Construction and Building Materials 138 (2017) 528–547

Contents lists available at ScienceDirect

Construction and Building Materials

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

Environmental and structural analysis of cement-based vs. natural material-based grouting mortars. Results from the assessment of strengthening works

Paloma Pineda [a,*], Antonio García-Martínez [b], Diego Castizo-Morales [c]

[a] Department of Building Structures and Geotechnical Engineering, Research Group Transhumancias HUM-965, School of Architecture, Universidad de Sevilla, Avda. Reina Mercedes, No. 2, 41012 Seville, Spain

[b] Department of Building Construction, School of Architecture, Research Group TEP 130, Universidad de Sevilla, Avda. Reina Mercedes, No. 2, 41012 Seville, Spain

[c] Undergraduate Research Assistant, Department of Building Structures and Geotechnical Engineering, School of Architecture, Universidad de Sevilla, Avda. Reina Mercedes, No. 2, 41012 Seville, Spain

HIGHLIGHTS

- Environmental, compatibility and structural safety issues are equally considered.
- Environmental-friendly potential of lime-based vs. cement-based grouting mortars.
- The manufacturing phase is the most contaminant stage.
- Best global behaviour provided by grouts with higher quantities of pozzolans.
- Results could be applied to use more eco-efficient strengthening materials.

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form 5 February 2017
Accepted 6 February 2017

Keywords:
Natural grouts
Lime-cement based grouts
Structural performance
Eco-efficient strengthening materials
Embodied Energy
Global Warming Potential

ABSTRACT

This paper focuses on the environmental and structural implications of grouting by means of mortar, one of the most commonly used techniques in the repair, strengthening and retrofitting works of damaged masonry buildings. Masonry structures represent a significant percentage of the building stock, and to guarantee their structural safety, minimizing the environmental impact of the repair works, is a main concern. However, few researches analyse the environmental consequences of those works and repair materials. Besides, the selection of the most adequate repair grouting, is a difficult task and an open research field. From the analysis of a representative strengthening work (the grouting of XVIth century columns in the Divino Salvador church, Cortegana, Spain), this study analyses the environmental and structural performance of different grouting mortars, extrapolating the results to different and more general scenarios. The analysed building materials are cement-based, natural hydraulic lime-based with or without artificial pozzolans and hydrated lime-based grouts with natural pozzolan and w/wo cement. After performing structural analyses, Incompatibility Risk assessment and Life Cycle Assessment (Embodied Energy and Global Warming Potential) on the strengthening works, normalization and weight factors have been applied to the results. Those factors make possible to compare substrate/grouting mortar compatibility, safety structural requirements and environmental impact. The results show that the best global behaviour, both structurally and environmentally, is provided by those grouts which contain higher quantities of pozzolans in the mix. The manufacturing phase is the less environmental-friendly stage. Results from this research could be applied to use more eco-efficient strengthening materials.

1. Introduction

Masonry constructions (both heritage and common) represent a significant percentage of the structural types that are present in the current building stock. Due to their specific mechanical and constructive features, they are especially prone to exhibit a deficient state of conservation. From the aforementioned, consolidation and repair works are usually required in order to guarantee the safety behaviour of the structure, preserving at the same time the architectural heritage.

* Corresponding author.
E-mail address: palomapineda@us.es (P. Pineda).

http://dx.doi.org/10.1016/j.conbuildmat.2017.02.013
0950-0618/

Grouting by means of mortars is one of the most commonly used techniques in the repair, strengthening and retrofitting works of masonry structures. Grout can be defined as a concentrated suspension used for the homogenisation and consolidation of systems with pores, voids and cracks, e.g. inner core of old stone masonry [1]. It is worth noting that when the preservation of architectural heritage structures is the main concern, the selection of the most adequate grout is particularly a crucial issue. Indeed, the use of inadequate consolidation materials could yield to local or global collapse phenomena. In addition, as grouting is an irreversible technique, a full control on the performance criteria (i.e. injectability, strength, durability and re-treatability [2]) is highly required.

In spite of being and old and widely used technique, nowadays it is the focus of outstanding researches (e.g. [3,1]). In fact, the selection of the most adequate repair grouting is a difficult task and an open research field.

As stated by Pacheco-Torgal et al. [4], lime-based mortars (that is, the mortars that were traditionally used in historic buildings) cease to be applied due to the long hardening period. According to Vintzileou and Tassios [5], the use of polymer-based grouts should be as restricted as possible, both because of the incompatibilities among materials and because of possibly sensitive in-time behaviour. Thus, lime-based mortars were substituted by cement-based mortars. During the XXth century, several historic masonry buildings that were grouted with cement-based have undergone undesirable secondary problems due to structural incompatibilities. In order to obtain more compatible grouts, from a structural perspective, several studies focused on reducing the cement content (e.g. [6]). Due to the aforementioned, lime-based mortars have been increasingly used for restoration works due to their compatibility with the ancient materials [7] and several researches focus on their advantages (e.g. [8,9]). Natural hydraulic lime is encouraged by several studies as they allow reducing the incompatibility with the old materials [8]. An interesting alternative are blended mortars, as they combine the advantages of both aerial lime and hydraulic lime [7]. However, lime compounds, both aerial and hydraulic, have a restricted availability when compared with Portland cement in many countries. As far as the use of cement within the mixture is concerned, there is no consensus within the scientific community. Thus, while a number of researchers state that lime-pozzolan mixes are the only acceptable solution, other authors state that lime-cement mixes can be adequate [4].

