



Structural and durability properties of hydraulic lime–pozzolan concretes



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ABSTRACT

This paper discusses the results of a suite of tests designed to assess the structural and durability characteristics of hydraulic lime–pozzolan concretes. Specifically, this paper reports on the rate of strength development, elastic modulus, linear shrinkage and rate of carbonation of four hydraulic lime–pozzolan concretes. The purpose of this investigation was to ascertain the technical feasibility of producing high strength concretes using hydraulic lime and pozzolans as an alternative binder to Portland cement. Results have demonstrated that 28-day compressive cube strengths of 35 MPa can be attained by water-cured lime–pozzolan concretes. The results are presented alongside comparable test results for Portland-cement (CEMI) and blastfurnace cement (CIII/A) concretes. Similarities and differences in material characteristics are discussed in terms of fundamental material properties and in terms of the emergent threats and opportunities for the potential development of these novel concretes.

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1. Introduction

Concern about the harmful environmental impact of Portland cement (CEMI) manufacture on a global scale has prompted an extensive search for clinker replacement materials and alternative low carbon cements (LCCs) that could succeed the current technology in time. Global CEMI production exceeds 3.4×10^9 tonnes per annum [1] and is widely thought to be responsible for 5–9% of anthropogenic carbon dioxide (CO₂) emissions [2,3] and 2–3% of primary energy use [4]. The production of CEMI is growing at a rate of 2.5% per year [2] driven by the increasing demand for concrete, which is acknowledged to be vital for meeting the basic needs of the global construction industry.

With no other single technology promising to match the global availability and manufacturing efficiency of CEMI, a palette of prospective binder technologies are being developed [5]. Collectively these new technologies constitute a second generation of cements, which will usher in a more sustainable post-CEMI era. Amidst the development of radical new binder technologies there has been a resurgence of interest in CEMI's predecessor – lime, which, when produced at a large enough scale with the same production efficiencies as CEMI can, and in the case of some modern

production facilities does [6], demand less energy and emit less CO₂ in manufacture.

A recent guide on specifying sustainable concrete in the UK has recommended that to minimise the environmental impact of concretes, best practice is to use alumino-silicate by-products, such as silica fume, fly-ash and ground granulated blastfurnace slag, in combination with Portland cement to improve aspects of performance [7]. These mineral by-products, amongst others, which are classified as Type II additions, have been shown to enhance the properties of Portland cement based concretes due to their pozzolanic or latent-hydraulic properties [8]. The utilisation of pozzolanic materials in the production of cementitious binders is far from being a new practice and long pre-dates the invention of Portland cement. Prior to the advent of Portland-cement, the cementitious properties of naturally occurring pozzolanic materials were exploited in lime-based building materials for thousands of years.

Despite a long and rich history of lime-concrete in construction, little research on the properties of hydraulic-lime concretes has been undertaken since the work of Smeaton (1724–1792) and Vicat (1786–1861). The potential use of lime-concrete as an alternative to Portland cement concrete for structural components has been recognised, but it is acknowledged that 'the science has not been developed' [9]. Ten years after this knowledge gap was identified, work in this area began by considering the mechanical

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properties of concretes made by combining Natural Hydraulic Lime (NHL5), a building lime with a characteristic compressive strength ($f_{ck,28}$) ≥ 5 MPa and classified in accordance with BS EN 459 [10], with modern Type II additions familiar in modern concrete technology. Specifically Velosa and Cachim [11,12] demonstrated that hydraulic lime–pozzolan concretes attained a mean 28-day compressive cube strength ($f_{cm,28}$) of 11 MPa with 20% of the NHL5 replaced with a waste residue of expanded clay production and a maximum $f_{cm,28}$ of 17 MPa with 20% of the NHL5 replaced with metakaolin, a calcined clay mineral.

For lime-based concretes to be a legitimate alternative to a cement-based concretes they must be capable of performing the same function, for at least as long, without any additional increase in overall binder content or total concrete volume. Although a low strength material might find some limited application a mean 28-day compressive cube strength ($f_{cm,28}$) ≥ 30 MPa, comparable with that of a low-strength cement-based concrete, is considered a minimum performance threshold. Initiated by the desire of a UK architect to build a doubly-curved shell roof for an eco-house using lime-concrete, this experimental investigation has built on the work of Velosa and Cachim [11,12] and focused on the strength and durability characteristics of a range of potential lime–pozzolan concretes believed to have the capability to attain compressive strengths suitable for modest structural applications.

