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Review

Recycling solid waste to produce eco-friendly ultra-high performance concrete: A review of durability, microstructure and environment characteristics

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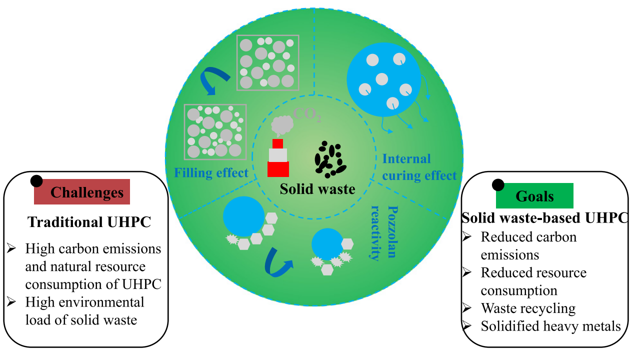
HIGHLIGHTS

- The durability of the eco-friendly UHPC was evaluated.
- The influence of solid waste on the microstructure of UHPC was reviewed.
- The environmental benefits of solid waste modified UHPC were compared.

GRAPHICAL ABSTRACT



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ABSTRACT

Recycling waste materials (WMs) is a cost-effective method for saving natural resources, protecting the environment, and reducing the use of high-carbon raw materials. This review aims to illustrate the impact of solid waste on the durability and microstructure of ultra-high performance concrete (UHPC) and to provide guidance for the research of eco-friendly UHPC. The results show that the proper use of solid waste to replace part of the binder or aggregate has a positive effect on the performance development of UHPC, but further enhancement techniques should be developed. When solid waste is prepared as a binder, the durability of waste based UHPC can be effectively improved by grinding and activation. When solid waste is used as an aggregate, its rough surface, potential reactivity and internal curing effect are also beneficial to the improvement of UHPC performance. Since UHPC has a dense microstructure, it can effectively prevent the leaching of harmful elements (heavy metal ions) in solid waste. However, the effect of waste modification on the reaction products of UHPC needs to be further studied, and design methods and testing standards

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Abbreviations: CA, Coarse aggregate; SCM, Supplementary cementitious material; CRT, Cathode ray tube; FS, Ferrosilicon; FA, Fly ash; FT, Freeze-thaw; GA, Gabbro aggregate; GGBS, Ground granulated blast-furnace slag; GP, Glass powder; HD, High-density; IOT, Iron ore tailings; IBA, Incineration bottom ash; ITZ, Interfacial transition zone; LCD, Liquid crystal display; NWG, nano-glass slag; UPOFA, Ultra-fine palm oil fuel ash; MSWIFA, Municipal solid waste incineration fly ash; MS, manufacturing sand; RCA, Recycled concrete aggregates; RHA, Rice husk ash; SF, Silica fume; SSA, Sewage sludge ash; SSP, Steel slag powder; SCBA, Sugar cane bagasse ash; SS, Steel slag; TGA, Thermo-gravimetric analysis; UHPC, Ultra-high-performance concrete; UHD, Ultra high-density; W/B, Water/binder; WM, Waste materials; WFS, Waste foundry sand; XRD, X-ray diffraction.

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suitable for eco-friendly UHPCs should be developed. The use of solid waste in UHPC effectively reduces the carbon footprint of the mixture, which is beneficial to the development of cleaner production technologies.

Contents

1. Introduction

In recent years, ultra-high-performance concrete (UHPC) has obtained increasing attention across the different sectors of the construction industry. UHPC has a dense microstructure, which effectively prolongs the durability and sustainability of concrete structures (Li et al., 2022). Furthermore, UHPC has an exceptionally high compressive strength, making it beneficial for use in multiple construction applications. The reported minimum compressive strength of UHPC is 150 and 120 MPa, as reported by ACI 239R-18 (Recommendations, 2002) and ASTM C1856 (Nodehi and Nodehi, 2022) international standards, respectively, with the latter standard recognizing the outstanding durability of UHPC. Therefore, UHPC is widely used in tunnels, bridges and high-rise buildings due to its high strength and excellent durability.

Although UHPC has proven to have successful applications in various areas in addition to exhibiting unique mechanical properties, UHPC is not used widely and is uncommon in the industry. There are many reasons for the delay in the promotion of UHPC in construction projects, the important being UHPC's high costs and the carbon footprint of its raw materials. The costs and environmental load of UHPC can be reduced by replacing its raw materials with costless and eco-friendly materials of similar properties. UHPC normally consists of cement, quartz powder, silica fume (SF), silica sand, supplementary cementitious material (SCM), fibers, and superplasticizer. The cement content can be reduced by using various pozzolanic materials with a lower cost like fly ash (FA), glass powder (GP), etc. (Pham et al., 2020; Soliman and Tagnit-Hamou, 2016; Wang et al., 2022b). Similarly, the dosage of quartz powder and SF can be reduced by other matching waste materials (WMs) (Soliman and Tagnit-Hamou, 2017a; Chen et al., 2022a, 2022b). Researchers have tried to improve the mechanics and durability of UHPC through the filling effect, pozzolanic reactivity and internal curing effect of solid waste. He et al. (2022a) used waste coral powder to replace part of the cement to produce UHPC and found that the compressive strength of the sample increased due to the filling effect and internal curing effect of coral powder. However, when coral powder was used to replace part of SF, it reduced the strength of UHPC due to its lower reactivity; however, it was beneficial to the improvement of UHPC's economic and environmental benefits. He et al. (2022b) also found that using an appropriate amount of waste concrete powder instead of cement to produce UHPC was beneficial to improve its strength and volume stability, and significantly reduced its non-renewable energy consumption and carbon emissions. Therefore, using an appropriate amount of solid waste to produce UHPC can maintain its strength and effectively reduce its cost and environmental load.

Similarly, UHPC mixed with waste also has an acceptable durability. Ahmed et al. (2021a) used FA to replace cement in various proportions up to 70 %. They observed that the use of FA up to 60 % has the same results as the control concrete. However, the 28-d water absorption increased by 1.01 % only, due to using 70 % FA. Meanwhile, another study reported that the use of FA as a cement replacement reduced the water penetration depth, where water depth decreased from 55 mm to 5 mm after the incorporation of 40 % FA in the UHPC (Sohail et al., 2021). Moreover, Tahwia et al. (2021) reported that resistance to chloride ion penetration of concrete is affected by FA content. The resistance of chloride ion penetration increased by 8 % due to use of 30 % FA as cement replacement, but, additional use of FA up to 50 % led to decreases in the resistance of chloride ion penetration. Red mud was also used as a cement replacement at varying percentages in the preparation of UHPC. The outcomes indicated that the addition of red mud enhanced the 7-d resistance of chloride ions of UHPC. Whereas, the depth of chloride diffusion of control specimens was 8.95 mm (Huang et al., 2017). The addition of red mud improved the durability of UHPC because red mud promoted the filling effect and early-ages hydration (Hou et al., 2021). Ahmed et al. (2021a) used 70 % FA as cement replacement in UHPC to test the carbonation resistance. The 28-d carbonation depth of UHPC samples mixed with FA was lower than the acceptable limit. Lu et al. (2021) examined the influence of different FA content ranging between 0 and 120 kg/m^3 on the resistance against freeze-thaw (FT) of UHPC. After 300 FT cycles, the resistance of FT was assessed in terms of mass loss and strength loss. The mass loss was reduced by 0.43 % due to the use of 60 kg/m^3 of FA, while the mass loss ratio was approximately 0.62 % in the case of control concrete without FA. Furthermore, Tahwia et al. (2021) used FA to replace cement in various replacement levels of 0 %, 30 %, and 50 % to study UHPC resistance against sulfate attacks; three concentrations of sodium sulfate (Na_2SO_4) solution was used for the test. The 90-d and 180-d compressive strengths of UHPC for all FA content had a similar result compared to the control concrete when the concentration of Na_2SO_4 solution was low. However, the compressive strength decreased due to increase the concentration of Na_2SO_4 solution up to 75 g/L. Therefore, the use of solid waste to produce eco-friendly UHPC also has good durability.

Recently, numerous types of non-traditional solid wastes have been explored and used to produce UHPC. Researchers used sugarcane ash, rice husk ash (RHA), and palm leaf ashes as a partial cement replacement to produce of UHPC (Faried et al., 2021; de Siqueira and Cordeiro, 2022). Other types of solid wastes have been used, such as ceramic tile waste, red mud, and waste glass, in UHPC mixtures to achieve better durability and mechanical properties (Amin et al., 2021; Xu et al., 2021). Nevertheless, investigations on the use of WMs in UHPC is still limited. This review aims to investigate the effect of WMs on the durability and microstructure of UHPC, as well as explore the use of WMs as a replacement for traditional materials to enhance the sustainability of UHPC and reduce the cost of final products. Finally, this review provides guidance for the design and preparation of eco-friendly UHPC.

