Experimental Study on Compressive Strength of Alkali-Activated Ultra-High Ductility Concrete

Bing Liu[1,2], Hao Mei[1,2], Fenghui Wang[1,2], Bingyu Mo[1,2] and Ting Huang[1,2*]

[1] Guangxi Key Laboratory of Green Building Materials and Construction Industrialization, Guilin University of Technology, Guilin, China, 541004
[2] School of Civil Engineering, Guilin University of Technology, Guilin, China, 541004
244871524@qq.com

Abstract. Engineered Cementitious Composite (ECC) materials have high ductility, but their large consumption of cement is not in line with the current demand for green economy. In contrast, alkali-activated ultra-high ductility concrete (AUHDC) without cement aligns better with the concept of green construction. In order to better understand the performance of AUHDC, this study investigates the compressive strength of AUHDC based on the proportions of waste marble powder (WMP) in the powder, water-cement ratio (W/B), and sand-cement ratio (S/B). The results indicate that the amount of WMP should be minimized, as excessive WMP primarily acts as filler dispersed in the specimens, leading to lower compressive strength when a crack appears upon reaching the maximum load. A W/B of 0.34 is recommended, as lower W/B result in faster material setting, inadequate transport of the solution and ions in the specimens, poor uniformity, and rapid crack propagation, thereby reducing the strength of AUHDC. A S/B of 0.7 is found to be appropriate, as higher S/B leads to insufficient colloidal content and thinner sand coating. Under pressure, cracks directly penetrate the specimens, resulting in an increase in crack width and lower strength.

Keywords: Ultra-high ductility alkali-activated concrete (AUHDC), waste marble powder (WMP), compressive strength, water-to-binder ratio (W/B), sand-to-binder ratio (S/B).

1 Introduction

In today's rapidly developing society, there is an increasing demand for materials in the construction of high-rise buildings and large-span structures, with higher ductility being one of the main requirements. Scholars have developed highly ductile ECC [1,2]. However, with the growing popularity of the low-carbon sustainable development concept in recent years, more and more people are focusing on the green and sustainable development of the construction industry. In the construction industry, cement is the main bonding material, and its production will emit a lot of carbon dioxide [3], which poses a significant burden on the environment. To reduce

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carbon emissions, it is necessary to consider improvements to ECC [4] for reducing the cement content, which presents new demands for the development of new materials.

To better align ECC with the principles of green and low-carbon development, incorporating green materials into ECC is a feasible research direction. For example, incorporating fly ash into ECC reduces the cement content and research has shown positive effects of fly ash on the ductility performance of ECC [6,7]. Another approach is to replace natural fine aggregates with municipal solid waste incineration bottom ash (MSWIBA) in ECC production [8], which not only reduces the consumption of natural river sand but also addresses the negative environmental impact of MSWIBA disposal [8]. Alternatively, using recycled polyethylene (PE) fibers and desert sand instead of traditional fibers and fine aggregates has been tested, achieving a tensile ductility of up to 7.7% while reducing carbon emissions by half [9]. In China, researchers have made use of the abundant WMP generated during the mining and processing of marble, using it as a precursor to produce alkali-activated cementitious materials in combination with ground granulated blast furnace slag (GGBFS) [10], which not only reduces cement consumption but also addresses the issue of WMP disposal.

The compressive strength of AUHDC is a crucial consideration in engineering construction. In order to examine the impact of the waste marble powder proportion in the powder mixture (WMP/P), water-binder ratio (W/B), and sand-binder ratio (S/B) on AUHDC's compressive strength, this study conducts cube compression tests to analyze these three factors. The findings aim to offer valuable insights for engineering applications.

2 Experimental

2.1 Raw Materials

The materials used in the experiment include fibers like polyvinyl acetate (PVA) fibers with a tensile strength of 1260 MPa, polypropylene (PP) fibers with a tensile strength of 460 MPa and PE with a tensile strength of 2800 MPa. Powders like WMP (Table 1) and GGBFS (Table 1). Quartz sand (diameter 120μm-380μm), sodium silicate solution (40°Bé), flake sodium hydroxide (>99% content) and hydroxypropyl methylcellulose (HPMC) with a viscosity coefficient of 200,000 Pa·s.

