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Development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses

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ABSTRACT

This paper addresses the development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses are investigated. The modified Andreasen & Andersen particle packing model is utilized to achieve a densely compacted cementitious matrix. Fly ash (FA), ground granulated blast-furnace slag (GGBS) and limestone powder (LP) are used to replace cement, and their effects on the properties of the designed UHPC are analyzed. The results show that the influence of FA, GGBS or LP on the early hydration kinetics of the UHPC is very similar during the initial five days, while the hydration rate of the blends with GGBS is mostly accelerated afterwards. Moreover, the mechanical properties of the mixture with GGBS are superior, compared to that with FA or LP at both 28 and 91 days. Due to the very low water amount and relatively large superplasticizer dosage in UHPC, the pozzolanic reaction of FA is significantly retarded. Additionally, the calculations of the embedded CO_2 emission demonstrate that the cement and mineral admixtures are efficiently used in the developed UHPC, which reduce its environmental impact compared to other UHPCs found in the literature.

1. Introduction

Since 1980s, High Strength Concrete (HSC) has attracted a lot of attention, which later triggered the development of Reactive Powder Concrete (RPC) [1–3]. In the components of RPC, coarse aggregates are normally eliminated with active powders (e.g. cement, ground granulated blast-furnace, silica fume) as the main ingredients. Due to the relatively dense and homogenous microstructure of RPC, its maximum compressive strength can even exceed 200 MPa [4,5]. However, with the quickly developing construction industry, concrete expect the compressive strength is also required to have high flexural strength, workability and durability, which resulted the development of Ultra-High Performance Concrete (UHPC) and Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) [6–8]. Nevertheless, as the sustainable development is currently a pressing global issue and various industries have strived to achieve energy savings, the high material cost, high energy consumption and CO_2 emission for UHPC are the typical disadvantages that restrict its wider application [9–11]. Hence, how to efficiently produce UHPC, based on materials point of view, still needs further investigation.

By far, the measures pursued to reduce the economic and environmental disadvantages of UHPC are limited in most cases to the application of industrial by-products or waste materials without sacrificing the UHPC performance [7,8,12–15]. Nevertheless, in most cases in the literature, for the mix design of UHPC, the amounts of mineral admixtures (e.g. fly ash (FA), ground granulated blast-furnace (GGBS), limestone powder (LP) and silica fume (SF)) are given directly, without any detailed explanations or theoretical support. Moreover, due to the complex cementitious system of UHPC (extremely low water amount and relatively high SP content), the influence of different mineral admixtures on the hydration kinetics and properties of UHPC still needs further clarification [6–8,11–15]. As commonly known, GGBS has hydraulic properties although the rate of the reaction with water is low [16]. The reaction can be activated by several methods, but the hydration product is always C–S–H. In blended cements, GGBS is chemically activated by $Ca(OH)_2$ and gypsum [17,18]. In most cases, GGBS reacts very fast, which causes that the enhancement of mechanical properties of mortar or concrete with GGBS can be observed already during the early age [19–21]. On the contrary, the pozzolanic reaction of FA is relatively slow, and the addition of FA can retard the hydration of cement [22–24]. The retardation phenomenon is related to the presence and properties of FA. It is suggested that the FA surface acts somewhat like a calcium-sink, and calcium in solution is removed by the abundant aluminum

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Nomenclature

b	empirical constant, –
d_0	base diameter of the used cone, mm
d_1	diameter of the spread concrete mixtures, mm
d_2	diameter of the spread concrete mixtures (perpendicular to d_1), mm
D	particle size, µm
D_{max}	maximum particle size, µm
D_{min}	minimum particle size, µm
k	empirical constant, –
m_d	mass of oven dried sample, g
m_s	mass of surface dried and water-saturated sample in air, g
m_w	hydrostatic mass of water-saturated sample in water, g
$m_{w\text{-}p}$	water demand of powder materials (from Puntke test), g
p	porosity of material, %
p_c	percolation porosity at failure threshold, %
P_{mix}	composed mix, –
P_{tar}	target curve, –
$P(D)$	fraction of the total solids being smaller than size D, –
q	distribution modulus, –
RSS	sum of the squares of the residuals, –
V_w	volumetric water demand of the powder material for saturation, cm^3
V_p	volume of the tested powder material, cm^3
φ	computed void fraction, %
$\varphi_{v,water}$	water-permeable porosity, %
σ	strength of the tested material, MPa
σ_0	strength of material at zero porosity, MPa
ρ_s	specific density, g/cm^3
$\xi_{Reschke}$	particle shape factor, –
ψ	void faction of the saturated powder material, –