2. Application of WMs in UHPC

2.1. As a cement replacement

The use WMs as a cement replacement is an effective solution to enhance the sustainability of construction and reduce the demand for cement (Ashraf et al., 2022; Zhao and Poon, 2021; Zhao et al., 2020). Researchers have investigated the effects of different types and contents of WM on UHPC mixtures. Table 1 shows the effect of WMs as a cement replacement on the durability of UHPC. Sugar cane bagasse ash (SCBA) has been used as a cement replacement in the production of UHPC, where a substitution ratio of 40 % SCBA did not significantly impact the UHPC strength but improved the workability and significantly reduced the autogenous shrinkage (Wu et al., 2022). Ganesh and Murthy (2019) used ground granulated blast-furnace slag (GGBS) as a cement substitute with proportions up to 80 % to study the effect of GGBS on the durability and mechanical properties of UHPC. The results of the study concluded that the performance of high-volume GGBS-based UHPC was significantly better than that of plain UHPC under an appropriate curing regime. Alani et al. (2019) used an ultra-fine palm oil fuel ash (UPOFA) as a 20 % and 40 % cement replacement along with recycled waste bottle to investigate the transport and engineering properties of UHPC. The use of polyethylene terephthalate fibers and 40 % UPOFA in producing UHPC mixture caused large enhancements in water absorption, porosity, rapid chloride permeability, water permeability, and gas permeability due to the high pozzolanic property of UPOFA. Moreover, Lv et al. (2022) investigated the influence of high temperature-treated municipal solid waste incineration fly ash (MSWIFA) on the properties of UHPC. The addition of MSWIFA played a significant role in reducing the porosity of UHPC due to their small particle size. Also, in a recent study, Gu et al. (2022) used sewage sludge ash (SSA) as a cement replacement in the production of UHPC to reduce the negative environmental impact of cement and improve UHPC durability. Therefore, replacing cement with an appropriate amount of solid waste and using suitable modification/activation measures can eliminate its adverse effects on the durability of UHPC.

Amin et al. (2022a) used ferrosilicon (FS) as cement replacement in the production of UHPC with different replacement levels of 0 %, 5 %, 10 %, 15 %, 20 % and 25 %. They investigated the water permeability, sorptivity coefficient, and chloride ion penetration resistance. They observed that the increase of SF and FS as a cement replacement up to 25 % improved the transport properties of UHPC, compared to the reference sample. In general, solid waste can play a filling role by adjusting its particle size of solid waste. Meanwhile, the active silicon/aluminum component contained in solid waste can dissolve and react with hydration products of cement, thereby exerting its pozzolanic reactivity. In addition, some porous wastes (e.g. RHA, biochar, and diatomite, etc.) can act as internal curing materials, which is beneficial to the improvement of the hydration degree of cement components (Zhao et al., 2015). Based on the above points, reducing the size of solid waste or increasing its potential pozzolanic reactivity is the

Table 1
Effect of WMs as cement placement on the durability of UHPC.

Ref.	WMs	Replacement level	Effect on the durability
Lu et al., 2022	Hollow glass microspheres	0, and 20 %	Adding hollow glass microspheres improved the high temperature resistance of UHPC.
Ganesh and Murthy, 2019	GGBS	0 %, 20 %, 40 %, 60 %, and 80 %	The use of GGBS could enhance the durability of UHPC and improve corrosion resistance, permeability, and chloride ion penetration.
Alani et al., 2019	UPOFA	0 %. 20 %, and 40 %	The use of 40 % UPOFA with PET fibers in UHPC improved the water absorption, water permeability, and gas permeability of UHPC.
Lv et al., 2022	MSWIFA	0 %, 5 %, 10 %, 15 %, and 20 %	The use of MSWIFA had a positive effect on the durability by reducing the porosity of UHPC.
Gu et al., 2022	SSA	0 %, 10 %, 20 %, and 30 %	The use of SSA led to forming a sulfate in UHPC mixtures, whereby the sulfate led to expansion of UHPC in water.
Hou et al., 2021	Red mud	0 %, 20 %, 40 %, and 60 %	The addition of red mud improved the 7-d chloride resistance of UHPC.
Nassar et al., 2022	RHA	5 %, 10 %, and 15 %	Adding an appropriate amount of RHA (5–10 %) increased UHPC strength, but further increase in RHA content caused the UHPC strength to decrease; however, the strength of RHA-containing UHPC was still higher than that of plain UHPC.
Nassar et al., 2022	Sugarcane bagasse ash	5 %, 10 %, and 15 %	Adding a small amount of sugarcane bagasse ash slightly degraded the mechanical properties of UHPC due to its low pozzolanic activity.
He et al., 2022a	Coral waste	5 %, 10 %, and 15 %	Using a small amount of coral waste instead of cement improved the mechanical properties of UHPC through pozzolanic activity and filling.
Nassar et al., 2022	Corncob ash	5 %, 10 %, and 15 %	Samples mixed with 10 % corncob ash performed best, but their strength was still lower than that of plain UHPC.
He et al., 2021	Waste brick powder	15 %, 30 %, and 45 %	Using 15 % waste brick powder instead of SF improved the mechanical properties and volume stability of UHPC.
Nassar et al., 2022	Wood ash	5 %, 10 %, and 15 %	UHPC mixed with wood ash not only exhibited lower mechanical properties, but also performed poorly in terms of durability.

Table 2
The effect of WMs as fine aggregate on the durability of UHPC.

Ref.	WMs	Replacement level	Effect on the durability
Shen et al., 2020a	IBA	0 %, 25 %, 50 %, 75 %, and 100 %	The use of IBA as a fine aggregate reduced crack formations owing to expansion.
Zhang et al., 2020	IOT	0 %, 20 %, 40 %, 60 %, 80 %, and 100 %	The use of different replacement percentages of IOT enhanced the durability of UHPC samples
Liu et al., 2020	CRT	0 %, 25 %, 50 %, 75 %, and 100 %	The use of CRT as a replacement of river sand increased the porosity of UHPC, which led to an increase in water absorption.
Khan et al., 2020	Hematite powder	0 %, 10 %, 20 %, 30 %, 40 %, and 50 %	The use of hematite powder as fine aggregate in the production of UHPC resulted in an enhanced durability.
Amin et al., 2020	Ceramic waste	0 % and 100 %	The adverse effect of ceramic waste as an aggregate on the water penetration resistance of UHPC could be effectively improved by optimizing the binder components.
Smarzewski, 2020	Waste foundry sand (WFS)	0 %, 5 %, 10 %, and 15 %	The use of 5 % WFS as fine aggregate replacement had an important influence on enhancing the microstructures of UHPC. Furthermore, WFS comprised 3.5 times higher CaO than that of quartz sand.
Liu et al., 2022	IOT	0 %, 20 %, 40 %, 60 %, 80 %, and 100 %	Although the use of IOT instead of natural sand reduced the workability of UHPC, it improved the mechanical properties and durability of the samples.
Jiang et al., 2019	Aeolian sand	0 %, 25 %, 50 %, 75 %, and 100 %	Using a small amount of aeolian sand instead of natural sand to prepare UHPC improved its mechanical properties due to the finer particle size.
Yang et al., 2020a	Recycled rock dust	0 %, 20 %, 40 %, 60 %, 80 %, and 100 %	Using an appropriate amount of rock dust to replace quartz sand produced a UHPC with higher strength and environmental friendliness.
Liu et al., 2021	Ceramic ball	20 % and 25 %	The addition of ceramic balls to UHPC improved the mechanical properties of UHPC prepared from geopolymers under impact loading.

simplest strategy. In addition, optimizing the binder components, using activators and changing the curing regime are also effective means to improve the performance of solid waste-based UHPC.

2.2. As fine aggregate replacement

The use of WMs as a fine aggregate replacement is applied by numerous studies to prepare the UHPC (Xu et al., 2022; Iqbal et al., 2021). Shen et al. (2020a) used incineration bottom ash (IBA) as fine aggregates at various replacement levels of 0, 25 %, 50 %, 75 %, and 100 %. The use of IBA as fine aggregate reduced formation of cracks in the concrete surfaces. Also, the addition of IBA increased the dry shrinkage of UHPC. Another study by Zhang et al. (2020) used iron ore tailings (IOT) as a fine aggregate replacement at different replacement levels of 0 %, 20 %, 40 %, 60 %, 80 %, and 100 %. They observed that the replacement level of 40 % IOT achieved the optimum performance. Yoo et al. (2022) reviewed the potential use of liquid crystal display (LCD) glass waste as fine aggregate replacements in the production of UHPC due to the high pozzolanic reactivity of glass waste. Rashad (2015) stated that the use of LCD glass waste enhanced the durability by reducing the chloride ion penetration and permeability, due to the filling effect of the LCD glass sand. Liu et al. (2020) used crush cathode ray tube (CRT) as a fine aggregate at different replacement levels in producing the UHPC mixtures. They concluded that the use of CRT led to an increase in the porosity, thus decreasing the strength and durability of UHPC. Table 2 summarizes the effect of WMs as fine aggregate on the durability of UHPC.

