Effect of Water-to-binder Ratio on the Mechanical Properties and Hydration Process of Solid Waste-Based Ultra-High Performance Concrete.

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Keywords: hydration process, mechanical properties, industrial solid waste, ultra-high performance concrete, water-to-binder ratio

ABSTRACT

Achieving a low carbon future and ensuring environmental protection are critical for sustaining the planet and mitigating climate change. Concrete, as the second most consumed material in the world, is associated with significant CO_2 emissions and natural resource depletion. Consequently, research is increasingly focused on reducing concrete's carbon emissions and environmental impact. This study proposes a fully waste-based ultra-high performance concrete (UHPC) formulation using refining slag, steel slag, blast furnace slag and desulfurisation gypsum as the binder, and coarse steel slag as the aggregate. This novel formulation has a significantly lower carbon footprint than the conventional UHPC mixtures while promoting safe and efficient utilisation of various industrial wastes. The effect of water-to-binder (w/b) ratio (from 0.18 to 0.22) on the workability, mechanical properties, and hydration products of the low-carbon UHPC was thoroughly investigated. It was demonstrated that workability decreased with the reduction of w/b ratio while compressive strength improved. The maximum compressive strength at 28 days exceeded 113 MPa at a w/b ratio of 0.18 while toughness peaked at a w/b ratio of 0.2. A higher w/b ratio enhanced the hydration degree of the mixture, leading to more hydration products, such as AFt and C-(A)-S-H gel, along with reduced gypsum and increased hydration heat. Backscatter electron images showed reduced porosity of the concrete at lower w/b ratios, corroborating the compressive strength results.

1. Introduction

Ultra-high performance concrete (UHPC) offers superior strength and longevity compared to ordinary concrete, potentially reducing the carbon footprint of the construction industry from a whole-life perspective [1]. However, UHPC requires more than three times the cement of ordinary concrete and additional natural resources like quartz sand, presenting short-term carbon emission challenges that hinder its widespread usage [2]. Thus, the focus has shifted to using green materials to produce UHPC, aiming to lower carbon emissions and environmental impact in both short and long terms.

Researchers have explored substituting natural aggregates with solid waste materials such as steel slag [3], recycled fine aggregate [4], glass sand [5], and tailings sand [6] to develop UHPC. There are also extensive studies on using industrial solid waste to replace Portland cement (PC), including blast furnace slag [7], steel slag [8], desulfurization gypsum [9], red mud [10] and fly ash [11]. These substitutions not only meet or exceed performance expectations but also substantially reduce carbon emissions of the concrete. Nevertheless, few studies have combined solid waste-based cementitious materials and aggregates to develop UHPC.

This study aims to develop a novel low-carbon UHPC using solid waste exclusively as cementitious materials and aggregates. This approach not only reduces the carbon footprint of UHPC but also promotes the comprehensive utilisation of various industrial solid wastes. Additionally, this research will address the hydration characteristics of solid waste cementitious materials at low water-to-binder ratios and the impact of these ratios on the performance of low-carbon UHPC.

2. Materials and Methods

The blast furnace slag (BFS), converter steel slag (SS), desulfurization gypsum (DG), and refining slag (RS) used in this study were sourced from Hebei Province, China. The converter SS is further categorised into hot stifle steel slag (HSS) and roller steel slag (RSS) based on the cooling method, which were used as the binder and fine aggregate, respectively in this study. The mix proportions of the UHPC are shown in Table 1, with water-to-binder (w/b) ratios at 0.18, 0.19, 0.20, 0.21, and 0.22, and labeled as W-18, W-19, W-20, W-21, and W-22, respectively.

Raw materials were thoroughly mixed for 10 mins according to the proportions in Table 1. After testing fluidity using the flow table, UHPC slurry was poured into 40×40×160 mm moulds for shaping. After demoulding, UHPC specimens were cured under standard conditions for 3, 7 and 28 days to conduct the compressive and flexural strength tests.

Table 1. Mix design of the UHPC (kg/m^3).

RS	DG	BFS	HSS	RSS (aggregate)	Superplasticiser	Steel fiber
46.7	186.7	525.0	175.0	1166.7	4.7	156

3. Results and Discussion

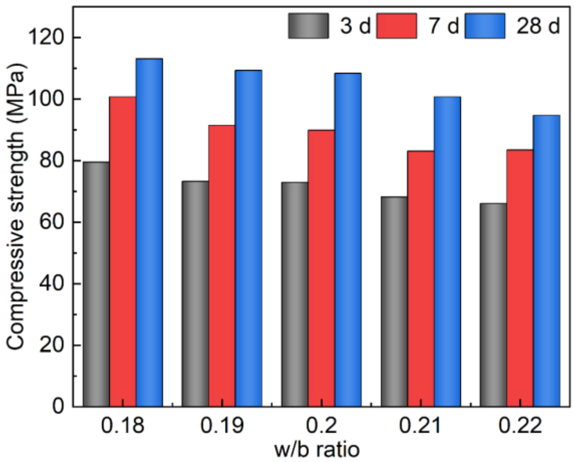

Figure 2. Compressive strength of UHPC at different w/b ratios and curing ages.