A preliminary investigation into the strength development of hydraulic lime mortars demonstrated that it is feasible to produce high-strength lime mortars, with a comparable 28-day compressive strength to Portland cement mortars, by combining lime with alumino-silicate materials, many of which are by-products of other industrial processes. Tests conducted at a mortar scale were a precursor to the work reported herein and were aimed at identifying a small number of lime–pozzolan blends with the potential to produce a structural grade material when scaled up to lime-concretes [13].

This paper reports on the mechanical properties of four hydraulic lime–pozzolan concretes; binary and ternary combinations of a natural hydraulic lime (NHL5), silica fume (SF), metakaolin (MK), ground granulated blastfurnace slag (GGBS) and fly ash (FA).

2. Materials and methods

The experimental programme comprised the production, curing and testing of four lime–pozzolan concretes, denoted (I)–(IV). Each binder is a binary or ternary combination of natural hydraulic lime (NHL5) and alumino-siliceous mineral additions as identified from earlier work [13].

70% NHL5 with 15% FA & 15% MK (I)

50% NHL5 with 25% SF & 25% GGBS (II)

70% NHL5 with 30% SF (III)

50% NHL5 with 25% SF & 25% FA (IV)

Two reference Portland cement based concretes, a 100% Portland cement (CEM I) concrete and a 50% CEMI & 50% GGBS concrete (CIII/A), were tested concurrently for comparison. CIII/A concretes are routinely specified in the UK and this particular CIII/A mix had 47% lower embodied CO₂ than the CEMI, based on calculations described in Mason et al. [14], and thus is considered an appropriate baseline for performance in the development of alternative LCCs.

2.1. Materials

The NHL5 used was manufactured in France and supplied by a specialist lime-building merchant in the UK. The SF was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass, and conformed to BS EN 13263 [15]. The GGBS and FA conformed to BS EN 15167 [16] and BS EN 450 [17] respectively. A proprietary MK, from France, was also used. This specific product was found to be the most favourable of three alternative MKs utilised in the earlier lime–pozzolan mortar study. The CEMI used was 42,5N conforming to BS EN 197-1:2000 [18]. The major oxide composition of the materials, where this information was available from the manufacturers, is shown in Table 1.

Although in the UK a water content of 175 l/m³ is typically used to produce concrete of average consistence [19], a free water content of 240 l/m³ was initially selected for the lime–pozzolan concretes due to the high surface area of the hydraulic lime, pozzolans and the coarse aggregate (a 10–14 mm carboniferous limestone). The Particle Size Distribution (PSD) of the coarse aggregate was determined in accordance with BS 933-1:2012 [20] and is shown in Fig. 1. All the aggregates were dried under ambient conditions in the laboratory for at least 24 h prior to use to ensure they were consistently in a lab-dry state. The coarse aggregates had an absorption coefficient of 0.6%. The total water content was corrected accordingly, to allow the aggregate to achieve a saturated surface-dry condition before mixing whilst maintaining the desired effective water content.

The fine aggregate was 50% Marlborough grit and 50% alluvial sand by mass. The PSD of these fine aggregates was also determined in accordance with BS 933-1:2012 [20] and is also shown in Fig. 1.

2.2. Mix design

Each of the four lime–pozzolan concretes were prepared at three discrete water-to-binder (*w/b*) ratios in order to assess the effect of the *w/b* ratio on the resulting properties of the hardened material. To account for the varying densities of the alumino-silicate additions, the mass of fine sand required to maintain a consistent volumetric yield was calculated for each concrete. The Building Research Establishment's (BRE's) mix design process for concrete [21] was used as the basis for proportioning aggregates. The required volume of material for each batch was calculated based on the total volume of all the test samples plus an additional 10% for losses. Details of the mix constituents are presented in Table 2.

2.3. Experimental procedures

A suite of experiments was used to assess the structural and durability characteristics of the hardened lime–pozzolan concretes. The concretes were prepared in a rotary pan mixer

Table 1
Properties of constituent materials.

	NHL5	SF	GGBS	FA	MK
<i>Oxide analysis (% by weight)</i>					
SiO ₂	15.0	94.5	33.0	53.0	55.0
Al ₂ O ₃	1.9	0.3	14.0	30.0	39.0
K ₂ O + Na ₂ O	0.3	1.3	0.8	0.7	1.0
Fe ₂ O ₃	0.6	0.3	0.4	7.0	1.8
TiO ₂	0.2	0.0	0.0	1.5	1.5
CaO + MgO	60.0	0.8	47.0	4.0	0.6
<i>Physical properties</i>					
BET specific surface area (m ² /kg)	800	22,000	2650	4090	19,000

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