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Research Paper

Study on flexural behavior of ultra-high-performance concrete beams using finely ground rice husk ash

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ABSTRACT

This research explores the application of finely ground rice husk ash (RHA), an agricultural waste material, in the production of ultra-high-performance concrete (UHPC). Due to its elevated SiO₂ content and small particle size, RHA is considered a potential substitute for silica fume in UHPC mixtures. The study investigates the flexural behavior of UHPC beams using RHA as a replacement for silica fume at replacement levels of 25% and 50%. The flexural behavior relationships, including load-deflection, stress-strain, and crack characteristics, will be determined. The experimental results indicate that UHPC beams reinforced with 10% RHA+10% SF exhibit initial crack loads, yield loads, and maximum loads comparable to the reference UHPC beams. The load-deflection relationship curves of the RHA-incorporated UHPC beams demonstrate greater stiffness than the reference beams during the linear phase. These results were also compared with simulations, showing a high level of consistency. The research findings provide important insights into the potential application of finely ground rice husk ash in UHPC, paving the way for new developments in sustainable and economically efficient construction materials.

1 Introduction

Climate change poses a significant threat to the environment and life itself. Greenhouse gas emissions, global warming, and increasingly severe natural disasters demand urgent action to reduce negative impacts [1-3]. Developing sustainable materials is one of the key solutions to address this challenge. Currently, UHPC has become a hot topic among scientists worldwide as it is considered for use in modern construction structures. UHPC consists of basic components like cement, water, aggregates, silica fume, superplasticizers, mineral powders, and high-strength steel fibers. According to research [4-9] finely ground RHA is a promising and available material that can partially replace silica fume. RHA is a highly reactive pozzolanic material that generates calcium silicate hydrate (C-S-H) and provides a filler effect, enhancing the mechanical

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characteristics of UHPC. Incorporating RHA into concrete, similar to silica fume, can reduce the amount of $\text{Ca}(\text{OH})_2$ in the interfacial transition zone (ITZ) between the aggregates and the cement paste and porosity.

In their study, Wang et al. [10] observed that incorporating RHA with an 84% SiO_2 content resulted in a substantial 50% improvement in concrete compressive strength. RHA contributes to enhanced resilience by increasing water resistance, freeze-thaw endurance, and chemical attack resistance. Furthermore, replacing SF with RHA in cementitious materials not only improves material characteristics but also contributes to lowering ecological impact and production costs. Tuan et al. [11] indicated that incorporating RHA into UHPC enhances cement hydration during later curing phases. Additionally, RHA improves the pore network of UHPC and reduces the calcium hydroxide concentration, though this effect is slightly less pronounced than that achieved with SF. The ITZ density between sand grains and cement paste remains consistently steady in all specimens after 28 days. UHPC with RHA can achieve compressive strengths of at least 175 MPa and 185 MPa at 28 and 91 days, respectively. The compressive strength progression of RHA-containing samples exceeds that of both control and SF samples after 7 days, likely due to optimized particle packing, internal curing effects of RHA, and a lower effective water-to-binder ratio in the RHA mixtures.

