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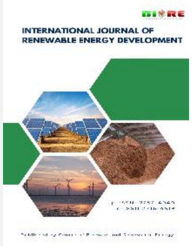

Research Article

Effects of carbon nanotubes and carbon fibers on the properties of ultra-high performance concrete for offshore wind power generation

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Abstract. Ultra-high performance concrete (UHPC), as one of the most eye-catching building materials, has been the subject of extensive research by scholars. On this basis, to expand the application of UHPC for offshore wind turbine towers in complex marine environments, three different fiber materials - copper-plated microfibre steel fibers, carbon fibers, and carbon nanotubes (CNTs) - have been selected for the study of the possibilities of further improving the mechanical properties of UHPC. This study focused on understanding the impact of various fiber combinations and dosages on the flowability, compressive strength, flexural strength, and tensile strength of UHPC. Our findings indicate that carbon fiber, when present at a concentration of up to 0.5%, the effect on the fluidity of UHPC is only about 1.05%. However, the addition of CNTs significantly diminishes the flowability of UHPC, with a consistent decrease observed as the CNT content increases. Notably, when carbon fiber and CNTs are used in combination, the maximum reduction in flowability reaches 7.8%. Furthermore, as the dosage of these fibers increases, the compressive strength, flexural strength, and tensile strength of UHPC all demonstrate a positive trend of improvement. It is observed that the optimal performance is achieved when both carbon fiber and CNTs are present. In particular, carbon fiber exhibits a more profound impact on enhancing compressive strength and flexural strength, when carbon fibers were doped by volume at 0.5%, the compressive and flexural strengths were increased by 6.7% and 11.7%, respectively, compared to the control group, while carbon nanotubes increased the tensile strength by 7.4% at lower dosage. These findings highlight the potential of fiber combinations to optimize UHPC's mechanical properties for various engineering applications..

Keywords: Ultra-high performance concretes, multi-scale, fiber, carbon nanotubes, carbon fiber

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1. Introduction

Ultra-high-performance concrete (UHPC), as a high-performance building material, is able to enhance the structural strength and durability due to its characteristics of ultra-high compressive strength, high toughness, and ultra-high durability. It has been applied in various projects such as bridges, high-rise buildings, nuclear power plants, and military facilities (Bajaber and Hakeem 2021; Jiang *et al.*; Ren *et al.* 2019; Deng *et al.* 2023). Currently, the distinctive features of these UHPC mixtures are as follows: (1) An exceptionally low water-to-binder ratio ranging from 0.15 to 0.24. (2) An optimized gradation of solid particles for achieving a high particle packing density of 0.825 to 0.855. (3) Fine-ground quartz sand with a maximum particle size of less than 0.6 mm. (4) A high cement content ranging from 800 to 1100 kg/m3, along with a silica fume content between 150 and 300 kg/m3. (5) A significant steel fiber content of 2 to 5% (Ahmad 2017; Chen *et al.* 2019). Mixing various high-performance fibers is one of the key factors for UHPC to achieve high performance. Currently, according to different projects, the fibers used to enhance the performance of UHPC mainly include copper-plated microfiber steel fiber, milling steel fiber, polypropylene fiber, PVA fiber, Polyethylene Fiber, etc (Kun *et al.* 2020; Yazan *et al.* 2022; Zhao *et al.* 2022; Zhang *et al.* 2023). The physical and mechanical properties of various fibers and the different dosages will greatly affect the performance of UHPC. Yang *et al.* (2021) conducted experiments on adding special fibers into UHPC and found that the increase in compressive strength of UHPC did not produce an effect. Steel fiber, as one of the main raw materials, has the effect of enhancing fracture toughness, increasing tensile strength, and preventing cracks from cracking. The addition of steel fiber prevents the expansion of concrete cracks, and the specimens show good integrity after compression (Wu *et al.* 2016). Wu *et al.* (2017) and other researchers have shown that there is a positive correlation between the dosage of steel fiber and the performance of UHPC. However, for compressive strength and flexural strength, there is a critical value for the dosage of steel fiber to achieve the highest mechanical properties. Chen *et al.* (2020) and other researchers have shown that when the dosage of steel fiber reaches a turning point, the increase in compressive strength and toughness is not significant or even reduced. Moreover, the shape, length, diameter, etc. of steel fiber will greatly affect its reinforcement and toughening effect.

In summary, the addition of fibers can enhance the mechanical properties of UHPC, but most of the current research is on a single fiber. Some scholars have also studied the effect of incorporating two types of fibers on UHPC

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(Assanvo *et al.* 2023; Al-Aasama *et al.* 2023). Wang *et al.* (2023) studied steel-polypropylene The effect of fiber blending on the tensile stress-strain of UHPC. The results show that adding steel-polypropylene hybrid fibers to the UHPC matrix can help improve the tensile mechanical properties, including tensile strength, peak strain, and especially tensile toughness. Rui *et al.* (2022) studied the effect of blending steel and polyoxymethylene fiber on the mechanical properties of UHPC. The test results showed that polyoxymethylene fiber has limited contribution to compressive strength, but can improve the bending and high-temperature properties. Li *et al.* (2023) mixed carbon nanotubes and steel fibers into UHPC, conducted dynamic mechanical tests, and gave suggestions on the dosage of carbon nanotubes is 0.1%. However, current research is lacking on the impact of fiber blending in three dimensions, millimeter, micron, and nanometer, on the fluidity and mechanical properties of UHPC mixtures.

