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Compressive strength development of binary and ternary lime–pozzolan mortars

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ABSTRACT

This study considers the compressive strength development of broad range of hydraulic lime mortars prepared with a range of commercially available alumino-silicate by-products and modern pozzolanic additions. Specifically this paper considers the effect of mineral addition selection, binary and ternary combinations, pozzolan content and the effect of curing conditions on the compressive strength development of hydraulic lime based mortars. The study was undertaken as the initial phase of a broader investigation considering the feasibility of producing modern, sustainable hydraulic lime–pozzolan concretes with comparable strengths to Portland cement based concretes. The aim of the initial phase was to identify a small number of additions, and combinations thereof, which would result in a structural strength lime–concrete when scaled up from mortars to concretes.

In the absence of a definitive source of information on the mechanical properties of hydraulic-lime mortars prepared with binary and ternary combinations of alumino-silicate by-products, 22 combinations consisting of Natural Hydraulic Lime (NHL5) and a range of possible additions, identified from historical and current practice, were prepared. The results have shown that combining an eminently-hydraulic NHL5 with silica fume and ground granulated blastfurnace slag can produce mortars with a 28-day compressive cube strength of around 28 N/mm^2, at a water-to-binder (w/b) ratio of 0.5. This is eight times the strength of an equivalent mortar prepared with NHL5 alone and broadly speaking comparable with that of low-heat cementitious mortars. The contribution of the pozzolanic reaction to the strength of hydraulic lime mortars is discussed for a range of alumina-silicious materials and combinations thereof.

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1. Introduction

Concern about the harmful environmental impact of global cement manufacture has prompted extensive research into the search for and development of more sustainable binders for construction. As a result there has been a resurgence of interest in building limes, which when produced at a large enough scale with the same production efficiencies as cement can, and in some cases do [1], demand less energy and emit less carbon dioxide in manufacture.

In looking to minimise the environmental impact of specified concretes, current best practise promotes the use of alumino-silicious by-products such as, silica fume, fly-ash and ground granulated blastfurnace slag, as partial clinker replacement materials or as additives to improve aspects of performance [2]. These mineral by-products, amongst others, have been classified as Type II additions, having been shown to enhance the properties of Portland-cement based concretes due to their pozzolanic or latent-hydraulic properties [3–5].

The use of pozzolanic minerals to enhance the properties of cementitious binders long pre-dates the invention of Portland cement. Ancient civilisations are known to have used naturally occurring pozzolanic materials in conjunction with lime and this was, until the 1850s, the principal binder for use in mortars and concretes.

Analysis of ancient mortars, dated to 7000BC, shows evidence of the inclusion of pozzolanic materials, but chemical analysis alone cannot conclude whether or not these materials were added deliberately in the knowledge of their beneficial effects [6]. The art of "gauging" lime mortars with natural pozzolanic materials was certainly appreciated by the ancient Greeks, who created hydraulic lime-mortars by utilising the volcanic ash that was deposited on the Island of Santorini by the eruption of Thera in 1500BC [7]. Lime–pozzolan technology was subsequently widely disseminated

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across the known-world under Roman occupation. Following the collapse of the Roman Empire in the fifth-century AD, knowledge of lime technology in Western Europe was gradually lost until its renaissance in 1755–1759 when English civil engineer John Smeaton, conducted extensive research into the hydraulic properties of lime–pozzolan binders.

Smeaton's work was shortly followed by relatively rapid advances in binder technology, which led to the development of Portland cements, which almost entirely replaced lime-based binders due to their superior strength and speed of set. Only relatively recently has damage to the fabric of historic buildings 'repaired' with cement-based building materials highlighted the incompatibility of impermeable, rigid, cement-based materials with their historic lime-based counterparts [8]. Furthermore it is recognised that the high strengths attained by Portland-cement based materials are unnecessary in many applications. Instead it is considered appropriate in modern practice to mitigate the environmental impact of concretes by specifying Portland-composite cements, in which a substantial proportion of the Portland cement is substituted by secondary materials, despite this in some cases resulting in reduced strengths [2].

Unlike the majority of current research into lime-mortars for masonry and render applications, the guiding philosophy of this research project was on the future potential of lime-binder technologies in concretes. Consciously deviating from the current wisdom on the appropriate specification of flexible and breathable lime-technologies, in both restoration and new-build construction projects, the aim of this experimental investigation was a compressive strength comparable to that of Portland cement based mixes. As a result this work is unique in considering the effect of combining NHL5 with modern Type II additions familiar in modern concrete technology. It is intended that by creating a modern, high-performance lime–pozzolan binder, and pushing the boundaries of lime technology, a broader range of lime-based materials could then be developed, with further reduced environmental performance.