Soliman and Tagnit-Hamou (2017b) found that using glass sand instead of quartz sand led to an acceptable degree of alkali-silica reaction, which was mainly due to the low free water content and low permeability of UHPC components. In general, solid wastes of higher hardness and lower reactivity are best used as aggregate, because its rough surface is beneficial for its adhesion to the UHPC matrix. Meanwhile, the cement mixture can penetrate into the voids of the aggregate and act as a rivet. However, some studies have also shown that the weak interfacial transition zone (ITZ) between waste aggregates and cement matrix is the main reason for the degradation of concrete properties. Therefore, increasing surface roughness, stimulating reactivity and improving ITZ are key factors that can be tuned to strengthen the performance of solid waste aggregate-based UHPC.

3. Durability

3.1. Water permeability

In order to reduce permeability, many factors should be considered such as the use of SCMs, reducing of water/binder (W/B) ratio, and improving the pore structure. Water permeability is an important property that should be considered when designing the UHPC mixtures. High water permeability of UHPC allows harmful materials like chloride ions, sulfate, and acid solutions to seep into the concrete, causing high corrosion of reinforcement bars. UHPC has lower porosity and denser microstructure than that of normal concrete, which leads to higher water impermeability (Abbas et al., 2015; Tayeh et al., 2012). Fig. 1(a) clearly shows the growth of the water

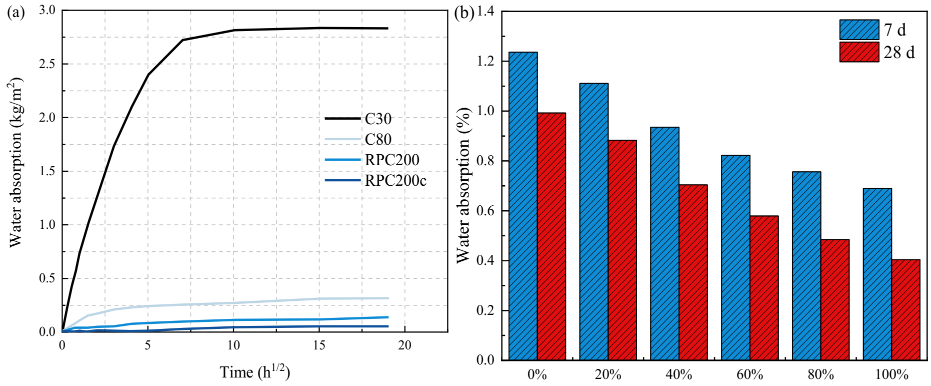


Fig. 1. Water absorption of different UHPC mixtures of different design strengths (a) (data from Li et al., 2020) and UHPC mortars with and without IOT (b) (data from Zhang et al., 2020).

absorption rate of UHPCs with different compressive strength designs ranging from C30 to RPC200C (Li et al., 2020).

However, the permeability of water is influenced by many factors including pore interconnectivity, pore diameter, use of SCMs, and W/B ratio. The W/B ratio has an important effect on the water permeability, whereas the permeability coefficient considerably decreases with reductions in the W/B ratio. Dobias et al. (2016) concluded that the 90-d water permeability coefficient of UHPC was reduced by 80 %, as compared to that of normal strength concrete. The use of nanoparticles and SCMs in UHPC, particularly nano-SiO_2 and SF, can support the production of C-S-H gels owing to nucleation effects and pozzolanic reactions, resulting in improved dis-connectivity and decreased fine pores. The use of nano-SiO_2 in UHPC decreased its porosity. Water permeability and other durability properties have been investigated by Yang et al. (2015). The results indicated that incorporating coarse aggregate (CA) in UHPC had a positive effect on the water permeation by increasing the resistance of water penetration, in addition to increasing resistance to chloride ion penetration. Zhang et al. (2020) used IOT to replace the manufacturing sand (MS) at different replacement levels (0 %, 20 %, 40 %, 60 %, 80 %, and 100 %) of total weight. The results showed that the IOT content was impacted the 7-d and 28-d water absorption of UHPC samples as shown in Fig. 1(b). Clearly, the sample without IOT has a higher absorption rate than other samples. The use high content of IOT led to reduced water absorption in UHPC for 7 and 28 d. The 7-d water absorption decreased by 9.7 %, 24.2 %, 33.1 %, 38.7 % and 43.5 % due to use of IOT at replacement levels of 20 %, 40 %, 60 %, 80 % and 100 %, respectively. A similar trend of reduction is observed in 28-d water absorption. The reduced water absorption rate increased UHPC durability. Furthermore, the use of GP as a cement replacement in the production of UHPC has an important influence on water absorption, where 8.25 % GP content led to a slight but significant improvement in water absorption. This improvement in water absorption could be attributed to the pozzolanic reactivity of GP (Dias et al., 2021). Tahwia et al. (2022a) used recycled GP to replace quartz powder or part of cement to prepare UHPC and found that both water absorption and water permeability were improved. UHPC resistance to water penetration was improved with increasing content of GP.

Beglarigale et al. (2021) systematically studied the water permeability of solid waste-based UHPC before and after cracking through a variety of test methods (Water permeability test (see Fig. 2(a)), total and capillary water absorption tests), and used it to evaluate the self-healing performance of UHPC. When the cement content was kept constant, adding 400 kg/m^3 of FA or GGBS to the UHPC mixture caused the total water absorption and adsorption coefficient of UHPC decrease. It was worth noting that after the addition of GGBS or FA, cracked UHPC had a higher performance recovery ratio than plain UHPC after secondary curing (See Fig. 2). This was not only due to the increase in the content of cementitious materials, but also closely related to the secondary hydration of solid waste.

3.2. Chloride-ion permeability and corrosion of steel reinforcement

Chloride ion permeability is another important property that should be considered during the design of UHPC (Liu et al., 2023). These ions can be dissolved inside concrete via chemical or physical processes. Fan et al. (2021) used steel slag powder (SSP) as a binder to improve the performance of UHPC; it was observed that although the addition of SSP reduced the chloride ion resistance of UHPC, it was still superior to ordinary concrete. Furthermore, heat-cured UHPC exhibited a lower passed charge, lower than 100 C; however, this can be neglect. The standard-cured UHPC presented somewhat high pass charges of up to 100 C (Graybeal, 2006). The use of appropriate content of SCM can significantly reduce the coefficient of chloride ion permeability. Moreover, the addition of SF had a positive effect on reducing permeability, which led to a considerably decreased conductivity compared to other ordinary cement-based materials (Matte and Moranville, 1999). Nevertheless, the electrical conductivity of UHPC decreased significantly; this decrease is not relative to SF content (Tafraoui et al., 2016). The study by Tafraoui et al. (2016) also found that UHPC doped with the same amount of SF has a lower chloride ion permeability coefficient compared to metakaolin-modified samples. From the results obtained abovementioned, it can be noted that the permeability of UHPC is affected by many factors, such as concentration of medium solutions, mixture composition, sample size, and testing method. While more researchers