To achieve the application of UHPC in structural components, numerous investigations on the performance of reinforced UHPC beams have been carried out [12-18]. Graybeal [19] discovered that the withdrawal of steel fibers from cracks governs the ultimate capacity of UHPC beams under flexural or shear loads, potentially reducing or removing the requirement for conventional shear reinforcement. Hassan et al. [20] performed tests on UHPC beams with mineral supplements and found that incorporating mineral supplements like fly ash and silica fume significantly influences the shear capacity of UHPC beams. In their study, UHPC beams enhanced with 10% fly ash and 5% silica fume exhibited a noticeable enhancement in shear capacity compared to beams without mineral supplements. Haryanto and colleagues further noted that this combination not only raised compressive strength but also boosted the shear resistance of the concrete by refining the microstructural composition of the concrete matrix, thus lessening the incidence of shear cracking. Their research underscores that the incorporation of mineral supplements is a practical approach to enhancing the efficiency of UHPC beams and advises that the optimum proportion of mineral supplements should be tailored based on the unique requirements of each project. Kim et al. [21] examined the bending behavior of reinforced UHPC beams and employed mineral supplements to upgrade their efficacy. In their study, UHPC beams were strengthened with longitudinal and transverse steel and enriched with 12% silica fume and 8% fly ash. The findings demonstrated that utilizing mineral supplements substantially augmented the flexural strength of the beams, minimized crack initiation, and improved ductility. Their research suggests that refining the proportions of mineral supplements and reinforcement can yield superior performance for UHPC beams. Lee et al. [22] investigated the bending characteristics of reinforced UHPC beams and examined the correlation between load and deflection, as well as stress and strain. In their study, UHPC beams were reinforced with longitudinal steel and subjected to flexural loads. Lee and colleagues observed that the load-deflection correlation indicated that UHPC beams with reinforcement displayed enhanced deformation resistance relative to unreinforced beams, due to the uniform distribution of stress across the reinforcement surface. They also reported that the stress-strain curves of UHPC beams revealed a significant enhancement in flexural capacity, with the stress-strain curve showing an extended elastic phase and higher load-carrying capability before fracture. This study emphasizes that the integration of reinforcement with UHPC increases flexural capacity and notably diminishes deflection under substantial loads, while allowing for a more precise projection of the behavior of UHPC beams in practical structural applications.

Current research on applying RHA in UHPC primarily concentrates on enhancing the microstructure and strength characteristics, but has not thoroughly investigated the impact of RHA on the flexural performance of reinforced UHPC beams. This leads to several limitations: an insufficient understanding of the flexural performance of UHPC beams incorporating RHA, challenges in predicting crack resistance and ductility, restrictions in fine-tuning RHA proportions, and decreased efficacy in real-world applications. However, studies on the flexural performance of UHPC have shown the substantial influence of other mineral additives, suggesting a strong potential for improving overall mechanical attributes.

To enhance the application of UHPC in structural elements, more detailed studies are needed on the effect of RHA on flexural behavior, which would help optimize RHA usage and improve UHPC performance in modern construction applications. The analysis suggests that investigating the flexural behavior of UHPC beams with varying RHA ratios is both beneficial and necessary for applying this new material in structural applications. This work aims to experimentally study the flexural behavior of UHPC beams with different proportions of SF and RHA. The research focuses on examining how different SF and RHA ratios affect the flexural capacity of UHPC beams, aiming to evaluate how these components

improve the strength and ductility of the concrete. Adjusting the ratios of RHA and SF can significantly impact the microstructure of the concrete matrix, thereby altering the flexural behavior of UHPC beams

2 Experimental Work

2.1 Materials and Mix Proportions

The study on using PC50 Portland cement to produce UHPC incorporated various essential materials and methods. Natural quartz sand, carefully selected for its purity and absence of salt, served as the primary aggregate. The aggregate mix included coarse quartz sand with particle sizes reaching up to 1 mm, making up approximately 31.8–35.8% of the total aggregate. A polycarboxylate ether (PCE)-based superplasticizer was used to reduce water content, achieving a 40% reduction. Steel fibers were included to reinforce the UHPC, with a tensile strength of 2800 MPa, and a length of 13 mm. Rice husks were burned between 800–1000°C for three hours to create RHA, which was then finely ground for 30 minutes to achieve fineness. Analysis of the particle size distribution using SEM (JSM-IT200, Japan) showed that the RHA particles were largely spherical, with an average diameter around 2.67 μm (Fig. 1). Controlled burning and grinding resulted in particles with a high specific surface area, making them suitable for UHPC applications.

