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Combined effect of superplasticizer, silica fume and temperature in the performance of natural hydraulic lime grouts

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HIGHLIGHTS

- We studied the effect of temperature over superplasticized hydraulic lime grouts proportioned with silica fume.
- A loss of workability occurs if the grout temperature increases beyond 20 °C.
- An environmental temperature of 20 °C allowed a more complete hydration reaction.
- Grouts performance could be improved if they were properly designed and a suitable processing temperature was ensured.

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ABSTRACT

Grouting is a current repair technique for consolidating and strengthening old masonry buildings. Grouts can be seen as mixtures of binder with water, admixtures and/or additives, which should present low viscosity and high penetrability. The grout specification involves the knowledge of the flow capacity within the masonry inner core and physic-chemical compatibility with the original materials. Nevertheless, the grout properties are affected by a large number of parameters, including binder type and composition, mixing procedure, type and dosage of admixture, environmental conditions such as temperature that may lead to different grout injection capacities, as reported by several authors.

This paper deals with the effect of environmental temperature over superplasticized hydraulic lime-based grouts with partial replacement of lime by silica fume. Grout performance was analysed in fresh and hardened state by testing its rheological behaviour, injectability as well as its hydration reactions kinetics. In spite of the considerable amount of information that exists for cement based mixtures with superplasticizers, there is little information about the effects of superplasticizers when used in natural hydraulic lime mixtures proportioned with silica fume. This study aims to contribute to a better understanding of the behaviour that superplasticized hydraulic lime grouts present under different temperatures. The results showed that hydraulic lime grouts performance could be improved, regarding rheological parameters and strength capacity if they are properly design and a suitable processing temperature were ensured.

1. Introduction

Multiple leaf stone masonry walls are common in many urban centres across Europe and can be characterized by their specific vulnerability, both under vertical and horizontal loads [1]. This masonry typology is made of two external stone leaves (with irregular texture and thickness) and an inner core filled by small stones, sand, mortar or other kind of unbounded material which lead to masonry with non-monolithic behaviour [2]. It is well known that the performance of masonry constructions relies on their monolithic behaviour rather than on the mechanical properties of the individual elements. Therefore the good condition of the structural elements and of the connections granting their continuity is essential towards good performance, for instance under a seismic event.

Grout injection allows an increase in masonry compactness and creates bonds between the internal and external leaves, therefore improving the masonry mechanical strength and monolithic behaviour. Grouts for injection should be adequately designed to achieve the best performance from injectability and durability points of view. The experimental program presented in this paper was carried out with the purpose of studying the effect of temperature on yield stress, plastic viscosity, thixotropy, injectability, and hydration kinetics of superplasticized hydraulic lime grout proportioned with silica fume. The grout properties are affected by a large

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number of parameters, including mineralogical composition of binder, mixing procedure, admixture type and dosage [3]. Moreover, other researches [5,6] have shown that the environmental conditions, such as temperature, lead to different grout injection capacities.

The grout must feature adequate fluidity and penetrability in order to be injectable and able to completely fill all cracks and voids, ensuring the continuity of the repaired masonry. This means that simple binder and water formulations are inadequate to achieve the desired performance. In previous experimental research [7] the effect of different admixtures and pozzolans on both fresh and hardened properties of natural hydraulic lime-based grouts has been investigated. According to the results previously obtained [7], the use of silica fume proved to be useful in enhancing stability and allowing better water retention (due to very fine silica fume particles). However, these finer particles are the source of additional surface area resulting in an increase of contact forces among solid particles (Van-der-Waal's interactions) requiring the presence of a dispersant admixture to minimize this problem [8,9]. Superplasticizers are dispersant admixtures whose action is based on repulsive forces. Polycarboxylate-type superplasticizer (PCE) was used in this study; the repulsion action of this type of superplasticizer is a combination of coupled steric and electrostatic effects, known as electrosteric repulsion [10]. This dispersion action helps to improve the grout rheological properties, such as reduction of plastic viscosity and yield stress [11]. From a practical point of view, yield stress is associated with the minimum stress that is necessary to apply for a grout to start flowing. On the other hand, plastic viscosity represents the flow resistance once flow is initiated. A low plastic viscosity means that the grout flows easily whereas for high plastic viscosity the flow will be much more difficult.