To investigate the effects of different combinations and dosages of the three fibers on the properties of UHPC, this study selected three fiber materials with different diameter scales, namely, flat copper-plated microfilament steel fibers, short-cut carbon fibers and carbon nanotubes, and designed seven sets of tests with different fiber combinations and dosages to test the flowability, compressive, flexural and tensile strengths of the mixes of UHPC, with the same conditions of the dry powder mix ratio and the water/cement ratio. Tests were conducted to explore the possibility of further improving the mechanical properties of UHPC.

2. Test Materials and Methods

2.1 Test Materials

Cement: P.O 52.5 ordinary Portland cement produced by Liuzhou Yufeng Cement Co., Ltd. Its main physical properties are shown in Table 1. Silica fume, a gray powder with a semi-dense consistency, exhibits a SiO2 content of ≥92% and a specific surface area of 28 m^2/g. The slag powder utilized in this study was produced by Liuzhou Iron and Steel Group Co., Ltd. and exhibits an S95 particle size. The fine aggregate utilized is desalinized sea sand with particle sizes ranging from 16-40 mesh and 40-70 mesh, forming a continuous gradation. The water reducer utilized is a polycarboxylic acid water reducer powder, exhibiting a water-reducing rate of 35%. The carbon nanotube dispersant utilized is the K30 dispersant. The steel fiber utilized is a straight-type copper-plated microfiber steel fiber, the carbon fiber utilized is shortcut carbon fiber, and the CNTs utilized are multi-walled in powder form. The physical and mechanical properties of the three fibers are presented in Table 2.

2.2 Experimental Methods

The design of UHPC mixtures aims to achieve a high particle packing density, which leads to low porosity, high mechanical strengths, and impermeability. The Anderson and Andreasen model is the most widely used theoretical model for designing UHPC to achieve the maximum packing density of particles involved (Yu *et al.* 2014). Nevertheless, this method only considers the particles under dry conditions, which may not accurately reflect the real particle packing of UHPC because the influence of water and other liquids is not taken into account (Li and Kwan 2014). Therefore, to obtain the "real" maximum particle packing, the wet particle packing density method was introduced (Wong and Kwan 2008). Nevertheless, the maximum packing density does not always result in the best performance of UHPC, thus the performance-based method was developed.

To further investigate the impact of carbon fiber and CNTs on the performance of UHPC, experiments were conducted utilizing the identical UHPC dry powder and steel fiber mixture, with the inclusion of varying dosages of carbon fiber and CNTs. The dosage of steel fiber is 2% by volume, the dosage of carbon fiber is 0.25% and 0.5% by volume, respectively, and the dosage of carbon nanotubes refers to the relevant research data and takes into account that this study additionally dopes carbon fiber as well as the actual engineering of the economic principle. the design of carbon nanotube doping for the weight of the gelling material was 0.1% and 0.2%, respectively, and converted into volume doping was 0.05% and 0.1%, respectively. The detailed mixing ratios are shown in Table 3.

2.3 Specimen Preparation and Testing Methods

To conduct a thorough investigation into the impact of carbon fiber and CNTs on the performance of UHPC, we conducted a series of experiments utilizing an identical UHPC dry powder and steel fiber mixture. By introducing varying dosages of carbon fiber and CNTs, we carefully calculated the mixing ratios and accurately weighed and prepared each individual component. The water amount was also calculated and weighed based on the water-binder ratio. Prior to mixing, the total mass of raw materials was converted based on 2/3 of the mixing machine's volume capacity.

For mixing, we first prepared a CNTs dispersion by combining CNTs, CNT dispersant, and 10% of the water. Subsequently, all the dry powder and the remaining 90% of the water were added to an HJW-60 single horizontal shaft forced concrete mixer. The mixer was turned on for 3 minutes, then turned off to allow for the addition of the prepared steel fiber (or

Table 1
Main performance indexes of cement

Setting Time/Min		Compressive strength/MPa		Flexural strength/MPa		Specific Surface Area/ (m^2/kg)
Initial setting time	Final setting time	3d	28d	3d	28d	
151	206	32.7	57.3	6.1	8.2	378

Table 2
Physical property index of fibers

Fiber	Length/μm	Diameter /μm	Aspect ratio	Tensile strength/GPa	Elastic modulus/GPa
Steel Fiber（SF）	13000	220	59	2.8	210
Carbon Fiber（CF）	6000	7	857	4.9	240
CNTs	3-12	0.008-0.015	375-800	800	1000

Table 3
Experimental mix design (kg/m³)

No.	Cement	Silica fume	slag	Sand	Water	Water	SF	CF	CNTs
S2	870	175	95	960	9	211	157	0	0
S2CF2.5	870	175	95	960	9	211	157	4.5	0
S2CF5	870	175	95	960	9	211	157	9	0
S2CN5	870	175	95	960	9	211	157	0	0.9
S2CN10	870	175	95	960	9	211	157	0	1.8
S2CF2.5CN5	870	175	95	960	9	211	157	4.5	0.9
S2CF5CN10	870	175	95	960	9	211	157	9	1.8

steel fiber + carbon fiber). The mixer was restarted for an additional 2 minutes to complete the preparation of the UHPC mixture. By following this meticulous mixing process, we aimed to ensure that each mixture contained uniform proportions of the ingredients, providing a more representative assessment of the impact of carbon fiber and CNTs on UHPC performance.

The flowability of UHPC was determined according to GB/T 50448-2015, the Technical code for the application of cementitious grout, Appendix A: Test Methods for Basic Properties of Cementitious Grouting Materials. For this purpose, a truncated cone mold with an upper inner diameter of 70mm, a lower inner diameter of 100mm, and a height of 60mm was utilized. A glass plate measuring 500mm x 500mm served as the base.