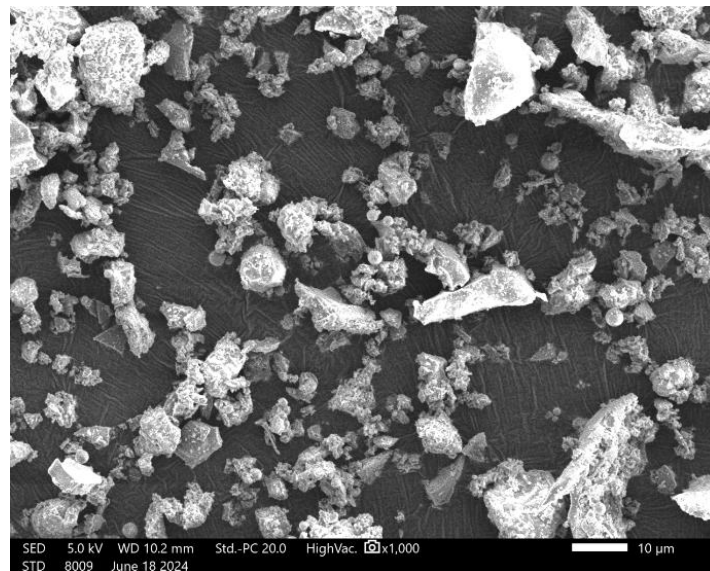


Fig. 1 – SEM image of RHA particles

By applying the EDS technique, the quantity of the chemical elements was also determined (Fig. 2 and Table 1). The results show that the RHA had a SiO₂ content of 88.39 % with LOI of 1.51%, as shown in Table 1.

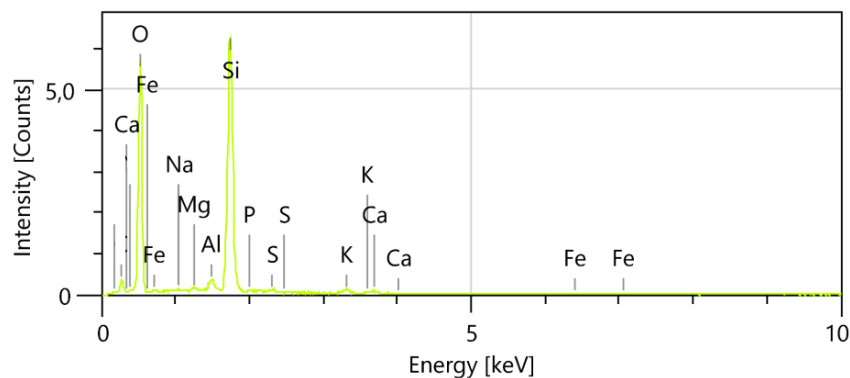


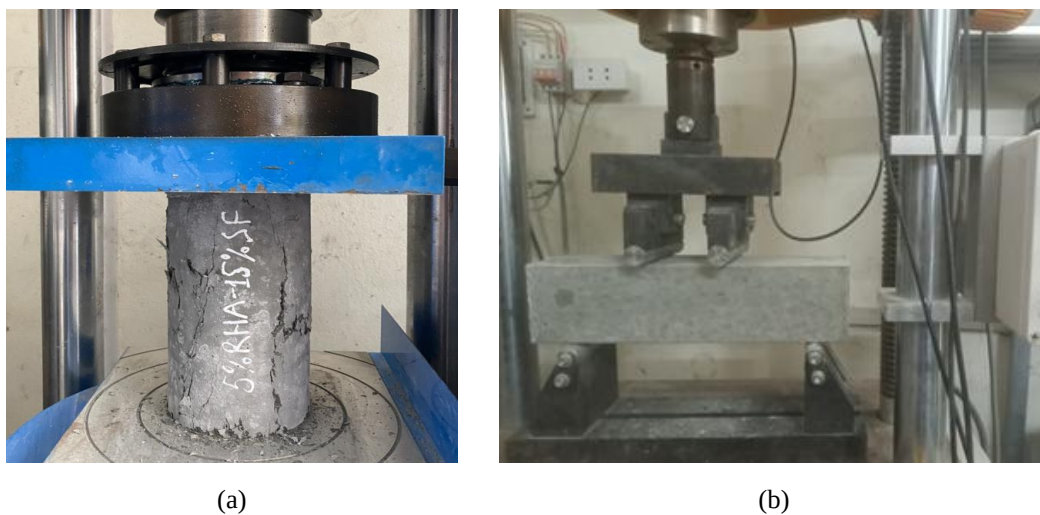
Fig. 2 – Elemental Composition Analysis of RHA via EDS