Table 1. The main oxide composition of WMP and GGBFS (% by weight).

Raw Material	CaO	SiO_2	Al_2O_3	Others	Loss on ignition
WMP	54.09	1.07	1.14	0.878	42.48
GGBFS	56.9	25.55	12.09	5.416	0.56

2.2 Experimental Design

To investigate the effect of different WMP/P, W/B, and S/B on the compressive strength of AUHDC, various parameters for these three factors were tested and are listed in Table 2.

Table 2. Baseline group and experimental group test parameters.

No.	W/B	S/B	WMP/P	No.	W/B	S/B	WMP/P
Group 1	0.34	0.7	50%	Group 7	0.34	0.7	60%
Group 2	0.30	0.7	50%	Group 8	0.34	0.7	70%
Group 3	0.38	0.7	50%	Group 9	0.34	0.4	50%
Group 4	0.42	0.7	50%	Group 10	0.34	0.6	50%
Group 5	0.34	0.7	30%	Group 11	0.34	0.8	50%
Group 6	0.34	0.7	40%				

The experiment used cubic mortar specimens with dimensions of $40mm \times 40mm \times 40mm$ as test specimens. At 28 days, during the uniaxial compressive test on the cubic specimens, the process involves capturing surface images of the specimens using a camera and calculating the strain cloud map in the X direction at stress levels of $0.4F_{max}$, $0.6F_{max}$, $0.8F_{max}$, F_{max}, and $F_{0.8}$ ($F_{0.8}$ represents the time when the load decreases to 0.8 F_{max} after its reaching of F_{max}) through software.

3 Results and discussion

3.1 Failure Phenomenon

Comparing the cloud diagram of specimens with different WMP/P (Fig. 1). Due to the good ductility of AUHDC, specimens with WMP/P ratios of 60%, 40%, and 30% only started to exhibit minimal crack development when the load reached $0.8F_{max}$. As the load increased to F_{max}, specimens with higher WMP/P ratios showed clearer main cracks, but with a reduced number of cracks. On one hand, this is because adding more WMP as filler does not significantly promote the hydration process, but instead leads to weak dispersion and weak interfaces within the specimens. Once cracks form, they rapidly propagate through the specimens, resulting in fewer micro cracks. On the other hand, a lower proportion of GGBFS can reduce the number and volume of micro cracks [15].

Comparing the cloud diagram of specimens with different W/B (Fig. 2). When the load reaches F_{max}, specimens with the lowest W/B (0.30) exhibit only one prominent crack, with few micro-cracks observed around it. Since water plays a crucial role in the hydration process of AUHDC, participating in material dissolution and ion transport. With less water, the flowability of the mortar is poor, significantly affecting material dissolution and ion transport [13]. As a result, the main crack appears before the formation of micro-cracks.