The well-mixed UHPC was poured into the mold and leveled to ensure a uniform distribution. Subsequently, the mold was lifted to allow the UHPC to flow freely on the glass plate without any external disturbance, once the flow had ceased, a steel ruler was to measure the maximum diffusion diameter of the UHPC mixture and its diameter in the vertical direction and calculate the average value as the fluidity, as illustrated in Fig.1. (a). By following these precise measurement procedures, we aimed to obtain accurate and reproducible results that would aid in assessing the flowability of UHPC under controlled conditions.

The compressive strength [Fig 1. (b)] and flexural strength [Fig 1. (c)] were tested in accordance with GB/T 50448-2015, the Technical code for application of cementitious grout, Appendix A: Test Methods for Basic Properties of Cementitious Grouting Materials. For these tests, 40mm x 40mm x 160mm molds were utilized. The specimens were molded at a temperature of 20℃ and a relative humidity of 50%. After demoulding, they were placed in a standard curing box and cured for 28 days before undergoing testing.

By following these standardized testing procedures, we aimed to ensure that the compressive and flexural strengths of the UHPC specimens were accurately measured under controlled conditions. This would provide valuable insights into the mechanical properties of UHPC and its potential applications.

The tensile strength test was conducted based on the tensile strength test method described in DL/T 5193-2004, the Technical code of epoxy resin mortar, Section 5.10: Epoxy mortar tensile strength test method. For this test, an “8” shaped

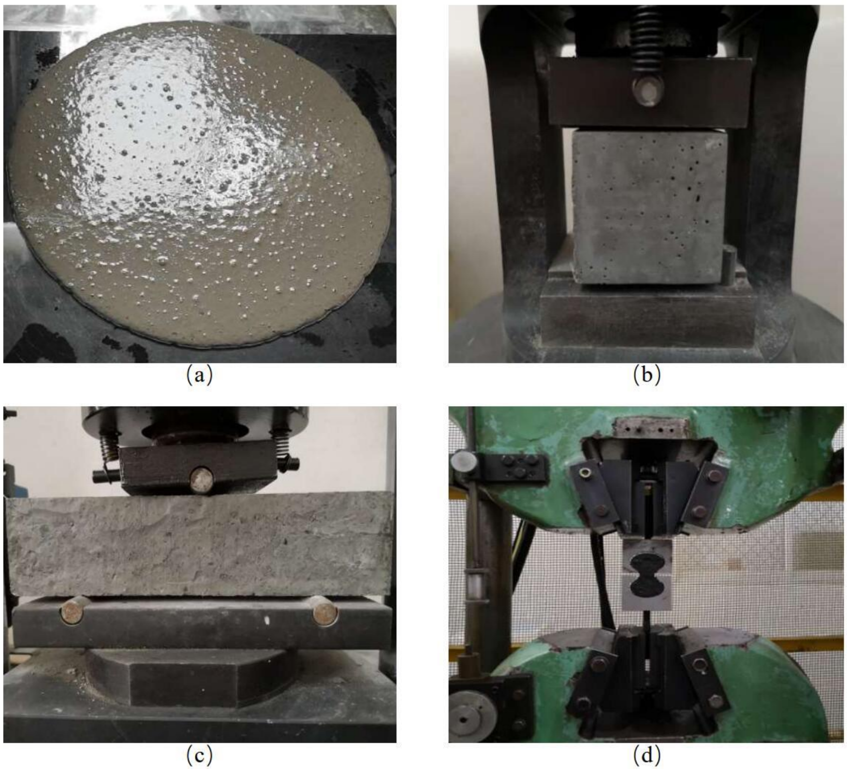

Fig. 1. (a)Fluidity test (b)Compressive strength test(c)Flexural strength test(d)Tensile strength test

mold with dimensions of 76.2mm x 44.4mm x 25mm was utilized. The specimens were prepared by curing them in a standard curing room for 28 days, after which they were tested for tensile strength [Fig 1. (d)].

By following this standardized testing procedure, we aimed to accurately measure the tensile strength of the UHPC specimens under controlled conditions. This would provide valuable insights into the tensile properties of UHPC and its potential applications. However, considering that the minimum cross-sectional size of the tensile mold was only 25mm, there may be a possibility of errors in the tensile strength data due to deviations in the homogeneity of the steel fibers in the UHPC mixture.

3. Results and Discussion

3.1 Effect of Hybrid Fibers on the Flowability of UHPC

Through testing the flow of ultra-high performance concrete mixes with different mix ratios, we observed that the combination of steel fiber and carbon fiber, with a volume content of short-cut carbon fiber less than 0.5%, exhibited excellent dispersion within the slurry. This prevented agglomeration and ensured uniform distribution of the fibers. Notably, this blend exhibited flowability comparable to that of the reference group S2, with deviations limited to ±3mm. Consequently, it can be inferred that this blend has minimal impact on the flowability of UHPC mixtures.

Moreover, the excellent dispersion of fibers within the slurry highlights the importance of fiber type and volume content on the flowability of UHPC mixtures. This observation provides valuable insights for further research on the optimization of fiber combinations and their effects on the flowability and mechanical properties of UHPC. When combining steel fiber with CNTs, a notable decrease in flowability is observed. More specifically, the flowability of S2CN5 exhibits an 8mm reduction compared to S2. As the CNTs content increases, the flowability continues to decrease, with a reduction range spanning from 2.8% to 7.6%. These findings suggest that CNTs have a significant impact on the flowability of UHPC mixtures. This may be due to the large specific surface area of CNTs and the adsorption of more water, which reduces the free liquid phase of the UHPC slurry and reduces the fluidity of the slurry. We consider that subsequent tests will replace several other types of water-reducing agents. In an attempt to improve this phenomenon without affecting the strength of the UHPC that is, water consumption cannot be increased.