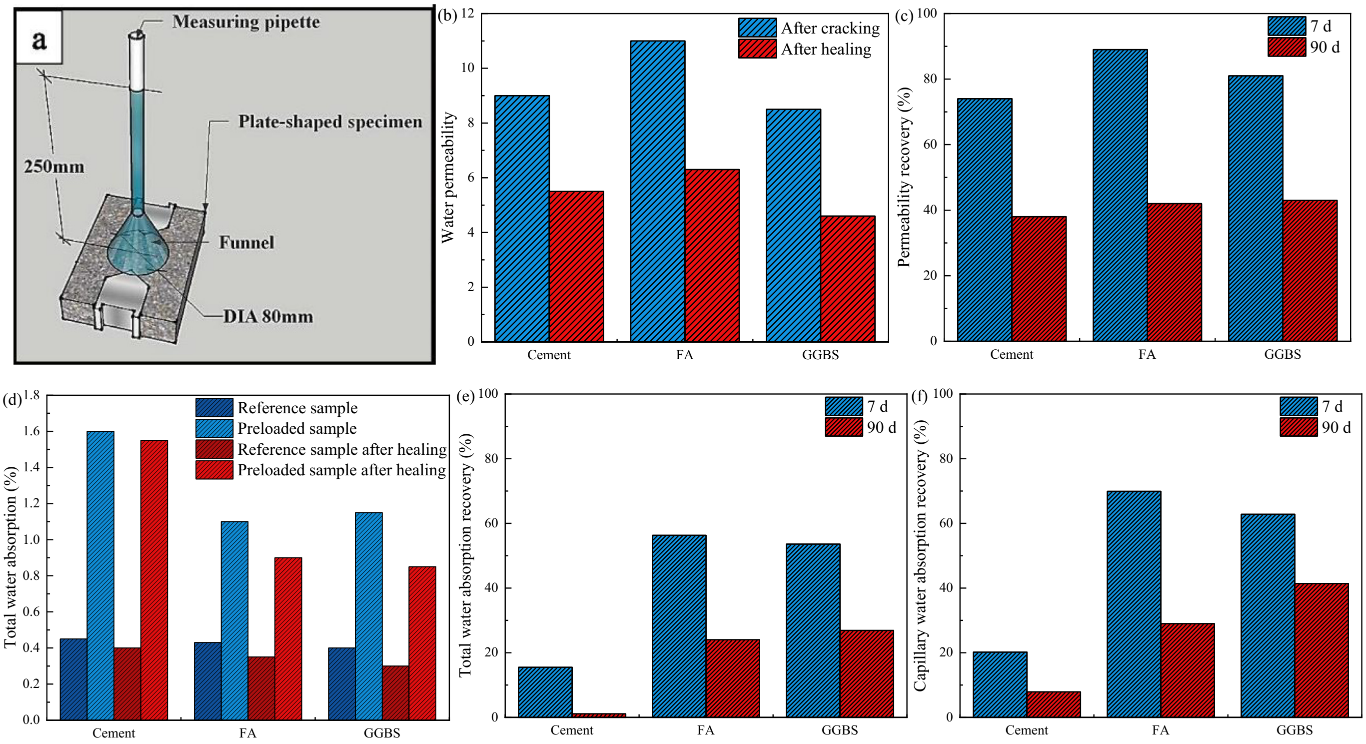


Fig. 2. Water permeability of UHPC mixed with FA and GGBS before and after cracking (data and figure reused under license number 5490540759739 from Beglarigale et al., 2021).

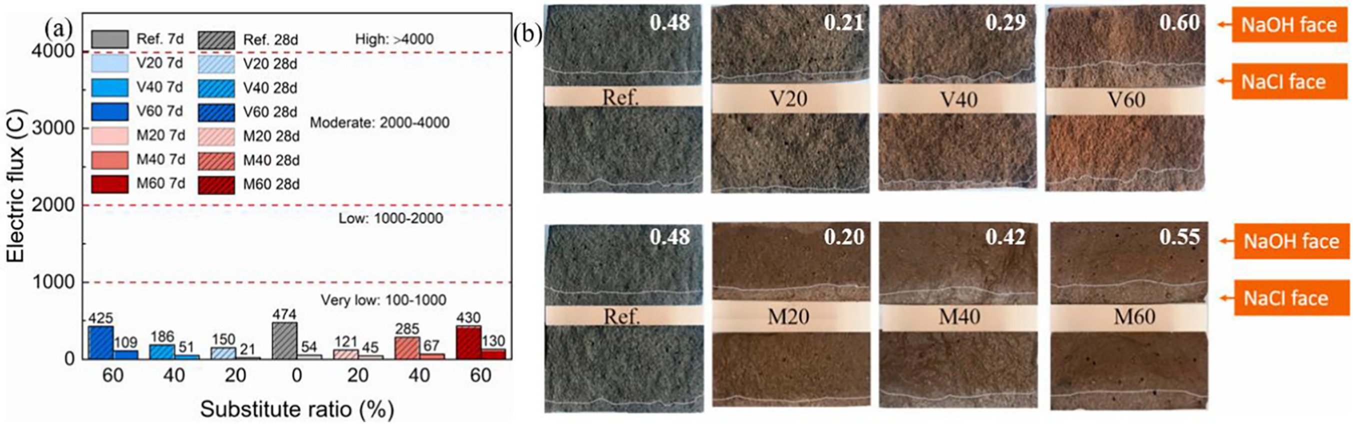


Fig. 3. Chloride permeability of UHPC with red mud; electricity flux test (a) and rapid chloride migration (b) (reproduced under license number 5490551028541 from Hou et al., 2021).

are investigating the effect of natural materials on the durability of UHPC containing CA, UHPC-CA also has an outstanding resistance to chloride penetration (Yu et al., 2022a). Zhang et al. (2020) used IOT as a fine aggregate to replace MS at various replacement levels (0 %, 20 %, 40 %, 60 %, 80 %, and 100 %) to determine the chloride ion penetration of UHPC samples. They observed that the total charge passed decreased somewhat as the IOT content in the UHPC mixtures increased. Thus, chloride ion penetration decreases when using IOT instead of MS. Hou et al. used red mud to replace part of the cement to produce UHPC and tested its ability to resist chloride ions using different accelerated experiments, as shown in Fig. 3. The results show that in both electricity flux tests and rapid chloride migration tests, the addition of an appropriate amount of red mud reduced the chloride ion diffusion coefficient of UHPC, which was due to its effect on improving the pore structure (Hou et al., 2021). The study by Wang et al. (2022a) also showed that the addition of tailings improved the conductivity of UHPC, which had an impact on the chloride ion diffusion coefficient of the sample in accelerated experiments. Although the strength of UHPC was increased by adding an appropriate amount of gold tailings, the chloride ion diffusion coefficient of the sample (as measured by the rapid chloride ion migration test) gradually increased with the increase of the gold tailing substitution content. Qian et al. (2020) used heat treatment of C&D waste to obtain dehydrated cementitious powder and found that adding an appropriate amount of dehydrated cementitious powder improved the ability of UHPC to resist chloride ions.

Wang (2009) illustrated that the use of LCD glass sand enhanced the resistance of concrete against chloride ion penetration. Concrete with LCD glass presented a chloride ion penetration ranging between 750 and 3250 C, which is an acceptable penetration rate based on the ASTM standard. Krstic and Davalos (2019) used 20 % and 40 % of GP as a cement replacement. The chloride ion penetration improved significantly due to use GP as cement replacement in the production of UHPC. Amin et al. (2022a) investigated the chloride ion penetration of UHPC mixtures containing FS as furnace slag. The results showed that the potential of chloride ions penetration reduced with the increase of the replacement levels of FS or SF. The passing charge over UHPC-FS specimens illustrated that the chloride ions penetration range was between 290 and 190C at various replacement levels ranging from 5 % to 25 % of cement weight. However, the study by Yu et al. (2022b) found that high metal component content in solid waste can also affect the accuracy of the rapid detection method. Therefore, it is necessary to verify the anti-chloride ion performance of eco-friendly UHPCs using natural immersion.

UHPC samples have a high resistance against corrosion because of the low chloride ion permeability. Ghafari et al. (2015) concluded that the resistance against corrosion of reinforcement steel in UHPC was much higher than that of HPC, where the time required for cracks to occur in HPC was lower than 50 % of the time required in the case of UHPC. Faizal et al. (2016) assessed the influence of nano-clay as a cement replacement (1 %, 3 %, and 5 %) on the occurrence of corrosion in UHPC reinforced by steel bars. The samples were exposed to 3 % sodium chloride solution for 91 d. The results obtained concluded the increase of nano-clay content led to a reduction in the corrosion rate, which caused a delay in corrosion, as shown in Fig. 4(a). Similar to nano-clay, the use of nano-silica in UHPC also had an important effect in reducing the corrosion rate of reinforcement steel bars (Ghafari et al., 2015). Esmaeili and AL-Mwanes (2021) conducted a review on the influence of waste glass on the durability and mechanical properties of UHPC. They observed that GP decreased the occurrence of corrosion and chloride ion penetration in UHPC due to high pozzolanic reactivity. Mostafa et al. (2021) used 1 % nano-glass slag (NWG), nano-RHA or nano-metakaolin to modify UHPC to increase the open circuit potential and corrosion potential and reduce the corrosion current density. The addition of nanomaterials improved the bulk resistance of UHPC and the charge transfer resistance of the steel-concrete interface and alleviated the corrosion of steel bars, as shown in Fig. 4(b and c).

3.3. Carbonation

Carbonation is a chemical reaction that occurs between hydration products and CO_2 in the presence of adequate moisture. $CaCO_3$ is the main product that is generated from this reaction and causes a low pH value reaching

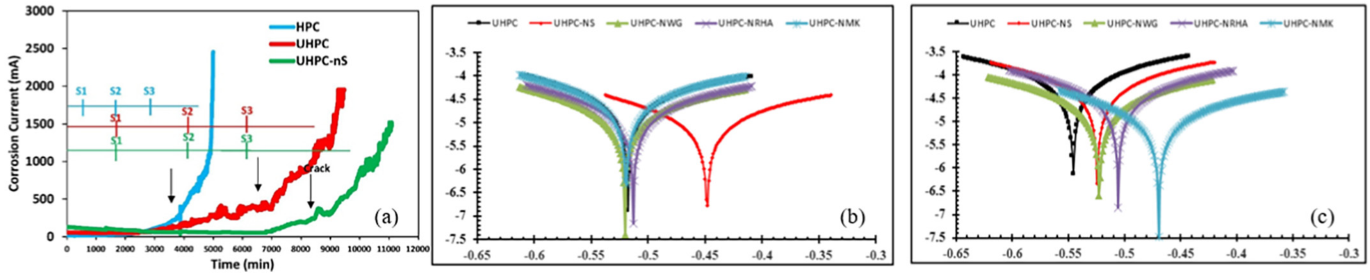


Fig. 4. The corrosion current of HPC, UHPC and UHPC-nano-SiO_2 (a) (reproduced under license number 5490560208588 from Ghafari et al., 2015), potentiodynamic polarization results of steel embedded in UHPC (3.5 % NaCl) in the normal (b) and accelerated conditions (c) (reproduced under Creative Commons license from Mostafa et al., 2021).