Table 1 – Chemical Composition of RHA(mass %)

Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	K ₂ O	CaO	FeO	LOI
0.18	0.90	2.82	89.39	0.79	1.45	1.79	1.54	1.13	1.51

The research focuses on designing UHPC mix proportions with varying ratios of SF and RHA. The UHPC mixes are defined as follows: Mix C1 uses 20% SF; Mix C2 combines 15% SF with 5% RHA; and Mix C3 incorporates 10% SF and 10% RHA. The total proportion of mineral additives (SF + RHA) in each UHPC mix is 20% of the binder content. The calculated component proportions for these UHPC mixes are detailed in the accompanying Table 2.

To evaluate the suitability of these mix proportions, the study prepared samples for both compressive and flexural strength testing at 28 days of curing. Compressive strength tests were performed on cylindrical specimens with dimensions of 100x200 mm, totaling 18 samples. Flexural strength tests were conducted on prismatic specimens measuring 100x100x400 mm, also with 18 samples. The compressive strength testing adhered to ASTM C39 [23], as depicted in Figure 3a, while the flexural strength testing followed ASTM C78 [24], as shown in Figure 3b. The results of the compressive and flexural strength tests for the UHPC mixes at 28 days are presented in Table 2.

**Fig. 3 – Compressive testing (a) and flexural testing (b) of UHPC****Table 2 – Mix Proportions and Some Mechanical Properties of UHPC**

Mix	Cement (kg/m ³)	SF (%) by weight	RHA (%) by weight	Coarse sand (kg/m ³)	Fine sand (kg/m ³)	SP (%)	Steel fiber (kg/m ³)	w/b	Compressive Strength (MPa)	Flexural Strength (MPa)
C1	850	20	0	740	195	2.4	160	0.165	157.20	28.95
C2	850	15	5	740	195	2.4	160	0.165	148.50	27.08
C3	850	10	10	740	195	2.4	160	0.165	156.03	31.32

2.2 Specimen Mixing, Casting, and Curing Process

The study employs a mixer with a body and frame made of steel to ensure stability and durability. The mixing drum has a capacity of 60 liters and is constructed from alloy steel. The mixing blades are made of steel and are designed to ensure an even and efficient mixing process, suitable for the characteristics of UHPC. The machine's high-power motor guarantees a strong and continuous mixing process.

Six rectangular cross-section beams are fabricated with the following dimensions: height 200 mm, width 120 mm, and length 1500 mm, as shown in Fig. 4. The UHPC beams are reinforced with two 20 mm diameter steel bars on the bottom and do not include shear reinforcement. Shear reinforcement is not used because the steel fibers in UHPC serve a similar role to that of shear reinforcement.

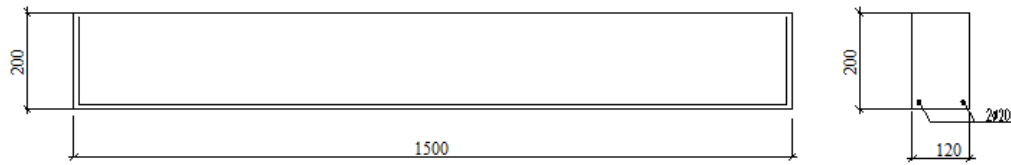
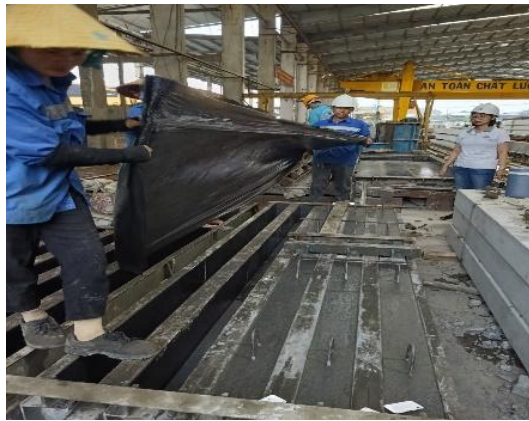