The results obtained from these experiments highlight the importance of fiber type and its volume content on the flowability of UHPC mixtures. The combination of steel fiber and CNTs leads to a noticeable reduction in flowability, indicating that the choice of fiber type and its proportion must be carefully considered when designing UHPC mixtures with optimal flowability.

The observed reduction in flowability may be attributed to several factors, including the increased viscosity of the slurry due to the presence of CNTs and their tendency to agglomerate. These findings suggest that further research is needed to explore potential methods of improving the dispersion and flowability of UHPC mixtures containing CNTs.

Interestingly, when combining steel fiber, carbon fiber, and CNTs, the resulting flowability is similar to that of the combination involving steel fiber and CNTs, with deviations limited to ±2mm. The comprehensive experimental data is summarized in Fig. 2.

3.2 Effect of Hybrid Fibers on the Compressive Strength of UHPC

The average 28d compressive strength of UHPC with various combinations and dosages of hybrid fibers is illustrated in Fig. 3. When utilizing the combination of steel fiber and carbon fiber, the compressive strengths of S2CF2.5 and S2CF5 exhibit respective increases of 3.5% and 6.7% compared to the control group S2. As the volume content of carbon fiber increases from 0.25% to 0.5%, a notable enhancement in compressive strength is observed. When a certain dosage of short-cut carbon fiber is properly dispersed within the UHPC mixture, it effectively couples with the steel fiber, resulting in improved bonding with the UHPC matrix. The length-to-diameter ratio of carbon fiber is 14.5 times that of steel fiber, offering superior bonding and making it less prone to slipping or being pulled out under compressive stress.

Under compressive stress, carbon fiber supplements the UHPC matrix, effectively offsetting the limited reinforcement effect of single steel fiber. In comparison to steel fiber only, the coupling effect of steel fiber combined with carbon fiber is more significant in restricting cracking, achieving a notable reinforcing effect.

These findings suggest that the combination of steel fiber and carbon fiber can enhance the compressive strength of UHPC mixtures, with increasing carbon fiber content leading to further improvements. The improved bonding between the

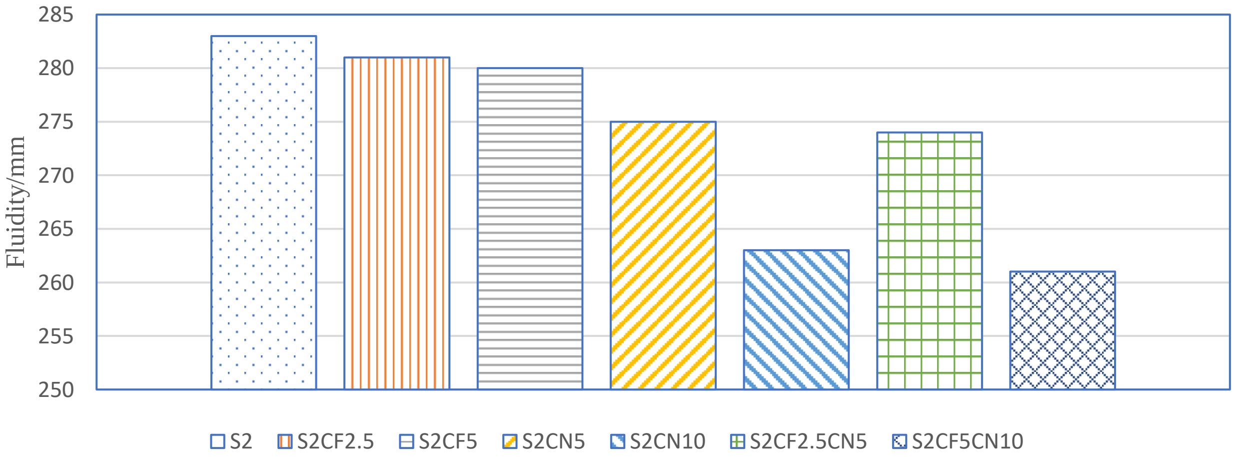

Fig. 2. UHPC mixing fluidity test

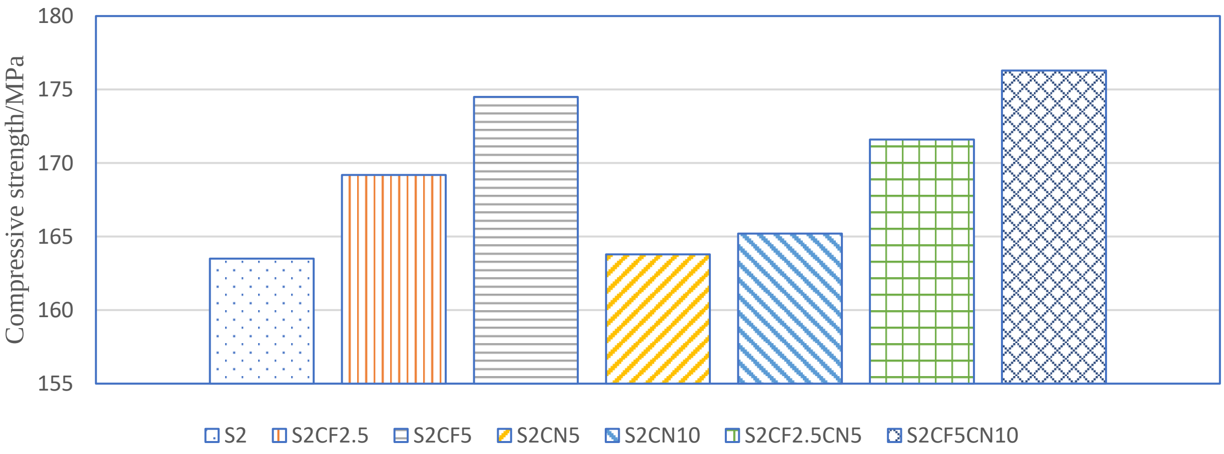

Fig. 3. UHPC compressive strength

fibers and the UHPC matrix, as well as the supplementary reinforcement provided by carbon fiber, contribute to the enhanced compressive strength observed. It is noteworthy that these results are consistent with previous studies that have investigated the use of carbon fiber in UHPC mixtures. The coupling effect between steel fiber and carbon fiber has been attributed to their different reinforcement mechanisms, with steel fiber providing pull-out resistance and carbon fiber enhancing bonding and restricting cracking.