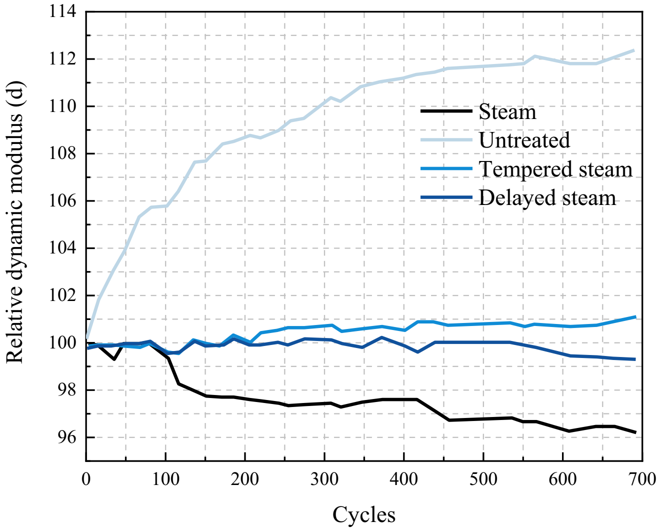


Fig. 5. The relative dynamic modulus of UHPC after FT cycle (data from Graybeal, 2006).

to 9. The reduction in pH leads to weakness in the protective oxide layer of reinforcing steel bars, thus causing corrosion of steel bars and crack formations in the concrete members (Bertos et al., 2004). Carbonation can occur in concrete with high permeability. In contrast, if the concrete is dense and very dry, the carbonation rate decreases to a lower value due to the lack of water required to dissolve CO_2 (Bertos et al., 2004). Moreover, porosity and W/B ratio of concrete have a substantial effect on the carbonation rate, where the carbonation rate increases significantly with high porosity and elevated W/B ratios. In general, UHPC excels in carbonization resistance, with a carbonization depth of approximately 1.5–1.7 mm even after 3 years of exposure (Alonso et al., 2006). In response to the cement mixture of low W/B ratio, researchers also use carbonized or fresh carbon dioxide gas mixing channels to achieve carbon storage. Nonetheless, it is important to acknowledge that the carbonization behavior the penetration of concrete are closely related, where the carbonization behavior can be improved by enhancing the impermeability of UHPC. Ahmed et al. (2021b) prepared UHPC with gold mine tailings instead of sand and found that it was hardly carbonized due to the compactness of the matrix.

3.4. Freeze-thaw (FT) resistance

Usually, concrete exposed to the FT process decreases in mass because it is exposed to spalling and reduction after micro-crack formations. Wang et al. (2017) observed that freeze-thawing UHPC at 500, 1000, and 1500 cycles reduced the mass of UHPC by 0.18 %, 0.50 %, and 0.62 %, respectively. However, Graybeal and Tanesi (2007) reported that after 125 FT cycles, UHPC mass increased by 0.2 %. Chen et al. (2017) conducted the testes required for the FT cycle on UHPC-CA according to ASTM C666. They observed that UHPC-CA has high FT resistance. This is attributed to the low water absorption capacity of UHPC-CA because the fairly low water content of UHPC-CA decreased the harmful impact of FT cycles. Although accelerated curing improved the early-age performance of UHPC, it was not conducive to the long-term FT resistance of UHPC, as shown in Fig. 5 (Graybeal, 2006). This was mainly due to the deterioration of the concrete microstructure due to early accelerated curing, which was not beneficial to the development of its long-term performance. In general, mixing a small amount of solid waste as a binder or aggregate can improve its FT resistance by improving the compactness of UHPC. Some studies have shown that porous solid wastes improve the hydration degree of the matrix as the internal curing agent, thereby improving the frozen resistance of UHPC. In addition, porous solid waste can also relieve the expansion pressure, which is beneficial in reducing the FT damage on UHPC.

3.5. Chemical attack resistance

All concrete structures exposed to marine environments suffer from chemical attacks, like chlorides, sulfates, acids, etc., resulting in spalling and corrosion. Because of the highly dense microstructure of UHPC, the effects of chemical attacks take a long time to appear. El-Dieb (2009) found that the compressive strength of UHPC mixed with SF and dune sand decreased by approximately 12 % after exposing the samples to high sulfate solution for 365 d. The fiber volume fraction had little effect on the erosion resistance of UHPC, which was mainly controlled by the impermeability of concrete (El-Dieb, 2009). Furthermore, Ye et al. (2006) studied the performance of UHPC exposed to various chemical solutions containing artificial seawater, 20 % $(NH_4)_2SO_4$, 20 % Na_2SO_4, and 5 % H_2SO_4. The transfer of sulfate ions to concrete and the corresponding sulfate uptake decreased regularly, allowing ettringite to crystallize (Bellmann et al., 2006). The use of FA and GGBS in the production of UHPC mixtures did not significantly affect the compressive strength of UHPC. However, when increasing the attack periods and exposing UHPC mixtures to 5 g/L light, the

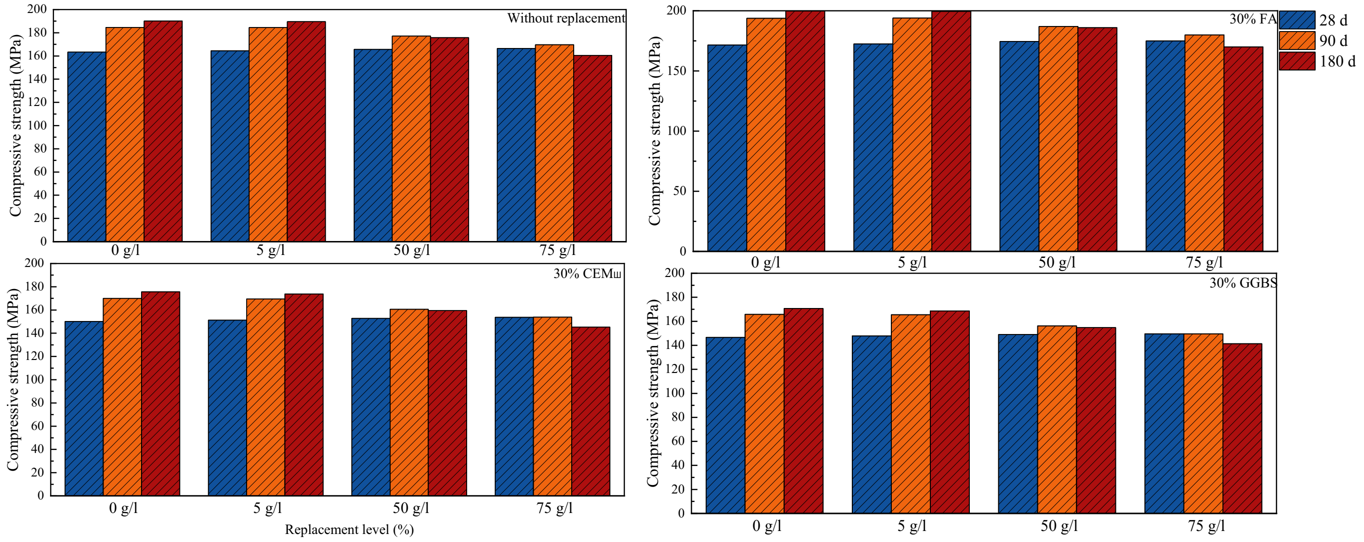


Fig. 6. The change of compressive strength under sulfate attack (reproduced under license number 5490571445303 from Tahwia et al., 2021).