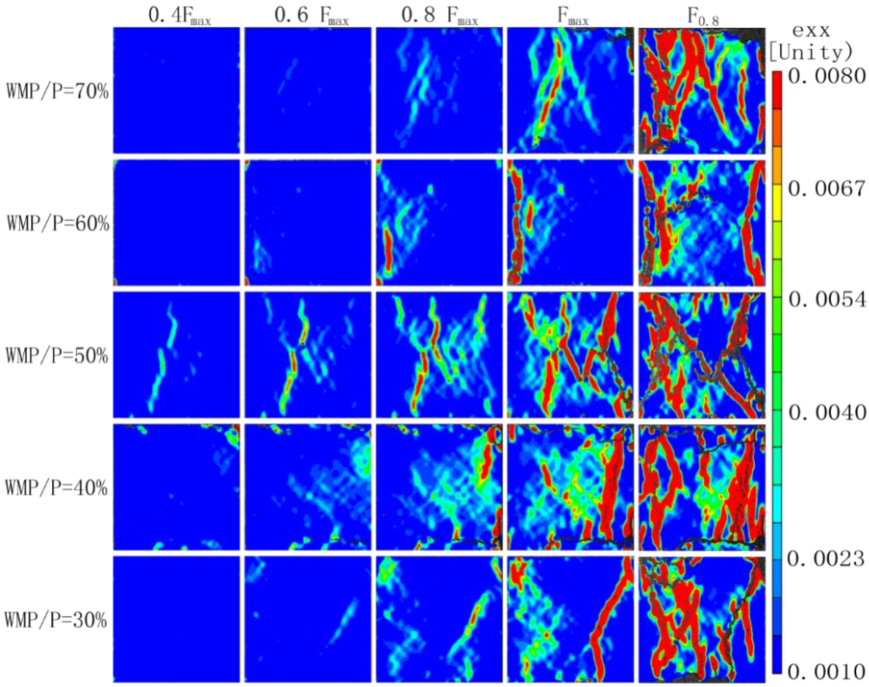

Fig. 1. Cloud diagram of specimens with different WMP/P at different loading levels.

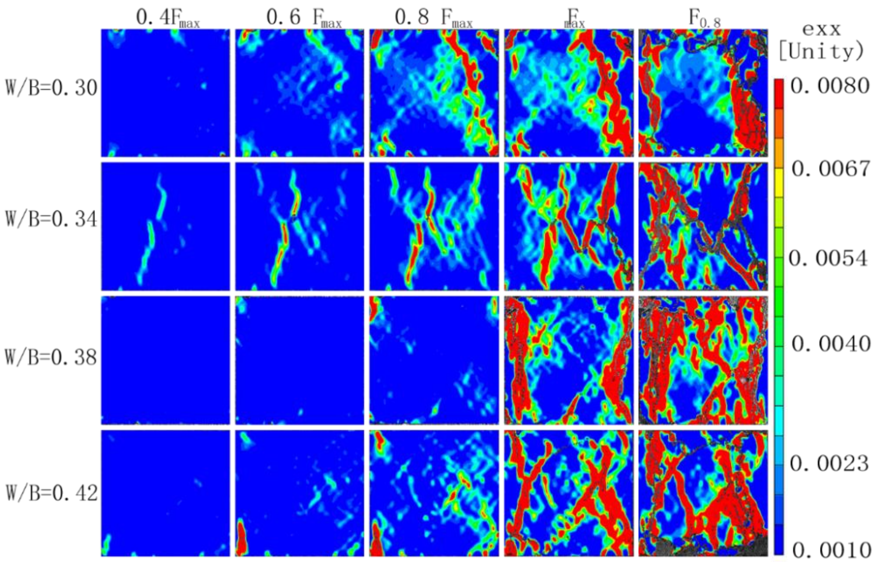

Fig. 2. Cloud diagram of specimens with different W/B at different loading levels.

Comparing the cloud diagram of specimens with different S/B (Fig. 3). As the load gradually increases to F_{max}, specimens with the highest S/B (0.8) show fewer micro-cracks around the main crack. This is because when the content of quartz sand is high, the thickness of the binder coating is thin [14], forming weak interfaces within the specimens. Cracks tend to form and propagate rapidly at these interfaces, without generating excessive micro-cracks.

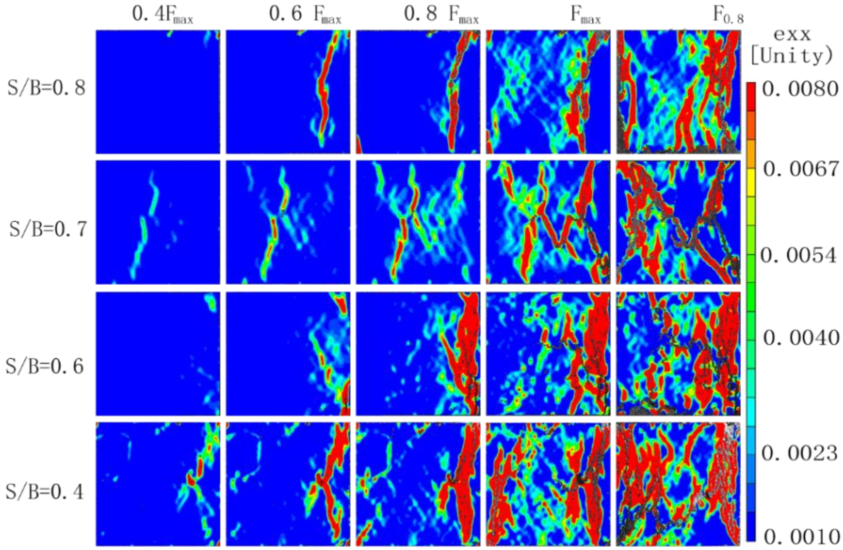

Fig. 3. Cloud diagram of specimens with different S/B at different loading levels.