Therefore, based on these findings, it can be inferred that the combination of steel fiber and carbon fiber can effectively enhance the compressive strength of UHPC mixtures, offering potential benefits in structural applications where high compressive strength is required.

Interestingly, the compressive strength of S2CN5 and S2CN10, which utilize the combination of steel fiber and CNTs, remain relatively unchanged compared to S2. This indicates that CNTs have a limited reinforcing effect due to their low dosage. When incorporating steel fiber, carbon fiber, and CNTs, the compressive strengths of S2CF2.5CN5 and S2CF5CN10 exhibit respective increases of 4.9% and 7.8% compared to S2, slightly outperforming the combination of steel fiber and carbon fiber. This observation highlights that at low dosages, CNTs have a limited effect on enhancing the compressive strength of UHPC.

The result obtained is consistent with that reported by Meng et al. (2016), who observed a minor enhancement in the compressive strength of UHPC following the doping of carbon nanotubes, amounting to approximately 5-8 MPa. Additionally, Jung et al. (2020). also discovered that the inclusion of a moderate amount of carbon nanotubes led to an increase in the strength of UHPC by 5.5%.

These findings suggest that at low dosages, the combination of steel fiber and carbon fiber provides a more significant reinforcing effect than CNTs alone. However, this result is still much higher than the compressive strength of 143.7 MPa for UHPC with CNTs and steel fiber blend (Zhao et al. 2022). Follow-up is needed to further research is needed to investigate the potential benefits of using higher dosages of CNTs in UHPC mixtures, as well as the mechanisms underlying their reinforcement effect.

3.3 Effect of Hybrid Fibers on the Flexural Strength of UHPC

The average flexural strength of UHPC at 28 days for each group is displayed in Fig. 4. The flexural strengths of S2CF2.5 and S2CF5 exhibit respective increases of 6.6% and 11.7% compared to the control group S2, indicating that the incorporation of a certain amount of carbon fiber can effectively enhance the flexural strength of UHPC, with a more significant improvement compared to the compressive strength. This improvement can be attributed to the superior bonding between the UHPC matrix and carbon fiber, which has a length-diameter ratio as high as 857, compared to the surface-smooth steel fiber with a length-diameter ratio of only 59. The aspect ratio is the ratio between fiber length (Lf) and fiber diameter (Df) (Chun and

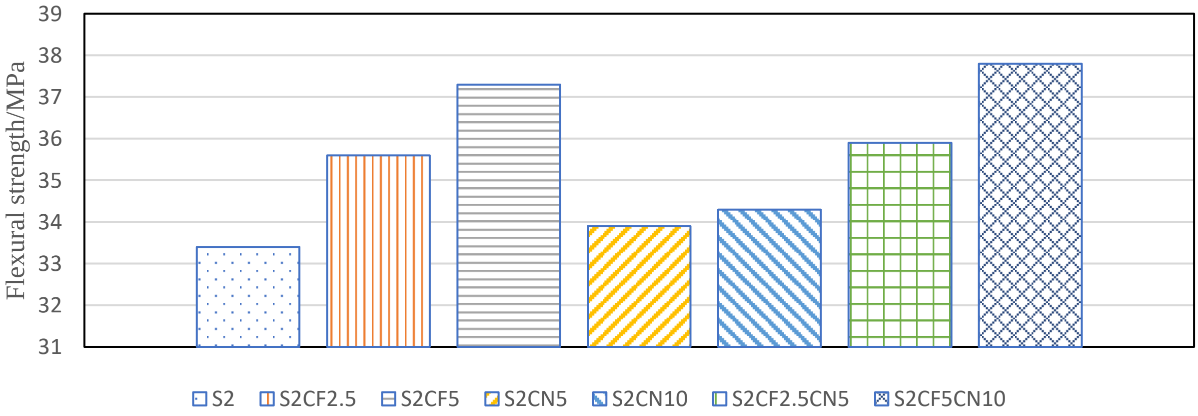

Fig. 4. UHPC flexural strength

Yoo 2019). In most cases, steel fibers with a higher aspect ratio provide better flexural performance (e.g., flexural strength, deflection capacity, and toughness) (Yoo et al. 2016; Yoo et al. 2017). This is because the reinforcing fibers with a higher aspect ratio have a larger effective fiber-matrix bond area, and thus provide better post-cracking behavior (Yoo et al. 2015). Some carbon fibers wrap around the steel fibers during mixing, enhancing the bonding between the steel fiber and UHPC matrix. The coupling effect of these two fibers enhances the flexural performance of UHPC.

