% Kilkenny dolomite lime	5%
1.15*	3:1	100% local limestone lime	1%
1.17*	2:1	NHL 3.5 natural moderately hydraulic lime	1%

The repair mortars

The physical properties of the new repair mortars and control mixes including real and bulk densities, total porosity, water absorption and compressive strength are included in table 4.

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Table 4 - Real and bulk densities, total porosity, water absorption and compressive strength of new repair mortars and control mixes - average of three values.*

Mortar	**Real density (g/cm^3)**	**Bulk density(g/cm^3)**	**Total porosity (%)**	**Water absorption (%)**	**Compressive strength (N/mm^2)**
1.9	2.31	1.77	23.19	11.55	1.86
1.13	2.34	1.84	21.44	10.95	1.57
1.15*	2.43	1.94	20.38	9.46	1.32
1.17*	2.50	1.94	22.34	10.23	2.37

<u>Property match –Matching properties of repair mortars to those of the original pointing</u>

The porosity of the original pointing mortars ranges between 17.17 and 25.65 % while that of the new repair mixes spans between 20.38 and 23.19 %. The water absorption of the original mortars varies between 7.92 and 12.77 % while the repair mortar values range from 9.46 to 11.55 %. See tables 2 and 4. The porosity and water absorption of the new repair mixes are very close to those of the original pointing. The values obtained are high, falling within the normal range for historical, lime-based, pointing mortars and renders. The bulk and real densities significantly different suggesting that, similarly to the original pointing, the repair mortars are not dense and contain empty spaces. The porosity values confirm this showing that, in fact, the repair mortars contain a high amount of pores.

<u>Repair mortars: Magnesian lime vs lime mortar</u>

There are no significant differences in the properties of the two magnesian mixes tested. The properties of both magnesian lime mortars compare well to those of lime putty and moderately-hydraulic lime mortar and there are no significant differences in densities, porosity and water absorption (see table 4). However, the compressive strength of the magnesian lime mortar is slightly higher than that of the lime putty mortar suggesting that magnesian lime possesses some hydraulicity.

The porosity and water absorption of the lime putty mortar are slightly lower than those of the hydraulic lime and magnesian lime mortars. These results are unexpected as, in theory, an increase of hydraulicity is coupled with a decrease in porosity and water absorption.

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Conclusion

Repair mortar match with limestone masonry

All repair mortars are chemically compatible with the limestone masonry of Ardamullivan Castle as they mainly consist of calcite (carbonated lime and limestone sand) and inert quartz. Because they are lime-based, they have a low content in soluble chlorine, sulphur and alkalis.

All repair mortars are also physically compatible with the limestone as they are substantially less dense, more porous and permeable and mechanically weaker than the limestone to be pointed.

Repair mortar match with original mortar

In all cases, the physical properties of the repair mortars match those of the original pointing however, the magnesian repair mortars are closer in composition to the original mortars.

Final choice

Any of the mortars tested can be used for re-pointing Ardamullivan Castle. However, the magnesian lime mortars are a closer match to the existing pointing mortar therefore they were selected for re-pointing. Due to contradictory reports and the lack of agreement on the hydraulicity of magnesian lime as well as the lack of experimental work in the subject, further testing to estimate setting times and shrinkage has been projected before conservation works on site take place.

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