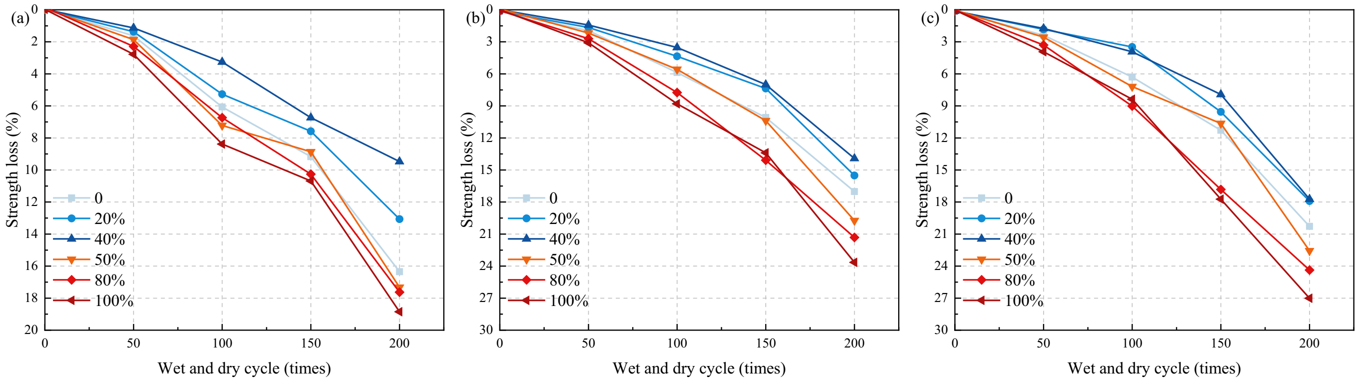


Fig. 7. Compressive strength loss of UHPC with IOTs in (a) Water, (b) 3 % Na_2SO_4 solution, and (c) 5 % Na2SO$_4$ solution (reproduced under Creative Commons license from Liu et al., 2022).

compressive strength increased in UHPC mixtures containing 30 % FA and GGBS as cement replacement, as shown in Fig. 6 (Tahwia et al., 2021). When replacing a specific amount of cement with SF, a chemical reaction occurs between cement hydration products to produce C-S-H, which subsequently stops gypsum and ettringite production by preventing the sulfate salt reactions with the cement hydration products (Bellmann et al., 2006). As a result, the use of 5 % SF increased the compressive strength of UHPC to 5.8 % while increasing SF content to up to 10 % increased the compressive strength to 12.4 %, as compared to the specimen comprising 15 % SF. Tahwia et al. (2022b) suggested that UHPC (geopolymer) mixed with waste glass performed better under the action of sulfate, which was mainly due to the continuous geopolymerization of waste glass.

Hakeem et al. (2023) found that adding 5 % oil ash or 20 % electric arc furnace dust to UHPC would reduce the sulfate resistance of UHPC due to its low pozzolanic reactivity. Similarly, Nassar et al. (2022) used finely ground agriculture waste ashes of rice husk, sugarcane bagasse, corncob, and waste wood to replace part of the cement during UHPC preparation. The mechanical properties of UHPC were improved by the addition of an appropriate amount of biomass materials, but the ability of UHPC to resist sulfate attack was reduced due to its porous nature. Zhang et al. (2022) used recycled aggregates in UHPC, and found that recycled aggregates introduced more ITZ, pores, and microcracks, which increased the concentration of sulfate ions in UHPC. Liu et al. (2022) found that UHPC undergoes dry-wet cycles in water, 3 % Na_2SO_4 solution, and 5 % Na_2SO_4 solution, and the strength decreased, as shown in Fig. 7. During long-term water immersion, ions leached out, and the internal damage of the concrete under dry-wet cycles caused a decrease in strength. Moreover, the strength reduction ratio of UHPC increased with increasing sulfate concentration. It is worth noting that the UHPC prepared with an appropriate amount of IOTs instead of natural sand showed better resistance to sulfate attack than plain UHPC, which is related to the tight ITZ between the aggregate and the matrix.

3.6. Fire resistance

Concrete is a higher fire-resistant material due to its high thermal capacity and low thermal conductivity. However, the compressive strength of concrete decreases with increased fire exposure periods. The high content of steel fiber also contributes to reducing the strength loss of UHPC after fire exposure because the steel fibers restrict crack spreading. Amin et al. (2022b) found that the addition of recycled aggregates had a positive effect on improving the high temperature resistance of UHPC. Tai et al. (2011) stated that after exposure to 200 °C, the compressive strength of UHPC increased by around 24 %, 4 %, and 7 %, due to the incorporation of steel fibers at 1 %, 2 %, and 3 %, respectively. Meanwhile, the compressive strength of UHPC decreased by around 82 %, 78 %, and 77 %, respectively, after exposing UHPC to high temperatures of up to 800 °C. Lu et al. (2022) jointly applied hollow glass microspheres and expanded shales in UHPC, which provided channels for the release of water and steam pressure; this significantly improved the high temperature resistance of UHPC (as shown in Fig. 8(c), 20L40H). In addition, the use of dry heating curing also reduced the water content in the sample, which further improved the explosive spalling resistance of UHPC (as shown in Fig. 8(a and b)) (Lu et al., 2022). Li et al. (2022) used steel slag (SS) aggregates of different sizes to prepare UHPC and found that as the aggregate size increased, the thermal incompatibility of the phases in UHPC caused more severe damage at high temperatures. Luo et al. (2022) used GP as a fine aggregate and found that the high temperature resistance of UHPC was improved.

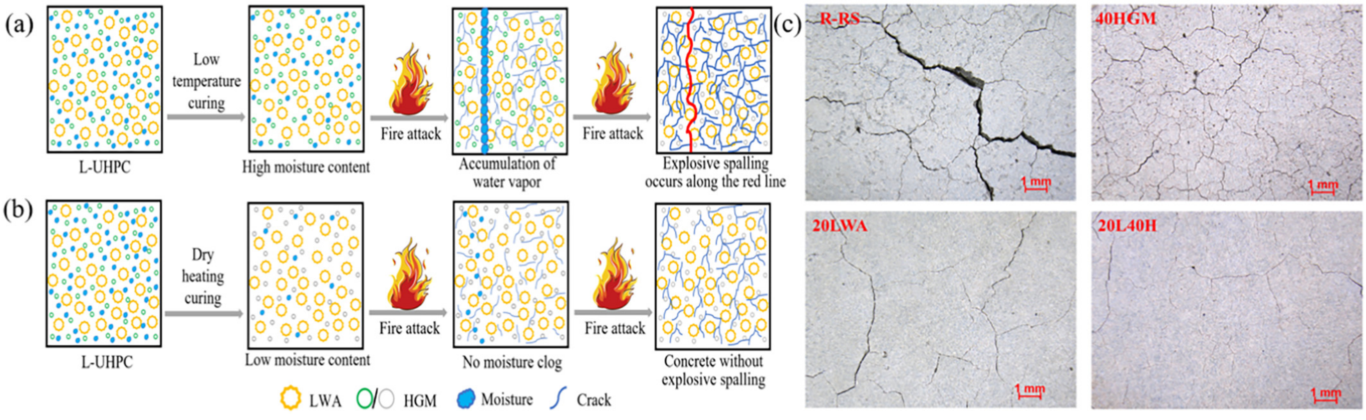


Fig. 8. The impact of curing strategy on UHPC (a and b), and the joint application of hollow glass microspheres and expanded shales (c) (reproduced under license number 5490571227479 from Lu et al., 2022).

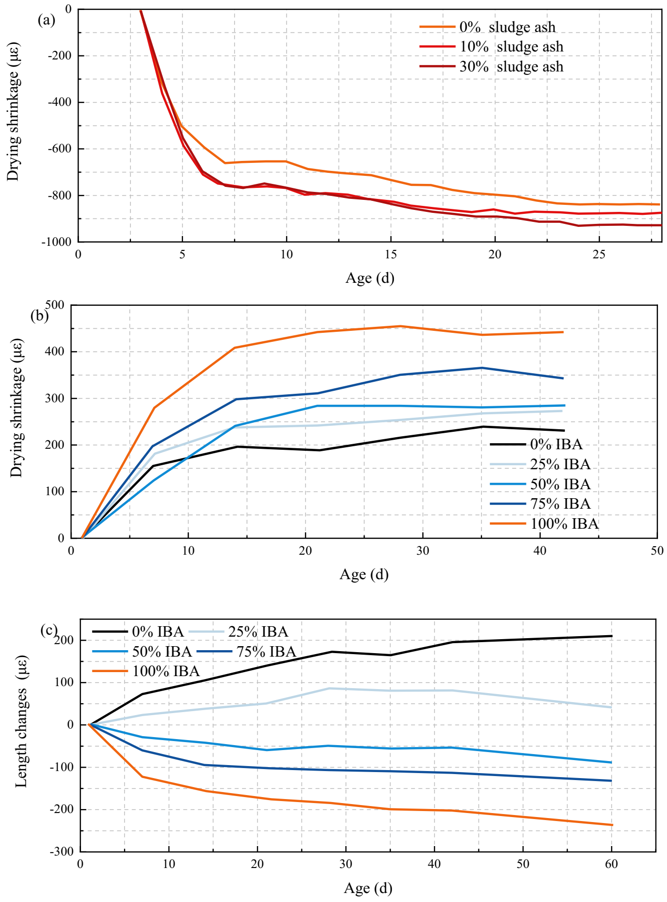


Fig. 9. Shrinkage deformation of UHPC with SSA (a), IBA (b), and IBA in NaOH solution (c) (reproduced under license number 5490570762067 and 5490571094263 from Shen et al., 2020a; Gu et al., 2022).

Under the action of high temperature, the reactivity of waste GP was activated, and the GP in the molten state hardened and provided strength again. This study also showed that the finer the particle size of the GP, the more obvious its effect on improving the high temperature resistance of UHPC, which was related to the improvement of the initial stiffness of the sample.