The flexural strengths of S2CN5 and S2CN10, which incorporate CNTs, exhibit respective increases of 1.5% and 2.7% compared to S2. This suggests that CNTs can enhance the flexural strength of UHPC, but the effect is limited due to their low dosage. When combining carbon fiber and CNTs, the flexural strengths of S2CF2.5CN5 and S2CF5CN10 exhibit respective increases of 7.5% and 13.2% compared to S2, slightly outperforming S2CF2.5 and S2CF5. This trend is consistent with the observation for compressive strength, where the enhancement mainly comes from the larger dosage and length-diameter ratio of carbon fiber. However, the combination of carbon fiber and CNTs can achieve the best improvement in flexural performance.

These findings suggest that the flexural strength of UHPC can be improved through the addition of carbon fiber and CNTs, but further research is needed to investigate the optimal combination and dosage of these materials for achieving the best flexural performance. It is also important to note that the flexural strength of UHPC is influenced by multiple factors, such as the microstructure, chemistry, and mechanical properties of the constituent materials, as well as the processing conditions during mixing and casting. Therefore, future research should consider these factors when optimizing the flexural performance of UHPC.

3.4 Effect of Hybrid Fibers on the Tensile Strength of UHPC

The average tensile strength of UHPC in each group at 28d is displayed in Fig. 5. By introducing short carbon fiber with a volume content of 0.5% into S2CF2.5 and S2CF5, their tensile strength has been significantly enhanced by 10.6% and 19.1%, respectively, compared to the control group S2. This substantial improvement in tensile strength surpasses the corresponding enhancements in compressive and flexural strengths. The remarkable adhesive bond between the UHPC matrix and carbon fiber, which has a long diameter ratio of 857, appears to be the primary factor behind this observation. This adhesive bond surpasses that between the UHPC matrix and steel fiber, which has a smooth surface and a long diameter ratio of only 59. Furthermore, the carbon fiber's tensile strain of 1.7% is only one-tenth that of steel fiber. Consequently, under tensile stress, the carbon fiber effectively collaborates with the UHPC matrix, offsetting the limited tensile performance of steel fiber. This synergy between the two fibers leads to substantial improvements in the tensile performance of UHPC.

Additionally, the introduction of CNTs with ultra-high tensile strength, ultra-high elastic modulus, and ultra-high long diameter ratio into S2CN5 and S2CN10 enhances their tensile strength by 3.2% and 7.4%, respectively, compared to S2. This finding suggests that CNTs significantly bolster the tensile performance of UHPC even at low dosages. Furthermore, when CNTs wrapped around the steel fiber surface produce relative slippage with the UHPC matrix, they significantly amplify the anchoring force of the UHPC matrix on steel fiber. This augmentation improves the utilization rate of tensile performance of steel fiber. This result is similar to the findings of Li *et al.* (2023).

Finally, the combination of carbon fiber and CNTs in S2CF2.5CN5 and S2CF5CN10 boosts their tensile strength by 12.8% and 24.5%, respectively, compared to S2. Among them, the tensile strength of S2CF5CN10 reaches 11.7 MPa, which is much higher than the tensile strength of Polyethylene Fiber doped UHPC of 7.37 MPa (Li et al. 2023). This finding underscores that the concurrent addition of carbon fiber and CNTs to UHPC results in a more pronounced reinforcement effect than either material alone. He et al. (2017) attributed the remarkable enhancement in UHPC tensile properties to the introduction of nanofibers, which strengthened the interfacial transition zone through the carbon nanotubes. This occurred primarily through the filling of nanopores and bridging of nanocracks, resulting in a more densely packed microstructure and increased resistance to fiber pullout. Notably, the scale of carbon fiber was larger than that of carbon nanotubes, making it more effective in preventing steel fiber slippage. Consequently, the tensile resistance of S2CF5 specimens surpassed that of S2CN10. When micron-scale fibers were combined with nanoscale fibers, it created a tangled mass of

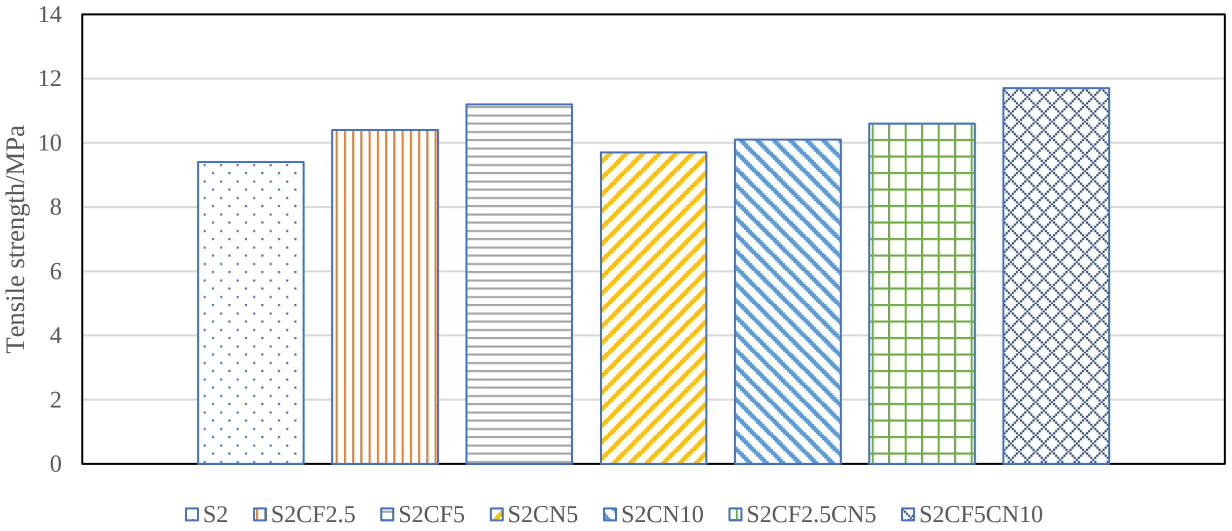

Fig. 5. UHPC tensile strength

fibers of different scales on the surface of the steel fibers, leading to significant tensile enhancement. This combination of fibers at different scales not only offered reinforcement but also improved the load transfer efficiency within the composite, further enhancing its mechanical properties. The findings of this study provide valuable insights into the design and optimization of UHPC materials with improved tensile properties through the judicious use of nanofibers.