3.2 Compressive strength Analysis

Alkali-activated concrete differs from ordinary concrete in that the reaction between GGBFS and alkaline solution is rapid, making it more susceptible to shrinkage cracking. However, in AUHDC, the incorporation of PP effectively prevents macroscopic cracking, while ultrafine PP inhibit the formation of early-stage micro cracks. Consequently, AUHDC exhibits superior performance.

Comparison of compressive strength of different test groups with the reference group at 28 days age was conducted in this study, and the reasons are analyzed as follows:

Effect of WMP/P: As depicted in Fig. 4a, increasing the WMP content results in a decrease in the strength of the specimens. This is because excessive marble powder does not have a significant effect on hydration but acts as a filler in the construction. Similar conclusions have been drawn by researchers who studied the replacement of sand with marble powder in concrete [11].

Effect of W/B: Fig. 4b shows that reducing the W/B from 0.34 to 0.30 results in a decrease in compressive strength from47.28MPa to 39.98 MPa. This reduction is due to the insufficient water content, which leads to incomplete hydration reactions and a decrease in the strength of the specimens. Furthermore, increasing the W/B to 0.38

and 0.42 further reduces the strength to approximately 32 MPa. It is because that the higher W/B leads to the formation of excess free water that does not participate in hydration after hardening, resulting in the formation of bubbles within the specimens. This reduces the effective cross-sectional area of the specimens under pressure, leading to a decrease in compressive strength [11,13].

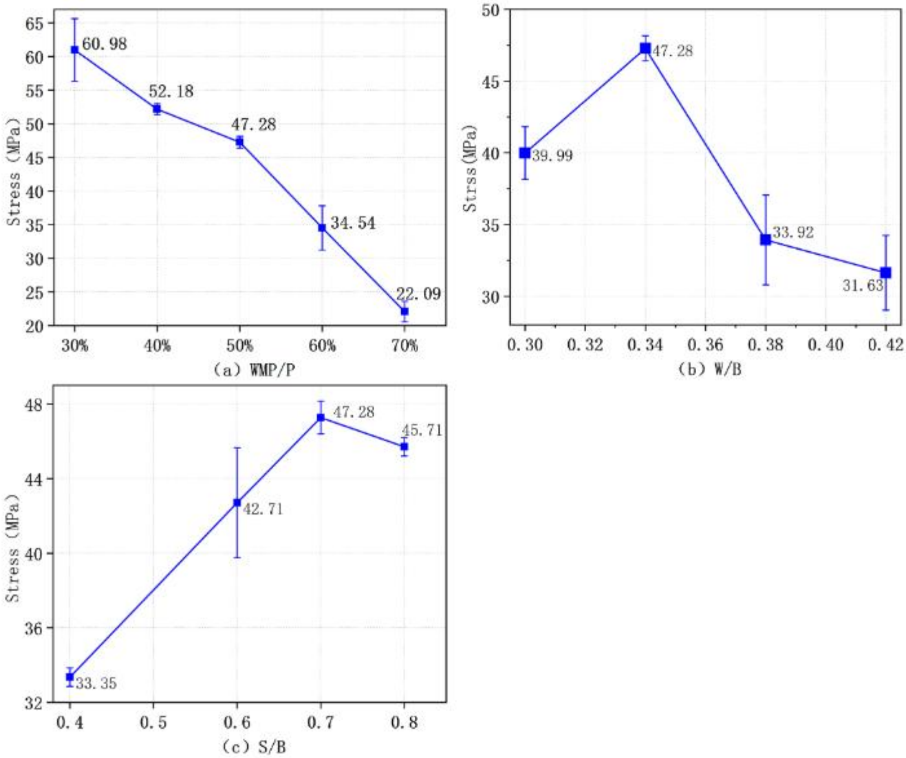

Fig. 4. Effect of various factors on compressive strength.