Figure 2 shows that the compressive strength of UHPC decreased with the increasing w/b ratio at all ages, peaking at 113 MPa at a w/b ratio of 0.18 after 28 days curing. The increase of water content led to an increase in pore volume, as well as the production of a loosely structured and low-strength C-S-H gel [12], consequently resulting in a reduction in the compressive strength. The fluidity of UHPC slurry increased almost linearly from 150 mm at w/b of 0.18 to 230 mm at w/b of 0.22.

According to phase identification in Figure 4, the hydration products of the waste-based cementitious material is similar to those of PC, mainly including ettringite (AFt, 2θ=8°) and C-(A)-S-H gel (wide peak at 2θ=25°~35). With the increase of w/b ratio, gypsum content decreased, while AFt content increased, indicating higher hydration degree.

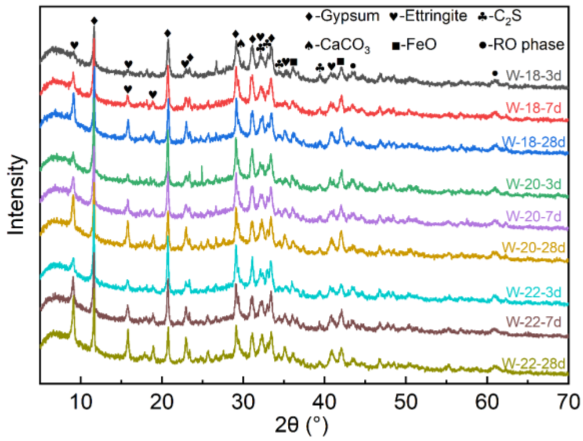

Figure 4. XRD spectra of the UHPC pastes at different curing ages and w/b ratios

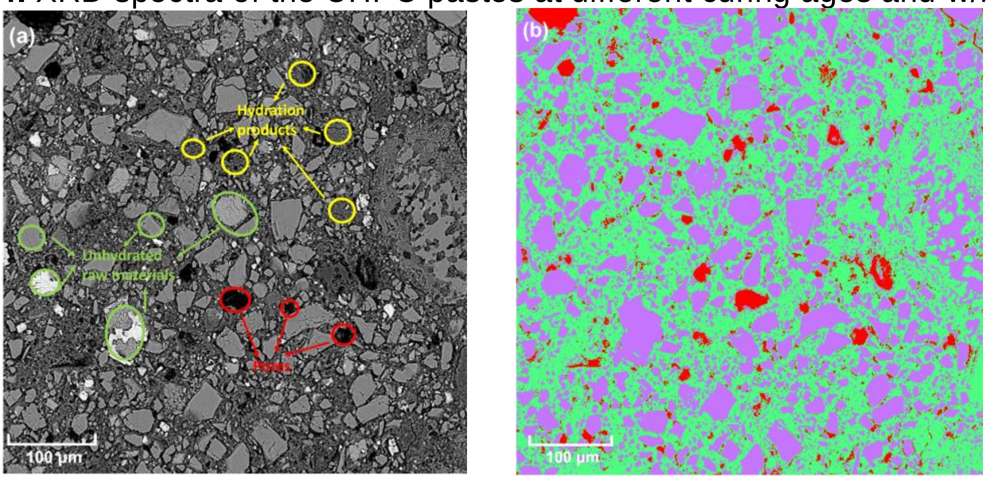

Figure 5. A typical BSE image (a) and phase identification and quantification (b) of the UHPC paste at a w/b ratio of 0.22 and curing age of 28 days. In (b), the red color indicates pores, purple means unhydrated materials while green shows the hydration products.

Table 2. Quantitative analysis of UHPC pastes cured for 28 days with BSE images (volume%).

Sample	Pores	Hydration products	Unhydrated raw materials
W-18	9.20	34.36	56.44
W-20	10.02	35.83	54.15
W-22	10.45	39.57	49.98

BSE observations were performed on UHPC paste samples with different w/b ratios after 28 days of curing. Ten images at 500× magnification (1024×1024 resolution) were taken for each sample, and ImageJ was used to identify phases (i.e., of the hydration products and unhydrated raw materials) and quantify pore volumes of samples. The representative phases identified and the quantitative analysis results are presented in Figure 4 and Table 2, respectively. As the w/b ratio increased, the content of hydration products increased, while the content of unhydrated raw materials decreased, with increased pore volume, corroborating with the results from XRD and isothermal calorimetry. The increased porosity also explained the reduced compressive strength of the UHPC with increased w/b ratio.

4. Conclusions

This study successfully utilised solid wastes to replace high-carbon and high-cost materials and developed a novel fully waste-based UHPC formulation with a 28-day strength of 113 MPa under standard curing conditions. This potentially offers an innovative and environmentally beneficial solution for waste treatment and producing ultra-low-carbon UHPC.

Microscopic analyses, including hydration heat, XRD and BSE, indicated that the main hydration products of the solid waste-based cementitious materials are similar to those of PC, which are C-(A)-S-H gel and AFt. With increasing w/b ratio, the hydration heat and the quantity of hydration products increased at the consumption of the raw material, indicating an enhanced hydration degree. However, the compressive strength of UHPC showed an inverse trend with the hydration degree, likely due to the increased porosity resulting from higher water content.

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