4. Conclusion and Outlook

The fluidity of UHPC exhibits a negative correlation with the content of various fibers, with CNTs exerting a particularly significant impact on fluidity. When only carbon fiber is added, the decrease in UHPC fluidity is minimal, not exceeding 1.1%. However, when only CNTs are introduced, there is a noticeable decline in UHPC fluidity, which increases as the CNTs content rises, ranging from 2.8% to 7.6%. When both carbon fiber and CNTs are incorporated, the maximum decrease in fluidity reaches 7.8%, highlighting the cumulative effect of both materials.

With the increase in the content of various fibers, the compressive, flexural, and tensile strengths of UHPC gradually increase. The maximum values are achieved when carbon fiber and CNTs are combined, at 176.3MPa, 37.8MPa, and 11.7MPa, respectively. This finding highlights the synergistic effect of these two materials in enhancing UHPC's mechanical properties.

Carbon fiber demonstrates a superior reinforcement effect on the compressive and flexural strengths of UHPC compared to CNTs. This effect is further enhanced when both carbon fiber and CNTs are incorporated into UHPC.

When only 0.1% volume content of CNTs is introduced, the tensile strength of UHPC increases by 7.4%. This significant enhancement in tensile strength can be achieved with low CNTs content, highlighting their efficient reinforcement potential. When steel fiber, carbon fiber, and CNTs are combined, carbon fiber and CNTs wrap around the surface of steel fiber, leading to a coupling and synergistic improvement in UHPC's mechanical properties. This observation highlights the potential for combining these three fibers to achieve enhanced mechanical properties in UHPC.

The results of this study help to build on existing research to further improve the mechanical properties of UHPC for the preparation of lighter and more durable concrete elements, which can help to reduce carbon emissions throughout the life cycle of a building. The dosage of carbon fibers and CNTs used in this study will raise the material cost of UHPC by about 15%, which is a potential factor that restricts the application of the research results in practical engineering applications, for this reason, we plan to consider conducting experimental studies on the effects of combinations of fiber types and dosage on the mechanical properties of UHPC (especially tensile strains) in our next study, to reduce the high cost of fibers and make it more cost-effective in the production of ultrahigh-strength concrete members such as ultrahigh-strength concrete beams without webs, and to promote the dissemination of the research results in engineering applications.

Foundation Project

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References

Ahmad, S. (2017). Use of alternative waste materials in producing ultra-high performance concrete. In *MATEC Web of Conferences* (Vol. 120, p. 03014). EDP Sciences. https://doi.org/10.1051/matecconf/201712003014

Aisheh, Y. I. A., Atrushi, D. S., Akeed, M. H., Qaidi, S., & Tayeh, B. A. (2022). Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete. *Case Studies in Construction Materials*, 17, e01234. https://doi.org/10.1016/j.cscm.2022.e01234

Al-Aasama, A. B., Ibrahim, A., Syafiq, U., Sopian, K., Abdulsahib, B. M., & Dayer, M. (2023). Enhancing the performance of water-based PVT collectors with nano-PCM and twisted absorber tubes. *International Journal of Renewable Energy Development*, 12(5), 891-901. https://doi.org/10.14710/ijred.2023.54345

Assanvo, E. F., Toure, K. J. Y. N. Z., N'Gatta, K. M., & Boa, D. (2023). Kinetic and thermodynamic study of composite with jute fiber as reinforcement. *International Journal of Renewable Energy Development,* 13(1), 1-9,https://doi.org/10.14710/ijred.2023.54407

Bajaber, M. A., & Hakeem, I. Y. (2021). UHPC evolution, development, and utilization in construction: A review. *Journal of Materials Research and Technology,* 10, 1058-1074. https://doi.org/10.1016/j.jmrt.2020.12.051

Chen, B., Lin, Y., Yang, J., Huang, Q., Huang, W., & Yu, X. (2020). Review on fiber function in ultra-high performance fiber reinforced concrete. *J. Fuzhou Univ.(Nat. Sci. Ed.),* 48, 58-68. https://doi.org/10.14359/1193

Chen, Y., Matalkah, F., Soroushian, P., Weerasiri, R., & Balachandra, A. (2019). Optimization of ultra-high performance concrete, quantification of characteristic features. *Cogent Engineering*, 6(1), 1558696. https://doi.org/10.1080/23311916.2018.1558696

Chun, B., & Yoo, D. Y. (2019). Hybrid effect of macro and micro steel fibers on the pullout and tensile behaviors of ultra-high-performance concrete. *Composites Part B: Engineering*, 162, 344-360. https://doi.org/10.1016/j.compositesb.2018.11.026

Deng, Y., Zhang, Z., Shi, C., Wu, Z., & Zhang, C. (2022). Steel fiber–matrix interfacial bond in ultra-high performance concrete: A review. *Engineering*. https://doi.org/10.1016/j.eng.2021.11.019

Du, J., Meng, W., Khayat, K. H., Bao, Y., Guo, P., Lyu, Z., ... & Wang, H. (2021). New development of ultra-high-performance concrete (UHPC). *Composites Part B: Engineering*, 224, 109220. https://doi.org/10.1016/j.compositesb.2021.109220