Effect of S/B: Fig. 4c shows that increasing the S/B from 0.4 to 0.7 results in an increase in strength from 33.4 MPa to 47.3 MPa. In cases of lower S/B, the excess binder and sparse distribution of sand within the binder make it difficult to form a robust skeleton. Therefore, lower S/B leads to a decrease in strength [11]. However, when the S/B continues to increase to 0.8, the proportion of sand becomes too high, and the binder cannot fully wrap the sand or the coating thickness is too thin, resulting in a decrease in strength [14].

4 Conclusion

The aim of this study was to investigate the effects of W/B, S/B, and WMP/P on the compressive strength of AUHDC. The main findings are as follows:

1) As the content of waste marble powder (WMP) increases, it functions as a filler dispersed within the hardened AUHDC specimens, creating weak interfaces. This consequently accelerates crack propagation after its initiation, leading to a decrease in compressive strength. Hence, an increase in WMP content hampers the strength of the specimens.

2) When the W/B is low, the material sets quickly, and the water cannot transport the solution and ions in the specimen effectively. This results in poor homogeneity of the specimens and rapid crack propagation, reducing their strength. Therefore, a W/B=0.34 is recommended.

3) For higher S/B, the lower amount of binder not only results in thinner coating of the sand particles but also may leave some sand particles without proper binder coverage. This leads to the inability to form a robust skeleton. Therefore, increasing the S/B beyond 0.7 further suppresses the strength of the specimens.

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References

1. Ahmed, S.: A review on durability properties of strain hardening fibre reinforced cementitious composites (SHFRCC). Cement and Concrete Composites 29(5), 365–376 (2007).
2. Meng, D.: Mechanical behaviour of a polyvinyl alcohol fibre reinforced engineered cementitious composite (PVA-ECC) using local ingredients. Construction and Building Materials 141, 259–270 (2017).
3. He, H.T.: Analysis and Quantification of Carbon Dioxide Emissions in Cement Production. Cement Engineering 334, 61–65 (2022).
4. Wang, B.: Green technology innovation path and policy paradigm transformation under the background of "dual carbon" goals. Sci. Manage. Res 40, 2–6 (2022).
5. Yaseen, N.: Synergistic impacts of fly ash and sugarcane bagasse ash on performance of polyvinyl alcohol fiber-reinforced engineered cementitious composites. Results in Materials 20, 100-105 (2023).
6. Yang, E.: Use of high volumes of fly ash to improve ECC mechanical properties and material greenness. ACI Materia ls Journal 104(6), 620–628 (2007).
7. Liu, Q.: Experimental Optimization of Fly Ash Content in High-Ductility Cementitious Composite Materials. Fujian Building Materials 02, 6–10 (2024).

8. Liu, J.: Recycling of municipal solid waste incineration bottom ash (MSWIBA) particles into natural fine sands for sustainable engineering cementitious composites. Construction and Building Materials 418, 135500 (2024).
9. Hou, M.: Green and durable engineered cementitious composites (GD-ECC) with recycled PE fiber, desert sand, and carbonation curing: Mixture design, durability performance, and life-cycle analysis. Construction and Building Materials 414, 134984 (2024).
10. Yi, Z.: Study on the Mix Proportion of Waste Marble Powder-Ground Granulated Furnace Slag-Based Alkali-Activated Ultra-high Ductility Concrete. In: Proceedings of the 2023 International Conference on Green Building, Civil Engineering and Smart City, pp. 357–368. Chian City Press, Guangxi (2023).
11. Corinaldesi, V.: Characterization of marble powder for its use in mortar and concrete. Construction & building materials 24(1), 113–117 (2010).
12. Wang, Y.: Mechanical Behavior of Concrete Prepared with Waste Marble Powder. Sustainability 14(7), 4170 (2022).
13. Ding, Q.: Study on Proportioning and Mechanical Properties of Geopolymer Concrete. Journal of Gold Science and Technology 30(02), 243-253 (2022).
14. Zheng, K.: Influence and Mechanism of River Sand and Quartz Sand on the Properties of Steam-Cured Ultra-High Performance Concrete (UHPC). Materials Review 38(07), 83-88 (2024).
15. Nodehi, M.: Alkali-activated materials and geopolymer: a review of common precursors and activators addressing circular economy. Circ Econ Sustain 2, 165–96(2022).