Fig. 4 – UHPC beam configuration



(a)



(b)

Fig. 5 – Preparation of UHPC beam specimens

Concrete curing must specifically prevent the loss of moisture before hydration and minimize micro cracking during the setting process. After pouring the UHPC beams, a three-layer plastic cover is applied to ensure moisture retention and protect the concrete from external environmental exposure, thus ensuring the quality of the UHPC (Fig. 5). After 48 hours, the formwork is removed, and the beams are then kept moist with water and their surfaces are smoothed

2.3 Testing of UHPC Beams

The flexural of the beams is conducted using a four-point flexural method, as shown in Fig.6. A hydraulic jack with a capacity of 50 tons is used for loading. A load cell is positioned at the force application point to measure the applied force during the experiment. To verify the accuracy of the test results, two reinforced UHPC beam specimens are tested for each mix configuration.

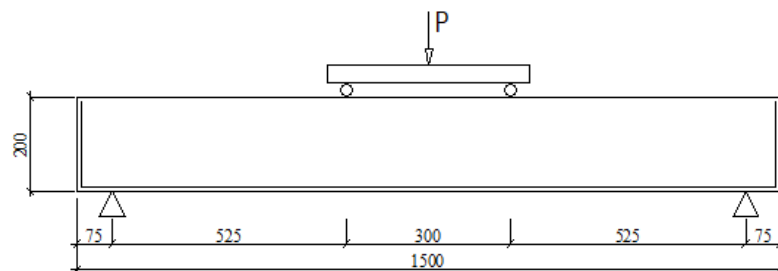


Fig. 6 – Schematic diagram of the flexural test of UHPC reinforced

To conduct the experiment, two LVDT sensors were used to measure vertical displacement and horizontal displacement of the beam. The LVDT sensors and load cell were connected to a data logger to collect and record the measurement values (Fig. 7).



Fig. 7 – Installation of experimental equipment

3 Results of tests

From the flexural test results, the load-deflection relationship (Fig. 8) and the stress-strain relationship (Fig. 9) for the reinforced UHPC beams with three different mix proportions (C1, C2, C3) have been established.