He, S., Qiu, J., Li, J., & Yang, E. H. (2017). Strain hardening ultra-high performance concrete (SHUHPC) incorporating CNF-coated polyethylene fibers. *Cement and concrete research*, 98, 50-60. https://doi.org/10.1016/j.cemconres.2017.04.003

Jung, M., Lee, Y. S., Hong, S. G., & Moon, J. (2020). Carbon nanotubes (CNTs) in ultra-high performance concrete (UHPC): Dispersion, mechanical properties, and electromagnetic interference (EMI) shielding effectiveness (SE). *Cement and Concrete Research*, 131, 106017. https://doi.org/10.1016/j.cemconres.2020.106017

Li, L. G., & Kwan, A. K. H. (2014). Packing density of concrete mix under dry and wet conditions. *Powder technology*, 253, 514-521. https://doi.org/10.1016/j.powtec.2013.12.020

Li, S., Yan, J., Ma, H., Lyu, X., Zhang, Y., & Du, S. (2023). Hybrid effects of carbon nanotubes and steel fiber on dynamic mechanical properties of ultra-high performance concrete. *Materials Research Express*, 10(2), 025503. https://doi.org/10.1088/2053-1591/acbd1b

Meng, W., & Khayat, K. H. (2016). Mechanical properties of ultra-high-performance concrete enhanced with graphite nanoplatelets and carbon nanofibers. *Composites Part B: Engineering*, 107, 113-122. https://doi.org/10.1016/j.compositesb.2016.09.069

Ren, L., Fang, Z., & Wang, K. (2019). Design and behavior of super-long span cable-stayed bridge with CFRP cables and UHPC members. *Composites Part B: Engineering,* 164, 72-81. https://doi.org/10.1016/j.compositesb.2018.11.060

Rui, Y., Kangning, L., Tianyi, Y., Liwen, T., Mengxi, D., & Zhonghe, S. (2022). Comparative study on the effect of steel and polyoxymethylene fibers on the characteristics of Ultra-High-Performance Concrete (UHPC). *Cement and Concrete Composites*, 127, 104418. https://doi.org/10.1016/j.cemconcomp.2022.104418

Wang, S., Xu, L., Chi, Y., Cui, K., Yin, C., & Li, B. (2023). Cyclic tensile behavior of ultra-high performance concrete with hybrid steel-polypropylene fiber: Experimental study and analytical model. *Composite Structures*, 321, 117255. https://doi.org/10.1016/j.compstruct.2023.117255

Wong, H. H., & Kwan, A. K. (2008). Packing density of cementitious materials: part 1—measurement using a wet packing method. *Materials and structures*, 41, 689-701. https://doi.org/10.1617/s11527-007-9274-5

Wu, Z., Shi, C., He, W., & Wang, D. (2017). Static and dynamic compressive properties of ultra-high performance concrete (UHPC) with hybrid steel fiber reinforcements. *Cement and concrete composites,* 79, 148-157. https://doi.org/10.1016/j.cemconcomp.2017.02.010

Wu, Z., Shi, C., He, W., & Wu, L. (2016). Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete. *Construction and building materials*, 103, 8-14. https://doi.org/10.1016/j.conbuildmat.2015.11.028

Yang, J., Chen, B., & Nuti, C. (2021). Influence of steel fiber on compressive properties of ultra-high performance fiber-reinforced concrete. *Construction and Building Materials*, 302, 124104. https://doi.org/10.1016/j.conbuildmat.2021.124104

Yoo, D. Y., & Yoon, Y. S. (2015). Structural performance of ultra-high-performance concrete beams with different steel fibers. *Engineering Structures,* 102, 409-423. https://doi.org/10.1016/j.engstruct.2015.08.029

Yoo, D. Y., Banthia, N., Kang, S. T., & Yoon, Y. S. (2016). Size effect in ultra-high-performance concrete beams. *Engineering Fracture Mechanics,* 157, 86-106. https://doi.org/10.1016/j.engfracmech.2016.02.009

Yoo, D. Y., Kim, S., Park, G. J., Park, J. J., & Kim, S. W. (2017). Effects of fiber shape, aspect ratio, and volume fraction on flexural behavior of ultra-high-performance fiber-reinforced cement composites. *Composite Structures*, 174, 375-388. https://doi.org/10.1016/j.compstruct.2017.04.069

Yu, R., Spiesz, P., & Brouwers, H. J. H. (2014). Mix design and properties assessment of ultra-high performance fibre reinforced concrete (UHPFRC). *Cement and concrete research*, 56, 29-39. https://doi.org/10.1016/j.cemconres.2013.11.002

Zhang, K., Ni, T., Sarego, G., Zaccariotto, M., Zhu, Q., & Galvanetto, U. (2020). Experimental and numerical fracture analysis of the plain and polyvinyl alcohol fiber-reinforced ultra-high-performance concrete structures. *Theoretical and Applied Fracture Mechanics*, 108, 102566. https://doi.org/10.1016/j.tafmec.2020.102566

Zhang, K., Ni, T., Zhang, J., Wang, W., Chen, X., Zaccariotto, M., ... & Galvanetto, U. (2023). Experimental and hybrid FEM/peridynamic study on the fracture of ultra-high-performance concretes reinforced by different volume fractions of polyvinyl alcohol fibers. *Polymers*, 15(3), 501. https://doi.org/10.3390/polym15030501

Zhao, X., Cai, L., Ji, X., Zeng, W., & Liu, J. (2022). Mechanical properties of polyethylene fiber reinforced ultra high performance concrete (UHPC). *Materials*, 15(24), 8734. https://doi.org/10.3390/ma15248734