associated with FA, as AFt phases preferentially forms on the surface of FA [22,23]. This depresses the Ca^{2+} concentration in solution during the first 6 h of hydration, and the formation of a Ca-rich surface layer on the clinker minerals is also postponed [22,23]. Therefore, the $Ca(OH)_2$ and C–S–H nucleation and crystallization are delayed and the cement hydration is simultaneously retarded [23]. Nevertheless, with a slow increase of the $Ca(OH)_2$ concentration in normal strength concrete (NSC), the pozzolanic reaction of FA can be further proceeded and the mechanical properties of NSC at 91 days can be further enhanced [25–27]. Additionally, the activity of LP in the cementitious system is still under debate. Many researchers treat LP as a filler and have experimentally demonstrated that the principal properties of cement are not negatively affected if small quantities of LP (5–6%) are added during the cement grinding [28–31]. On the other hand, some investigations [32–34] showed that, during the hydration process of cement with LP, tri-calcium aluminate (C_3A) can react with calcium carbonate to form both high- and low carbonate forms of calcium carboaluminate (CCA) in much the same manner as C_3A reacts with calcium sulfate to form high- and low-sulfate forms of calcium sulpoaluminate (CSA). Furthermore, the reaction of LP largely depends on its fineness, which can be demonstrated by the phenomenon that the LP with d_{50} of about 0.7 µm could effectively enhance the heat flow of cement during the hydration process [35]. Although a significant amount of investigations regarding the effect of mineral admixtures on the physical and chemical characteristics of mortar or concrete can be easily found, they all focus only on NSC, in which the water to binder ratio is relatively high and very limited SP dosage is utilized. However, the cementitious system of UHPC is very different from that of NSC, which cause that it is difficult to evaluate the influence of mineral admixtures on the cement hydration and properties development of UHPC, based on the knowledge obtained from NSC. Therefore, to efficiently develop UHPC, it is important to understand the effect of different mineral admixtures on the properties and hydration process of UHPC.

For the design of mortars and concretes, several mix design tools are in use. Based on the properties of multimodal, discretely sized particles, De Larrard and Sedran [36,37] postulated different approaches to design concrete: the Linear Packing Density Model (LPDM), Solid Suspension Model (SSM) and Compressive Packing Model (CPM). Furthermore, Fennis et al. [38] developed a concrete mix design method based on the concepts of De Larrard and Sedran [36,37]. However, all these design methods are based on the packing fraction of individual solid components (cement, sand, etc.) and their combinations, and therefore it is complicated to include very fine particles in these mix design tools, as it is difficult to determine the packing fraction of such fine materials or their combinations. Another possibility for mix design is offered by an integral particle size distribution approach of continuously graded mixes (modified Andreasen & Andersen particle packing model), in which very fine particles can be integrated with considerably lower effort, as detailed in [39]. Additionally, based on the previous experiences and investigations of the authors [40–42,73], by applying this modified Andreasen & Andersen particle packing model, it is possible to produce a dense and homogeneous skeleton of UHPC or UHPFRC with a relatively low binder amount (about 650 kg/m^3). Consequently, it can be shortly concluded that such an optimized design of concrete with appropriate amount of mineral admixtures can be a promising approach to produce Ultra-High Performance Concrete (UHPC) in an efficient way.

In general, based on these premises, the objective of this study is to develop UHPC and evaluate the influence of different mineral admixtures on the fresh and hardened behavior, hydration kinetics and thermal properties of the developed UHPC. Techniques such as isothermal calorimetry, thermal analysis and scanning electron microscopy are employed to investigate the hydration mechanism and microstructure development of concrete. Additionally, to evaluate the environmental impacts of the designed UHPC, its embedded CO_2 emission is calculated and compared with that of UHPCs found in the literature.

2. Materials and experimental methodology

2.1. Materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI (the Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of UHPC. The FA, GGBS and LP are used to replace cement. Two types of sand are used, one is a normal sand with the fraction 0–2 mm and the other one is a micro-sand with the fraction 0–1 mm (Graniet-Import Benelux, the Netherlands). One type of nano-silica slurry is selected as an high active pozzolanic material in this study. More detailed information and characteristics of the used materials are shown in Tables 1–4 and Figs. 1 and 2. It can be noticed that the particle size distribution of the used FA, GGBS and LP is comparable to that of cement. Therefore, when the cement is replaced by FA, GGBS or LP, the particle packing of the whole solid skeleton is only slightly affected.