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The development of a low carbon binder produced from the ternary blending of cement, ground granulated blast furnace slag and high calcium fly ash: An experimental and statistical approach

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HIGHLIGHTS

- A new, low-carbon binder was developed.
- HCFA contributed significantly to reduce the cement content in the developed binder.
- The hydration properties of the new binder were evidenced via the SEM techniques.
- The developed MR model showed results close to that obtained from experimental work.

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ABSTRACT

This research aims to develop a new, environmentally friendly, cementitious material by blending Ordinary Portland Cement (OPC), Ground Granulated Blast Furnace Slag (GGBS) and High Calcium Fly Ash (HCFA). Compressive strength and electrical resistivity tests were used to evaluate the mortars' performance. A multi-regression (MR) model was also utilised to study the effects of curing time and content of OPC, GGBS and HCFA on the mortars' strength and to identify the relationship between measured and predicted compressive strengths. The results indicated that the newly developed binder was composed of 35 wt% OPC, 35 wt% GGBS and 30 wt% HCFA that showed a compressive strength and surface electrical resistivity of 30.8 MPa and 103.5 kΩ.cm after 56 days of curing, respectively. Significant changes in the microstructure of the developed binder paste over curing time were evidenced by SEM imaging. The statistical analysis indicated that the influence of the parameters examined on the development of the mortars' compressive strength could be modelled with a coefficient of determination, R^2 of 0.893, and that the relative importance of these parameters followed the order curing time $(t) >$ HCFA% > OPC% > GGBS%. This new binder could contribute significantly to decreasing the cost of construction materials and to reducing CO_2 emissions.

1. Introduction

Greenhouse gases, global warming and waste management have become incredibly important issues worldwide. Universally, cement manufacturing creates approximately 7% of CO_2 emissions [1]. The production of one tonne of cement results in about one tonne of CO_2; it consumes approximately 5.6 GJ of energy and requires roughly 1.5 tonnes of raw materials to manufacture [2]. This ranks the cement industry as the third main producer of greenhouse gases, after transportation and energy generation sectors [3,4]. In 2015, the world production of cement was around 4.6 billion tonnes. However, because of rapid development of the construction industry worldwide and an expected increase in the world population, it is estimated that the production of cement will reach around 9 billion tonnes by 2050 [5,6].

The UK cement industry aims to reduce greenhouse gases, including CO_2, by around 81% relative to 1990 levels, by the end

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of 2050 [7,8]. To achieve this, two methods are proposed, the first to reduce the production of cement. This however, cannot be achieved as the global population is increasing, creating a substantial expansion of infrastructure [9,10]. The second, and more achievable method, is the replacement of cement with viable alternatives, where possible [11,12].

Recently, significant interest has been shown in the production of blended cements incorporating Portland cement with supplementary cementitious materials (SCMs) from different resources. Research has been carried out with the aim of producing new (binary or ternary), environmentally friendly, cementitious materials with tailor-made properties [13–15]. Khalil and Anwar [13] reported that ternary blended cements could significantly enhance the performance of concrete compared with Ordinary Portland Cement (OPC) or binary blended cements. This is due to the blending operation where homogeneous nucleation may occur between various particle sized fractions leading to the development of a dense microstructure of hardened product with higher durability [14]. Currently in several countries, there are numerous types of ternary blended cements with various combinations of OPC, with either ground granulated blast-furnace slag (GGBS) and fly ash, GGBS and silica fume (SF) or fly ash and SF which are more commonly used [13,15].

There are still a number of obstacles that prevent ternary blended cements from being more universally applied such as the higher cost of SCMs (especially silica fume or metakaolin), the generation of larger amounts of heat during hydration, variability of the properties and the high water demand. This means that there is the need for various, cheap SCMs that could be used to produce low cost ternary blended cements with a comparable performance to conventional OPC or binary blended cements.

GGBS is one viable alternative SCM in the production of binary and ternary blended cements, and useful in different applications such as concrete production, soil stabilization and road construction [16–18]. GGBS, is a by-product of the iron industry and is extracted from blast furnaces [19]. Due to the chemical and physical properties of GGBS, it has many advantages relative to OPC, such as improved workability, enhanced durability and increased compressive strength [1,20–22]. Because it is a very fine glassy powder, GGBS increases the bond between particles and minimises concrete permeability, thereby making the concrete more resistant to chloride ingress. This, in turn, protects the internal reinforcement from corrosion [23–25]. However, the presence of GGBS in high content could lead to increasing the depth of carbonation due to the reduced calcium hydroxide produced during hydration [26,27].