3.7. Volume stability

In general, the long-term stability of UHPC is affected by the stiffness of the sample and the relative humidity. Pozzolanic reactivity and filling effect of solid waste can improve the stiffness and pore structure of UHPC, which is beneficial to improve its volume stability. Ahmad et al. used natural pozzolan to replace part of the cement or microsilica and found that the drying shrinkage of UHPC was improved. This was mainly attributed to the potential pozzolanic reaction that refined the pore structure and hindered water evaporation (Ahmad et al., 2019). Meanwhile, part of the unreacted natural pozzolan was used as a micro-aggregate to help reduce drying shrinkage. From the perspective of internal curing of porous solid waste, its positive effect on the long-term volume stability of UHPC needs to be further discussed. Gu et al. (2022) used SSA to replace part of the cement to produce UHPC and found that its drying shrinkage increased, as shown in Fig. 9(a). This was mainly because the addition of sludge reduced the stiffness of the sample and increased the porosity, which allowed faster water loss. Similarly, another study by Shen et al. (2020a) showed that the drying shrinkage of UHPC became larger after adding IBA, which was inconsistent with the internal curing effect of porous materials (See Fig. 9(b)). This was mainly because the pre-adsorbed water in IBA was released at an early stage and lost its positive effect on drying shrinkage. Most current studies have shown that the internal curing effect of porous waste can improve the autogenous shrinkage of UHPC, but has little effect on drying shrinkage, and its negative impact on stiffness and porosity may even aggravate drying shrinkage. This is mainly because UHPC is different from ordinary concrete, and its lower W/B ratio can cause the internal curing water to be released and consumed prematurely (Shen et al., 2020b). In addition, the application of solid waste in UHPC also faces volume expansion or stability issues. Shen et al. (2020a) found that IBA in UHPC contained glass and Al components, which generated gas or gel in an alkaline environment thereby causing expansion, as shown in Fig. 9(c). In addition, the gypsum in the IBA was also one of the reasons for the swelling. Therefore, when using solid waste in UHPC, it is necessary to pay attention to the components containing RO phase (E.g. CaO and MgO), and effectively utilize it to resist shrinkage deformation.

4. Microstructure

4.1. Micromorphology

The micromorphology of concrete can be evaluated by scanning electronic microscopy (SEM). Zhang et al. (2020) used IOT as a fine aggregate to replace MS in the production of UHPC; it was found that IOT and the matrix had a close bonding. Similarly, Shen et al. used IBA to replace some sand during UHPC preparation and found that the ITZ performance between IBA and the matrix was better (See Fig. 10(a)). The backscattered electron image clearly illustrates that the compactness of ITZ between IBA and the matrix was better than sand (See Fig. 10 (b)). Another study by Ganesh and Murthy (2019) investigated the microstructure of UHPC samples made up of a high volume of GGBS as cement replacement through SEM imaging. They concluded that the microstructure of the UHPC sample containing a high volume of GGBS had a higher compactness than the normal UHPC made without GGBS. Therefore, the use of GGBS as cement replacement in production of UHPC in high volume can enhance the durability, such as water absorption, porosity, and chloride ion penetration. For porous CAs, despite their own porosity and low stiffness, their internal curing may improve the performance of ITZ. Zhu et al. (2022) used coal gasification coarse slag instead of river sand to prepare UHPC and found that the ITZ around the slag aggregate was denser and had fewer non-hydrated phase (see Fig. 10(c)).

Shao et al. (2022), in a recent study, reported that the use of FA, SF, and GGBS in the production of UHPC had a significant effect on the durability, strength, and microstructure. They observed that large amount of SF and unreacted spherical FA particles were interlaced/embedded in C-S-H gels, which resulted from the hydration of binders. de Matos et al. (2020) studied the potential use of eco-friendly UHPC with basalt, granite, and other wastes as alternatives to conventional fillers of limestone and quartz. The SEM-EDS images showed that similar microstructures have been obtained for all mixtures. Therefore, the appropriate amount of the alternative materials abovementioned can be used as filler materials in the production of UHPC without impacting its microstructure. Meanwhile, the aggregate shape has a significant effect on the UHPC microstructure, where the surface roughness of aggregate was closely related to the compactness of ITZs (Jiao et al., 2020). Wang et al. (2019) also used C&D waste to replace part of the sand to prepare UHPC and found that the bond between it and the matrix was tighter, which was related to its high water absorption, surface roughness and reactivity (See Fig. 11).

There are virtually no crack formations in ITZ when the replacement level of GGBS was 75 %; this reduced crack formation in ITZ enhanced the interface strength, which is the cause behind UHPC strength. The SEM images of the UHPC above show the effects of using 30 % GGBS, CEM III, and FA as replacement on the microstructure of cement paste (Tahwia et al., 2021). The use of 30 % FA as cement replacement improved

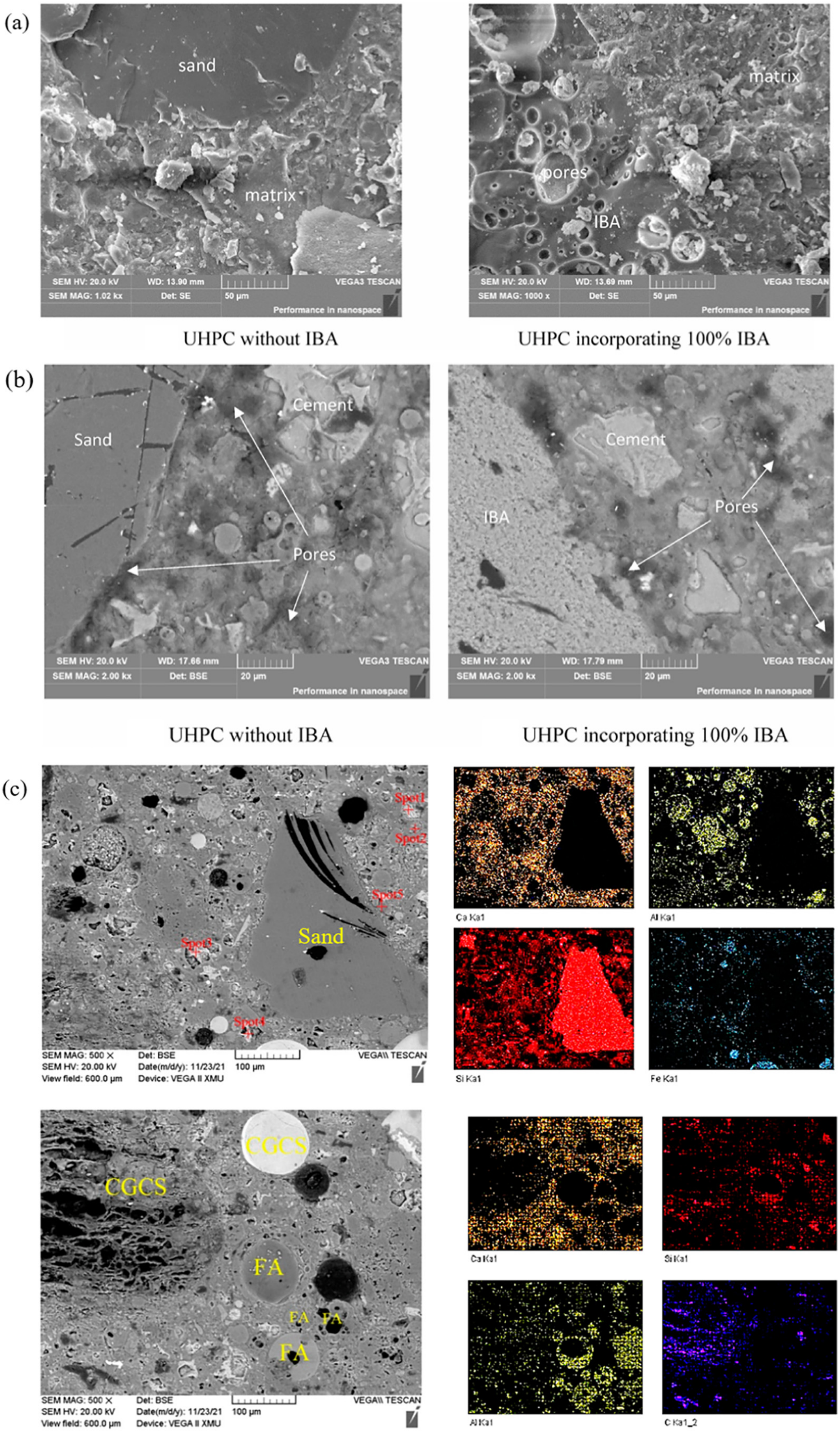


Fig. 10. SEM images of UHPC with IBA (b and c) and coal gasification coarse slag (CGCS) (reproduced under Creative Commons license from Zhu et al., 2022; reproduced under license number 5490570762067 from Shen et al., 2020a).

