Construction and Building Materials 28 (2012) 807–818

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental testing of the durability of lime-based mortars used for rendering historic buildings

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ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form 19 September 2011
Accepted 2 October 2011
Available online 3 December 2011

Keywords:
Freeze–thaw
Salt capillary absorption
Salt surface deposition
Environmental scanning electron microscopy
Ion chromatography

ABSTRACT

To find out which render mortar mix shows the best durability properties, we have designed four ageing tests that aim to simulate water movements, ice formation and salt crystallization in lime mortars exposed to an extreme, but realistic, range of temperature and humidity. It has been found that the response of individual mortar mixes differs according to the mechanism and the agent of attack. These findings suggest that in order to provide useful data both the experimental testing approach and the types of mortar tested need to be tailored for the particular circumstance in which the render will be applied.

1. Introduction

Rendering mortars have always been considered the sacrificial layers of walls and building facades because their main purpose, as well as an aesthetic one, is to protect the masonry structure against weathering, slowing its decay. To ensure this function, renders need to be maintained and repaired or substituted by other compatible mortars when damaged. The major benefit achieved by covering a building with a render is the reduction of moisture present inside the masonry structure [1]. The presence of water and its movement inside the pore network of mortars are among the biggest causes of their degradation [1–3]. In fact, depending on the conditions of temperature and humidity, water in both vapour and liquid state can allow freezing–thawing phenomena, can favour the entry of salts which crystallize inside the matrix, and can cause the reduction of mortar mechanical strengths and adhesion to the masonry. As a general rule, a render should be characterised by low water absorption and high water vapour permeability, so that the water which enters the mortar can easily and quickly evaporate [4], as well as by high flexibility, good adhesion and compatibility with the support (i.e. stone, brick) [5,6]. Adequate design of the masonry materials and good knowledge of their characteristics (pore system, hygric and physic-mechanical properties) are required to predict and, consequently, minimise their decay.

Accelerated weathering tests are the easiest, quickest and most commonly used way to study the resistance of a construction material exposed to certain environmental conditions as well as to know which factors are involved in its decay and in which way the material properties are affected [7]. However, one must bear in mind that natural weathering is a combination of conditions (i.e. temperature, relative humidity, solar radiation, wind, rain, salts and pollutants) which are hard to reproduce faithfully by a laboratory test. Moreover, the layer of mortar (1–3 cm thick) applied on the surface of a wall may show different textural characteristics (such as pore systems) to a laboratory sample (the standard size is $4 \times 4 \times 16$ cm) and consequently, it may be affected in a different way by weathering. However, the performance of accelerated ageing tests is still the most useful tool for understanding the mechanisms of decay occurring in rocks and masonry structures.

Freeze–thaw cycles, mechanical stress and salt crystallization are the most effective causes of degradation of mortar used in renders. According to some authors [8,9], decay due to freezing–thawing cycles, rainfall and salts attack is more noticeable in mortars with high porosity and low strength.

Good understanding of the growth mechanisms of salts in porous materials has been achieved by many salt crystallization tests performed during the last 20 years [9–21].

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doi:10.1016/j.conbuildmat.2011.10.059

In mortars, sulphate attack consists of a sequence of three sub-processes: firstly, sulphate ions diffuse into the pores of the mortar, more or less easily depending on its permeability; secondly, the sulphate ions react with calcium hydroxide, thus enhancing further penetration of sulphates into the matrix; finally, gypsum or ettringite precipitates, depending on the composition of the binder (lime or cement) [21]. Gypsum and ettringite are responsible for the development of cracks and spalling, respectively [9]. In cement mortars, further deterioration is due to the degradation of calcium silicate hydrates with consequent leaching of calcium hydroxide [9]. The presence of thaumasite, which is similar to ettringite but derives from the reaction between calcium silicate hydrates and sulphate ions, has also been reported in cement, lime and gypsum-based mortars [22,23].

Magnesium (epsomite and hexahydrite) and sodium (thenardite and mirabilite) sulphates are the most dangerous salts for building material durability, because they normally crystallize inside the material [24] often only a few millimetres below the surface, depending on the salt viscosity and the drying rate of the material [25]. Due to their high crystallization pressure [26], these salts cause cracks, sanding and spalling.

Karatasios et al. [11] described the degradation of calcitic lime mortars due to sodium sulphate crystallization and demonstrated how the addition of barium hydroxide enhances the resistance to salts, by blocking Ca^{2+} dissolution and further precipitation of salts. The use of industrial residues (such as blast furnace slag) as additives in mortars has proved to be effective in reducing the damage caused by salt crystallization and freezing–thawing cycles [27].

The objective of this work is to study the durability of lime-based mortars to be used as rendering materials in restoration interventions. To study the effect of ageing on the properties of these mortars, they have been subjected to accelerated weathering, by simulating the extreme atmospheric conditions (of temperature and relative humidity) which occur during 1 year in the city of Granada (Andalusia, South of Spain) (Table 1).

The damage caused by rain and freezing–thawing cycles has also been studied by simulating rainfall (that mostly occurs in winter time in Granada).