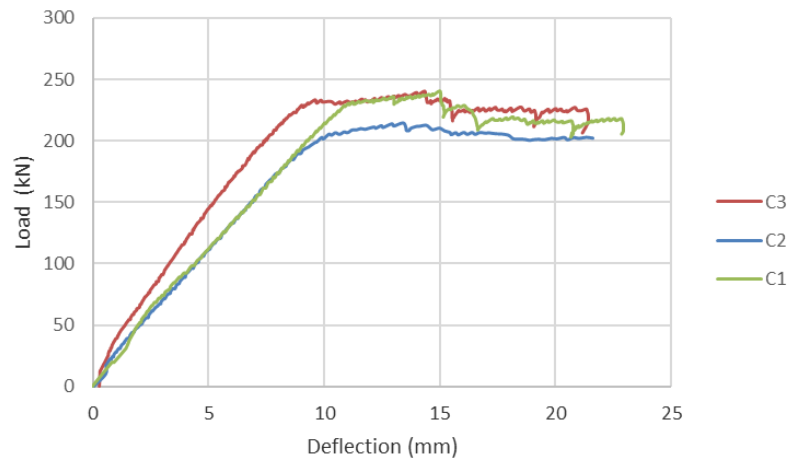


Fig. 8 – Relationship of load – deflection of UHPC beams

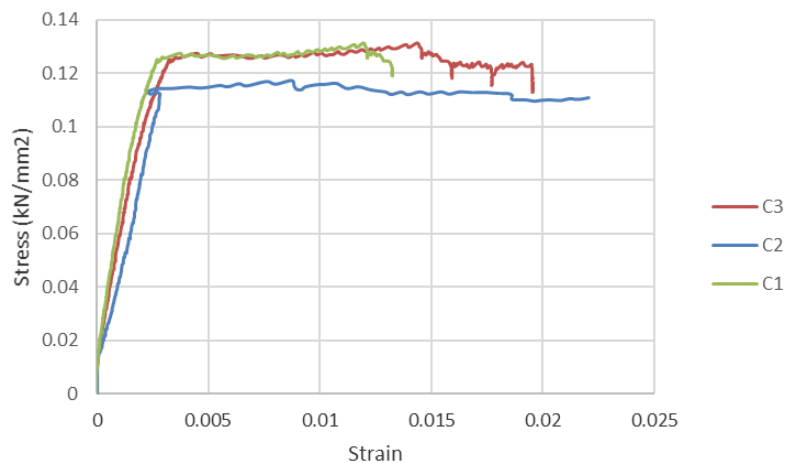


Fig. 9 – Relationship of stress – strain of UHPC beams

In the initial linear stage of the load-deflection relationship curve, the UHPC mixes C1, C2, and C3 all exhibit elastic behavior, with load increasing linearly with deflection. However, the influence of RHA and SF on the modulus of elasticity varies significantly between the mixes. Mix C3 with 10%SF+10%RHA demonstrates a higher modulus of elasticity, characterized by a steeper slope of the load-deflection curve compared to C1. This indicates that when combined with SF,

RHA can enhance the initial stiffness of UHPC. Conversely, mix C2 shows lower stiffness, likely due to the insufficient RHA content that does not fully optimize the density of the UHPC mix. The gentler slope of the load-deflection curve suggests that using 15% SF+5% RHA in the UHPC mix may reduce the initial load-bearing capacity during the elastic stage. The C2 mix beams exhibit load capacities at the first crack, yielding, and maximum loads equivalent to those of the control UHPC beams. This indicates improved crack resistance, with steel fibers effectively transferring stresses and restraining crack propagation. In contrast, the C3 beams, which have a higher RHA ratio, show a rapid decline in stiffness after reaching the first crack load, reflecting the complex interaction between RHA and SF in adjusting the mechanical properties of UHPC.

Based on Fig. 9, the stress-strain curves reveal that for UHPC beams with mix C1, the stress increases rapidly with only minimal strain, reaching a peak of approximately 0.13 kN/mm^2 at a strain of 0.012 mm . After this peak, although strain continues to increase, the stress remains stable, which can be credited to the contribution of the steel fibers in UHPC. The C2 mix beams initially show a similar rapid increase in stress with strain, reaching a lower peak stress compared to C1, though the difference is not significant. After peaking, the stress slightly decreases and stabilizes around 0.118 kN/mm^2 at a strain of 0.008 mm , indicating that C2 experiences a reduction in stress after reaching the maximum level before stabilizing. For the C3 mix beams, the stress initially increases rapidly with strain, reaching a peak stress of about 0.13 kN/mm^2 at a strain of 0.014 mm . Subsequently, the stress remains stable, suggesting that C3 maintains its maximum stress over a relatively larger strain range.



Fig. 10 – Cracking of UHPC beams contain RHA

The initial fracture characteristics of all UHPC beams tested are largely consistent. As loading begins, flexural cracks form on the tensile side (the bottom of the beam) around the mid-span between load points. These cracks then propagate upwards toward the compression side (the top). Notably, no shear cracks were observed, attributed to the steel fibers' presence, despite the absence of shear reinforcement in the beams (see Fig. 10).

The presence of steel fibers mitigates the brittleness associated with diagonal cracks, allowing these cracks to extend upward and widen until the fracture occurs due to excessive deformation of the longitudinal reinforcement. Rather than breaking, most steel fibers are pulled out during flexural. UHPC beams lacking shear reinforcement demonstrated ductile flexural fracture, characterized by progressively widening cracks. At the beginning, the load-deflection relationship curve response is generally linear. However, as tensile cracks develop and propagate on the surface, the curvature of the load-deflection curve changes. All beams ultimately failed due to flexural. This suggests that substituting SF with RHA does not significantly alter the overall fracture behavior of UHPC beams. Notably, for the C2 mix (10%RHA+10%SF), crack width is reduced and cracks extend further towards the support, indicating enhanced ductility of this mix. The fracture mode of UHPC beams is not appreciably affected by RHA. However, UHPC beams incorporating RHA (10%RHA+10%SF) tend to exhibit cracks that extend further towards the supports, indicating improved ductility. This observation aligns with the behavior seen in the load-deflection relationship curves of the UHPC mixes.