The primary purpose of this study was to investigate the feasibility of producing a modern structural-strength lime–pozzolan concrete. Within this broader project context this study had three specific aims:

(i) To investigate the range of compressive strengths attainable by hydraulic lime-mortars prepared with modern alumina-siliceous additions, or combinations thereof.
(ii) To identify a small number of hydraulic lime–pozzolan combinations with the potential capability to achieve 28-day compressive strengths of 30 N/mm^2, or above, when scaled up to lime–pozzolan concretes.
(iii) To investigate the sensitivity of hydraulic lime–pozzolan binders to curing conditions.

Although cement technologists have demonstrated that ternary combinations of alumnio-silicate materials in combination with Portland cement, can have a synergistic effect on resulting properties [9], it is acknowledged that further research is needed to understand the mechanisms by which these materials interact [7]. Given that many of these supplementary cementitious materials are activated by the calcium hydroxide, $Ca(OH)_2$, in Portland-cement based systems, their activity with hydraulic lime is of broader interest.

2. Experimental method

The experimental programme comprised the production, curing and compressive strength testing of hydraulic-lime mortars.

2.1. Materials

The NHL5 used was a natural hydraulic lime manufactured in France and supplied by a specialist lime-building merchant in the UK. Eight alumino-silicate mineral additions were used in this study. Silica Fume (SF), conforming to BS EN 13263 [10], was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass. The Ground Granulated Blastfurnace Slag (GGBS) and Fly ash (FA) conformed to BS EN 15167 [11] and to BS EN 450 [12] respectively. Three forms of metakaolin, with varying pozzolanic indices and surface areas, were used and these were designated MK1, MK2 and MK3. Finally, for comparison, two red-brick dusts were supplied by a stockist of traditional building materials; one an English Red Brick Dust (ERBD) and the other an Italian Red Brick Dust (IRBD). The oxide compositions of these materials are shown in Table 1.

Two fine aggregates were used in this investigation. All except one of the mortars were prepared with Guiting dust, limestone fines from Guiting Quarry, in Gloucestershire. The particle size distribution (PSD) of this fine aggregate was determined in accordance with BS 933-1:2012 and is shown in Fig. 1 [13]. One mortar was also prepared using a CEN standard sand as a point of reference, when considering the resulting mortar strengths. The PSD of the CEN standard sand, in accordance with BS EN 196 [14], is also shown for comparison.

Alongside the binary and ternary lime combinations, three control samples were prepared, against which the resulting mechanical properties could be benchmarked. These control mortars were:

- NHL5 only, prepared with a CEN Standard Sand in accordance with BS EN 196-1 [14].
- NHL5 only, prepared with Guiting dust.
- NHL-PC, a commercially available formulated lime mortar consisting of NHL and Portland cement (PC).

2.2. Sample preparation

Mortars corresponding to each of the 22 combinations were prepared in a paddle mixer in the ratio 2 parts binder:3 parts sand:1 part water (450 g binder, 1350 g sand, 225 g water), in accordance with BS EN-196-1 [14], as shown in Table 2. Despite the demand for water varying depending on the water absorption characteristics of the materials in each combination, the mass of water was kept constant according to BS EN-196-1. This allowed

Table 1
Oxide analysis of constituent mineral additions.

	NHL5	NHL5–PC	SF	GGBS	FA	MK1	MK2	MK3	IRBD	ERBD
Oxide analysis (weight %)										
SiO_2	15.0	16.0	94.5	33.0	53.0	55.0	55.0	55.0	23.7	38.4
Al_2O_3	1.9	2.1	0.3	14.0	30.0	41.0	40.0	39.0	7.7	7.3
$K_2O + Na_2O$	0.3	0.3	1.3	0.8	0.7	2.0	0.8	1.0	3.3	1.6
Fe_2O_3	0.6	1.1	0.3	0.4	7.0	0.6	1.4	1.8	5.7	8.5
TiO_2	0.2	0.2	0.0	0.0	1.5	0.0	1.5	1.5	0.0	0.8
CaO + MgO	60.0	60.9	0.8	47.0	4.0	0.2	0.3	0.6	10.1	3.0

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