Two further tests have also been carried out to study the impact of salt crystallization on mortars: the salt solution was applied during the weathering cycles as a "salt fog" on the surface of mortars, whilst other samples were placed in contact with a combination of sand and salt and periodically activated by water. In the first case, previous studies have found that fog enhances stone decay by salt because it is a source of moisture [20] and it controls the rate of breakdown, whilst salt controls timing [17]. In the second case, simulations of hyper-arid environments (such as deserts) previously performed on stone samples have demonstrated that salt weathering can operate quickly on samples not fully immersed in saline solutions but in contact with a combination of salt and sand [20].

The effect of these four weathering cycles on mortar samples has been monitored by means of visual and photographic observations, as well as by using weight loss and microscopic techniques.

1.1. Atmospheric conditions of the city of Granada (Andalucía, Spain)

Granada is located at the foot of Sierra Nevada Mountains in Spain at an elevation of 738 m above the sea level and at a distance of 60 km from the Mediterranean coast. Due to this particular geographic location, the city is characterised by extremely hot summers, during which temperatures can reach 40 °C (and about 50 °C in the sun), and quite cold winters when temperatures sometimes fall below 0 °C (see Table 1). Moreover, a temperature range of 30 °C can be registered between night and day.

Granada is one of the most polluted cities of Spain, especially because of the high amount of particulate matter produced by traffic. The amount of PM_1, PM_{10}, and NO_2, recorded in 2009 and 2010 in many areas of the city [28,29], was higher than the legal limit. On the other hand, the lowest values of contamination were registered for SO_2 and CO gas in 2009 [28]. However, the accelerating effects of suspended particles on mortar decay caused by the interaction with SO_2 gas and the formation of deleterious sulphate salts should be taken into account [30–33]. The main sources of sulphate ions which give rise to these salts are thought to be traffic and industries, as only a small portion of SO_4^{2-} ion incorporated into the atmospheric aerosol originates in sea spray [34]. Moreover, the most deleterious damage found in stones and composite materials of ancient buildings of Granada has been caused by the crystallization of magnesium salts [35,36]. Sulphate and magnesium ions are likely to come from the soil (ground water) and/or from adjacent lime or gypsum mortars, often prepared with dolomitic aggregates because dolostones commonly outcrop near Granada. In modern repair works, dolomitic lime and aggregate have been substituted by calcite due to the harmful effect of magnesium ions [24–26,30]. However, the high abundance of these elements is still a big cause of deterioration of the materials present in the historic buildings of Granada [36].

2. Materials and methods

The following components were used in the production of the test mortars: a calcitic dry hydrated lime (CL90-S [37]) produced by ANCASA (Seville, Spain), a calcareous aggregate (CA) with a continuous grading from 0.063 to 1.5 mm, a pozzolan (CLASS N POZZOLAN, [38]), produced by Burgess Pigment Company (USA) as additive, and three different admixtures: a lightweight aggregate (perlite), a water-retaining agent (cellulose derivative) and a plasticiser (polycarboxylate) (additional detail can be found at www.argosdc.com). Four types of lime mortars were prepared, in which the binder-to-aggregate (B/S) ratios were 1:3, 1:4, 1:6 and 1:9 by weight, whilst the pozzolan was kept at 10% of the total binder (by mass) and the total admixtures proportion was less than 2% of the total mass, as shown in Table 2. The mortars have been labelled M3, M4, M6, M9, according to their B/S ratio. Mortars were stored for 7 days in normalised steel moulds (4 × 4 × 16 cm) at

Table 1
Atmospheric conditions occurred in Granada in 2009. Data were taken from the Meteorological station 84,190 (LEGR) of Granada Airport (latitude: 37.18°; longitude: −3.78°; altitude: 567 m). The most extreme conditions were registered in July and January.

Year 2009	T_{max} (°C)/average	T_{min} (°C)/average	HR_{max} (%)/average
January	15/10	−6/1	99/87.9
February	19.3/14.4	−3/1.5	90/77.3
March	24/18.7	−0.2/4.5	97/71.3
April	24.8/18.6	−1.8/4.2	85/64.7
May	34/27	3.6/9.3	67/52.2
June	38/31.8	9.4/14.5	70/45.5
July	39.7/35.8	11.7/16	47/37.3
August	37/34.4	11.3/15.6	57/46.1
September	35.7/27.3	7.5/12.8	90/65.1
October	32.8/26.3	5.5/9.2	85/64.4
November	27/19	−0.7/4.3	96/69.3
December	19.4/13.8	−4.1/3	95/85.4

Table 2
Proportions (expressed in g) of components used in the elaboration of the four mortar types. Abbreviations indicate: calcitic lime (CL); metakaolin (MK); calcareous aggregate (CA); admixtures (perlite + cellulose derivative + polycarboxylate).

Mortars name	Components name and proportions			
	CL	MK	CA	admixtures
M3	450.0	50.0	1500.0	34.0
M4	360.0	40.0	1600.0	34.0
M6	257.1	28.6	1714.3	34.0
M9	180.0	20.0	1800.0	34.0