4 Comparison with simulation results

The nonlinear analysis of the UHPC beam's behavior was conducted using Midas FEA software. A total strain crack model was applied, which offers two methods: fixed and rotating crack models, depending on the reference axis of the

cracks. The beam structure was modeled using 8-node solid elements, with a nominal element size of 10mm (Fig. 11). Additionally, the reinforcement elements were included in the analysis as embedded reinforcement within the solid elements (Fig. 12).

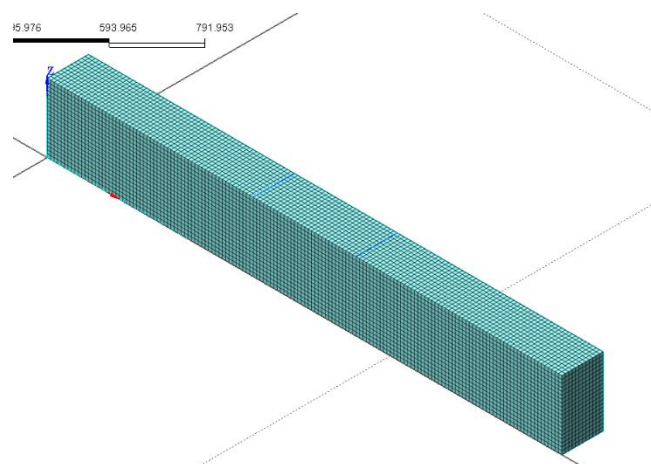


Fig. 11 – Numerical model of UHPC beams

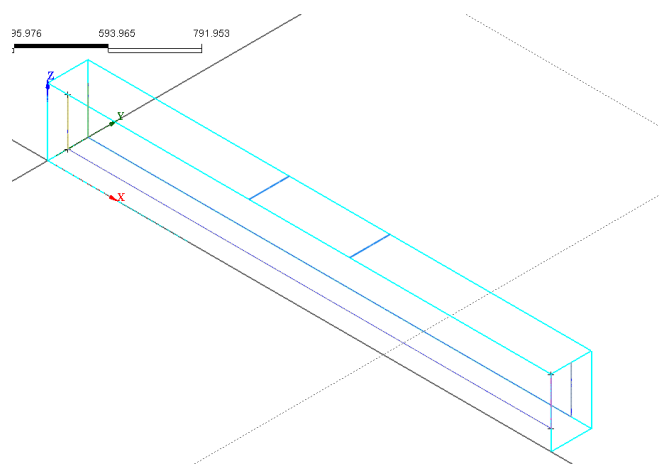


Fig. 12 – Reinforcement model of ultra-high-performance concrete beams

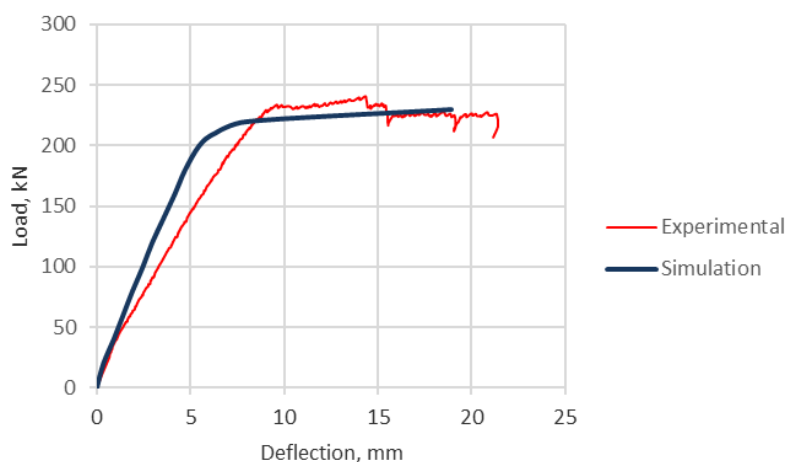


Fig. 13 – Comparison of experimental results and numerical simulation of load-deflection relationship curves

Base on Fig. 13, observing the load-deflection relationship curves from both experimental and simulation data reveals that both curves demonstrate a rapid increase in load as the deflection reaches approximately 5mm. This consistency

indicates that the initial load-carrying capacity of the UHPC beam is well-aligned between the experimental results and the simulation, suggesting a high level of agreement between the two methods in accurately capturing the beam's performance.