In spite of the discrepancies within the scientific community, there is consensus on the factors that must be taken into account in the selection process: (i) structural compatibility, (ii) durability, (iii) preservation of the heritage value and (iv) economic viability. However, it is no usual to merge environmental issues to the aforementioned factors. Nevertheless, the manufacturing of mortars and concretes imply the consumption of a huge amount of energy and the generation of considerably amounts of wastes and emissions [11–13]. It is well known that cement manufacturing accounts for about 7% of CO_2 worldwide emissions [10–13]. Several authors have focused on the environmental consequences of these types of building materials. Many of them have underlined the Life Cycle Assessment, LCA, as the proper methodology for analysing the environmental consequences linked to those buildings materials (e.g., [14] and [15]). From this perspective, Van den Heede and De Belie [15] analysed concrete components (i.e. cement, additives, cementitious materials and aggregates), describing the main LCA methodological options for concrete and mortar. In the last years, many researches focus on the environmental impact quantification of concrete as building material ([11,16–22]), specially that of the Portland cement ([19,23–31]). In a lesser extent, some studies focus on other cementitious materials such as hydraulic or hydrated lime ([32–34]). There are very few researches comparing the environmental consequences of different cementitious materials. The environmental impact linked to other materials, such as fly ash, silica fume and pozzolans, have been recently studied, mainly from the perspective of their potential as environmental impact when used in concretes and mortars ([16,21–23,35,36]). Juenger and Siddique [44] provide a review on the effects of supplementary cement materials (e.g. fly ash, silica fume and natural pozzolans) on concrete properties. The study points out that several new insights have been gained recently (e.g., the improvement on workability, cement hydration and mechanical properties, and protection from sulphate solutions). Nevertheless, the authors conclude that the field is far from mature, and new researches are needed. In the last few years, interesting advances on the proposal for alternatives to the conventional concretes and mortars have been achieved. Thus, Turk et al. [21] study the potential of the use of by-product from the industry (foundry sand, steel slag and fly ash). That research concludes that this new ecological alternatives could reduce the environmental impact in a range between 65% and 95%. Jimenez and Barra [37] assessed the use of recycled and conventional concrete from an environmental perspective. Moraes et al. [38] determined the technical and environmental viability of the incorporation of rice husk ash waste in mortar coatings, in order to reduce the consumption of natural resources. Bras and Gomes [39] assessed the environmental impact of specific rendering mortars able to be applied in the vertical opaque envelopes of an existing school building. Ordinary cement and hydraulic lime mortars where compared to cork-added and EPS-added mortars.

From the aforementioned, it follows that it is essential, from an eco-efficient perspective, to analyse the feasibility of reducing Portland cement content, preserving the structural performance. In fact, if the amount of cement into the mixture is reduced, the carbon footprint is minimized.

The main objective of this research is twofold:

- To analyse the environmental and structural performance of cement-based, lime-cement based and hydraulic lime-based mortars;
- From the Life Cycle Impact assessment and the structural analysis, to provide a technical guidance within the grouting selection procedure, merging environmental and safety issues.

In order to achieve that objective, from the analysis of a representative strengthening work (the grouting of XVIth century columns in the Divino Salvador church, Cortegana, Spain), this research analyses the environmental and structural performance of different grouting mortars, extrapolating the results to different and more general scenarios: (a) general strengthening works assuming the same location, and hydrated lime-based or natural hydraulic lime-based substrates; (b) the case study neglecting delivery distances of the raw materials; (c) the case study assuming a delivery distance (two way) of 100 km; (d) general strengthening works neglecting delivery distances of the raw materials, and assuming natural hydraulic lime-based or hydrated lime-based substrates. The structural compliance factors, α (or *cf* under normalization), associated to Ultimate Limit States are calculated. An Incompatibility Risk analysis is performed, applying the following compatibility indicators: type of binder and chemical composition (*TB*), compressive strength (f_c), Young's modulus (E), Poisson's ratio (ν) and density (ρ). Normalization and weight factors have been applied to the results, in order to merge substrate/grouting mortar compatibility, safety structural requirements and environmental impact. The following normalized values are compared: Embodied Energy (EE), Global Warming Potential (GWP), hydrated lime-based substrate/grouting compatibility (CRA1), natural hydraulic lime-based substrate/grouting compatibility (CRA2), and grout compressive strength ($f_{gr,c}$) structural compliance factor (*cf*). The