Other major issue on rheology of cementitious suspensions is the time dependent behaviour i.e. thixotropic behaviour; this means that in the case of cementitious suspensions the viscosity depends not only on the applied shear stress, but also on the time for which the suspension has been submitted to a shearing stress and on the shear history, which leads to the hysteretic behaviour. Hydraulic lime-based grouts can be seen as thixotropic materials, since they show a shear-thinning and time dependent behaviour as stated in other studies [3,11]. During shearing of hydraulic lime grout, the weak interparticle bonds are broken by the mechanical stress and the network among them breaks down into separate agglomerates (structural breakdown). If the grout is at rest, the particles will start to flocculate into agglomerates again (structural build-up), leading to a loss of workability. Others studies [12,13] indicated that these structural changes are dominant and reversible but only on short period of time, which also depend on grout temperature. Grout injection can occur under different environmental conditions, which lead to different grout injection performance. For instance, an increase in the temperature and in the resting time may lead to more binder particles being connected and consequently a workability loss will occur, which will therefore slow down the grout flow. Thus, temperature and resting time have their determinant role in the success and, therefore, on the quality of the grouting intervention.

In the framework of cultural heritage conservation an adequate choice of binder is critical to the success of the conservation process; in this context ordinary Portland cement has been found to be highly incompatible with elements present in historic masonry [14–16]. This is where natural hydraulic lime (NHL) plays a role of great importance in the rehabilitation of historic masonry buildings, due to its chemical and physical properties being closer to those of the pre-existing materials in old masonries [17]. However, very few studies have been done with NHL-based grouts [3,11,18]. In addition, the NHL used in this research was produced according to new European standard EN 459:2010, meaning that the hydraulic lime used has a different formulation from those that were produced until the year 2011 and previously studied. It is clear, that a better understanding and classification of the basic principles that govern both fresh and hardened state properties of NHL-based grouts are necessary in order to enable a composition optimisation for masonry consolidation. Thus, for that purpose some guidelines are presented in this paper.

This paper is composed mainly of three phases: (i) The effect of grout design variables (such as silica fume, polycarboxylate-based superplasticizer and water dosage) on the properties of NHL-based grouts, such as its workability, wettability, stability and mechanical strength. The different grouts were analysed in order to obtain a grout composition which leads to the best fresh and hardened performance. (ii) The effect of temperature on the grout rheological properties was studied through rheometric measurements in order to better understand the flow behaviour of NHL-based grouts under different environmental temperatures. Additionally, injection tests in reduced models were made to analyse the injectability of the grout at different temperatures. (iii) The influence of environmental conditions on grout hydration was carried out by means of thermogravimetric analysis. The results summarised in this paper aim to contribute for a better knowledge affecting both the scientific community and industry as well as to extend the results carried out by previous works on NHL-based grouts [3,11].

2. Experimental details

2.1. Materials

The experimental program was carried out using grouts made with NHL produced in Portugal by Secil-Martingança according to the European Standard EN459-1:2010 and labelled as NHL5. A commercially available silica fume was used, namely undensified silica fume. The physical and chemical properties of the hydraulic lime and silica fume are listed in Tables 1 and 2. The polycarboxylate-type superplasticizer used has the characteristics listed in Table 3.

2.2. Mixing procedures

The hydraulic lime grouts were prepared at room temperature of 20 ± 2 °C and a relative humidity of 60 ± 5 °C. For the preparation of grouts ordinary tap water, at a temperature of 18 ± 2 °C, was used. Silica fume and dry hydraulic lime were hand mixed to ensure a homogeneous distribution before the beginning of the mechanical mixing. The mixture procedure adopted was obtained in previous research using the design of experiments method [3]: the whole powder (lime + silica fume) is added to 70% of total mix water and mixed for 10 min. The remaining water (with diluted superplasticizer) is added within 30 s (without stopping the mixer). After all materials had been added, the mixture was maintained for an additional 3 min at 800 rpm. At the end of mixing, each grout sample was passed through a sieve with 1.18 mm (No. 16 ASTM) before the experimental measurements.

2.3. Grout design

Grouts for injection should have good fluidity and penetrability, thus an optimization of the flow properties of the NHL grout was necessary in order to understand how the grout composition affects its behaviour. The analysis of each constituent of

Table 1
Natural hydraulic lime characteristics.[a]

Compression strength at 7 days (MPa)	>2.0	
Fineness		
	90 μm	15.0%
	200 μm	2.0%
Setting time		
	Start	>1 h
	End	<15 h
Expansibility	<2.0 mm	

[a] As stated in the technical data sheet from the supplier.