After reaching the peak load, the experimental curve exhibits an uneven decline, while the simulation curve shows a more gradual and consistent decrease. This discrepancy may be attributed to the complex and unpredictable factors present in the experimental environment, such as material variations and testing conditions. The unstable drop in load during the experiment could be due to cracks or other damages in the beam. In contrast, the simulation curve's steadier decline suggests that the numerical model may not fully capture the complex behaviors and damage phenomena occurring in the real material.

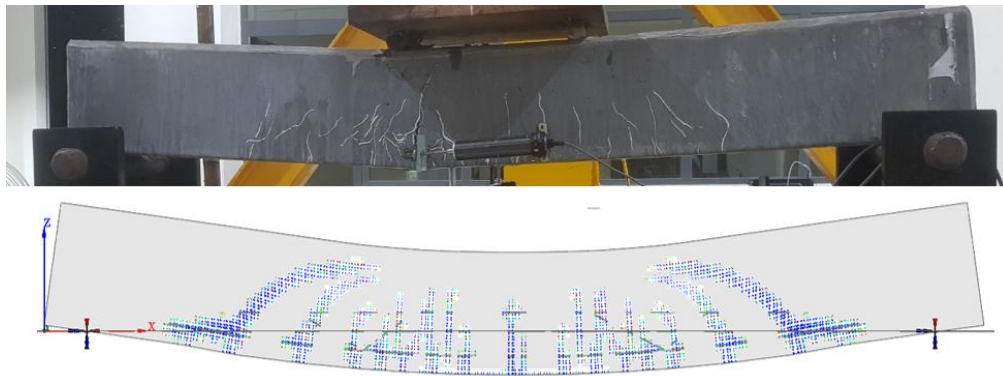


Fig. 14 – Comparison of cracking in experimental and model ultra-high-performance concrete beams

Observing Fig.14 reveals the development of cracks in both the model and experimental beams. Diagonal cracks begin to appear and propagate in both cases. The cracks appear relatively symmetrical, with those in the model closely resembling those observed in the beam bending tests, demonstrating consistency between the simulation and experimental results. The similarity between the cracks observed in the simulation and the experiments confirms the model's suitability for predicting the actual behavior of the beams under bending load.

5 Conclusion

The experimental and computational analysis of the bending performance of UHPC beams incorporating RHA and SF has been carried out in this study. The compressive capacity and bending strength of UHPC have been evaluated to ensure the reliability of the UHPC mixtures. The study provides the following conclusions:

Using RHA to replace SF at a ratio of 10% in UHPC can maintain the desired mechanical properties. Specifically, the UHPC mix C3, which includes 10%RHA+10%SF, exhibits a compressive strength of 156.03 MPa, which is comparable to the reference UHPC mix (20% SF), and a bending strength of 31.32 MPa, which is around 8% higher than the reference mix.

UHPC beams with steel reinforcement, and RHA exhibit good flexural behavior, even without shear reinforcement. The UHPC beams with 10%RHA+10%SF demonstrate similar first-crack, ultimate, and post-yield loads compared to the reference UHPC beams. The load-deflection curves for UHPC beams containing up to 10% RHA show greater stiffness than the linear phase reference beams. The fracture mode of UHPC beams is not considerably affected by RHA. The cracks in UHPC beams with RHA (10%RHA+10%SF) tend to extend further toward the supports, indicating higher ductility. The numerical simulations and experimental results of UHPC beams with RHA show high similarity in the load-deflection relationship curves and failure characteristics.

The findings suggest that UHPC containing RHA could be a viable option for structural applications, supporting sustainable development in the construction industry through increased utilization of waste materials.

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