Therefore, in order to produce a ternary blended cement with better performance than binary blending of GGBS-OPC cement, High Calcium Fly Ash (HCFA), a waste material that is produced from the burning process in local power plants, has been used in addition to OPC and GGBS.

HCFA is classified as fly ash class C. It has some self-cementing properties attributed to a high proportion of free lime, in addition to its pozzolanic properties [28,29]. HCFA has been used by the authors in the production of binary and ternary blended binders as an alternative to cement in different applications [15,30,31].

Other new cementitious materials include those developed by Sadique et al. [15] using a high calcium fly ash (FA1), an alkali sulphate rich fly ash (FA2) and silica fume (SF), with a maximum of 5% waste gypsum incorporated as a grinding aid. The best mix to increase the compressive strength of mortars has been achieved using 60% FA1, 20% FA2 and 20% SF in addition to 5% waste gypsum as the grinding aid and a supplementary alkali activator e.g. NaOH. Jafer et al. [30] found that the ternary blending of HCFA, palm oil fuel ash (POFA) and rice husk ash (RHA) can be used as a cement replacement in the stabilisation of soft soil giving a superior performance to that of OPC. The efficacy of HCFA in road construction has been evidenced by Dulaimi et al. [31] who established that the combination of 4.5% HCFA with 1.5% fluid catalytic cracking catalyst (FC3R), improved the stiffness modulus by around 9% in comparison to a mixture treated with OPC alone.

Evaluating the durability performance of a new cementitious binder is essential factor when selecting a binder for mortar and concrete production. Recently, the use of electrical resistivity measurement techniques are becoming increasingly popular for the durability assessment of mortars and concrete [32–34]. Similar to the rapid chloride permeability test (RCPT), electrical resistivity can be used as a measure of mortar and concrete resistance to chloride penetration [34,35]. Many studies have confirmed the suitability of the electrical resistivity measurement for assessing the chloride penetration of mortar and concrete as an alternative to the RCPT [34–36]. The test is non-destructive and can be performed faster and with less effort compared with RCPT while providing reliable results [35–37].

Researchers have shown a great deal of interest in the development of models to reproduce their experiments as they are of great benefit regarding the design process, optimisation and reproduction of experimental works [38,39]. Therefore, part of the current study has been devoted to developing an empirical model to reproduce the development of the compressive strengths of mortars as a function of curing time (t) and the proportional contents of OPC, GGBS and HCFA in the newly developed binder.

In summary, this paper presents the results of the experimental work and statistical analysis modelling to study the influence of the partial replacement of OPC by GGBS and HCFA, using binary and ternary blending procedures, to produce a low carbon binder with properties comparable to OPC.

2. Materials and methodology

2.1. Materials

2.1.1. Sand

The sand used in this investigation was 100% building sand passed through a 3.35 mm IS sieve, with a specific gravity of 2.62 and a particle size distribution as shown in Fig. 1.

2.1.2. Water

Normal tap water supplied by United Utilities (city of Liverpool) was used in all mixtures.

2.1.3. Binder materials

The materials used to produce the binders in this study were OPC, Ground Granulated Blast Furnace Slag (GGBS) and High Calcium Fly Ash (HCFA). The cement used in this study was OPC type CEM-II/A/LL 32.5-N. This cement was supplied by CEMEX Quality Department, Warwickshire, UK, and has a specific gravity of 2.936. The GGBS was provided by the Hanson Heidelberg Cement Group, Scunthorpe, UK,

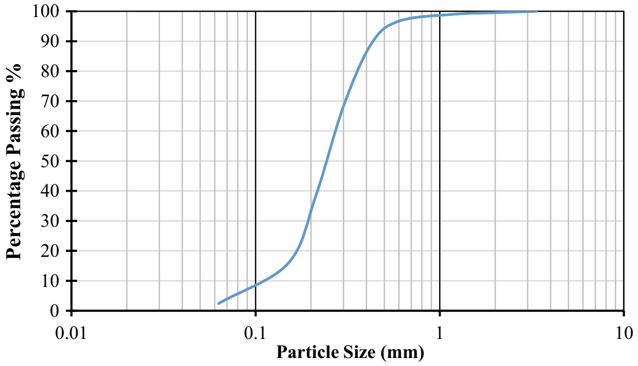

Fig. 1. Particle size distribution of the sand.