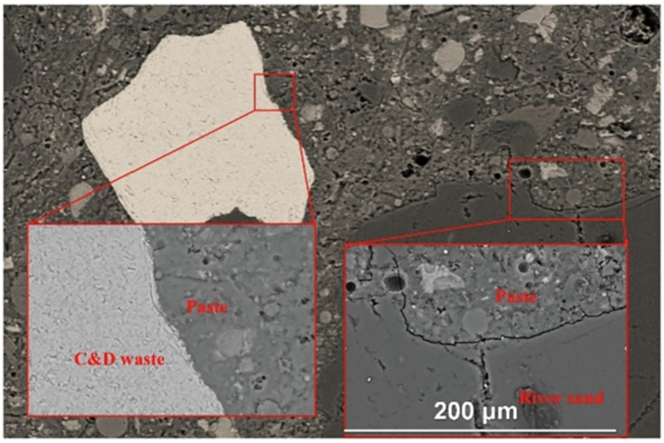


Fig. 11. The backscattered electron image analysis of ITZ (reproduced under license number 5490570485041 from Wang et al., 2019).

the microstructure of UHPC, where 30 % FA-UHPC had a lower porosity than that of the control mixtures. Also, the EDS spectroscopic analysis was conducted identify the UHPC components. The existence of FA in the UHPC sample led to an increase in the silica content of UHPC mixtures, resulting in the production of extra C-S-H gels that can be considered a main source to the pozzolanic activity. Yalçınkaya and Çopuroğlu (2021) studied the effect of GGBS content on the microstructure of UHPC and found that the Ca/Si ratio of the UHPC matrix decreased with the increase of GGBS substitution level (Fig. 12).

4.2. Pore structure

The porosity of UHPC decreased significantly to the minimum and the compressive strength increased considerably due to use of 20 % SCBA as a cement replacement. However, the porosity increased to the maximum when using 60 % SCBA as a cement replacement (Wu et al., 2022). Because of the internal curing and high porosity of RHA, Kang et al. (2019) used RHA as a reactive filler in UHPC to increase its mechanical properties. This approach used the reactive RHA filler instead of inert quartz filler to increase the amorphous silica content while maintaining the physical role of the micron-sized quartz filler, which was effective in refining the sample pore structure. Abushanab et al. (2021) studied the effect of recycled concrete aggregates (RCA), SS aggregates, and gabbro aggregates (GA) on the durability and mechanical properties of UHPC. They observed that the porosity of all UHPC samples ranged between 0.86 % and 3.41 %, which was approximately 30 % lower than that of normal concrete samples. This decrease in porosity of UHPC was attributed to the SF, FA, and fine sand particles and their pozzolanic reactivity that generated extra C-S-H gels, which assisted in filling the micro pores and voids thus producing high-density microstructure UHPC (Zhou et al., 2016). Feng et al. (2022a) used aeolian sand to replace all the river sand and produce UHPC; they found that the porosity of the sample was slightly reduced, as shown by the CT scan in Fig. 13.

Nguyen (2011) investigated the influence of SF and RHA on the porosity of UHPC. The use of 20 % of RHA and SF as a cement replacement in producing the UHPC decreased the porosity as compared to the reference specimen. Alani et al. (2019) investigated the effect of UPOFA as a cement replacement in at 0 %, 20 %, and 40 % proportions in addition to recycled waste bottles to examine the engineering and transport properties of UHPC.

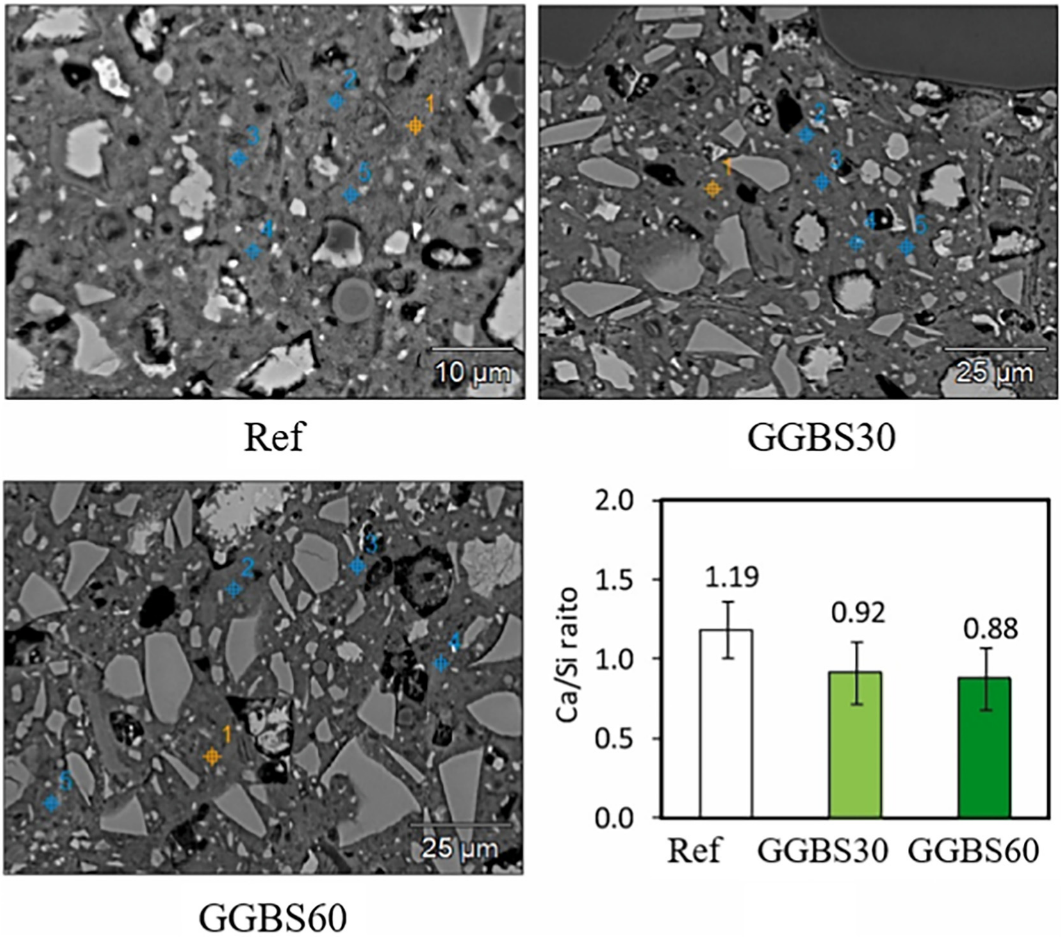
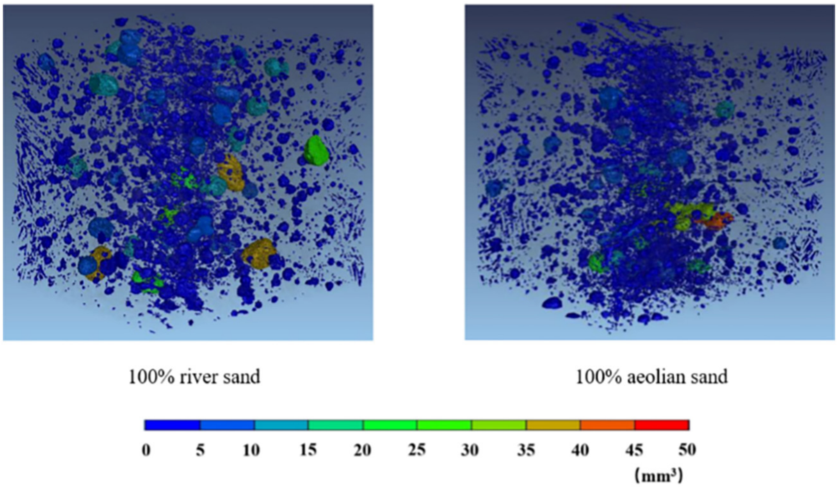


Fig. 12. SEM images of UHPC containing GGBS (reproduced under license number 5490570177953 from Yalçınkaya and Çopuroğlu, 2021).



100% river sand

100% aeolian sand

Fig. 13. X-CT results of UHPC with aeolian sand (reproduced under license number 5490570067846 from Feng et al., 2022a).

They observed that the porosity of UHPC decreased with increasing of curing ages for all concrete mixtures. The use of high volume UPOFA up to 40 % reduced the porosity to the lowest value (Alani et al., 2019). The porosity of UHPC mixtures with 40 % UPOFA was 2.5 % at 3 d and became 1.1 % at 28 d. This reduction in porosity could be attributed to the high pozzolanic reactivity of UPOFA, which resulted in the production of extra C-S-H gels and thus produced a denser UHPC samples. Shen et al. (2020a) used municipal solid waste IBA as fine aggregates in the production of UHPC. They investigated influence of IBA on the microstructure of UHPC. The use of a suitable quantity of IBA

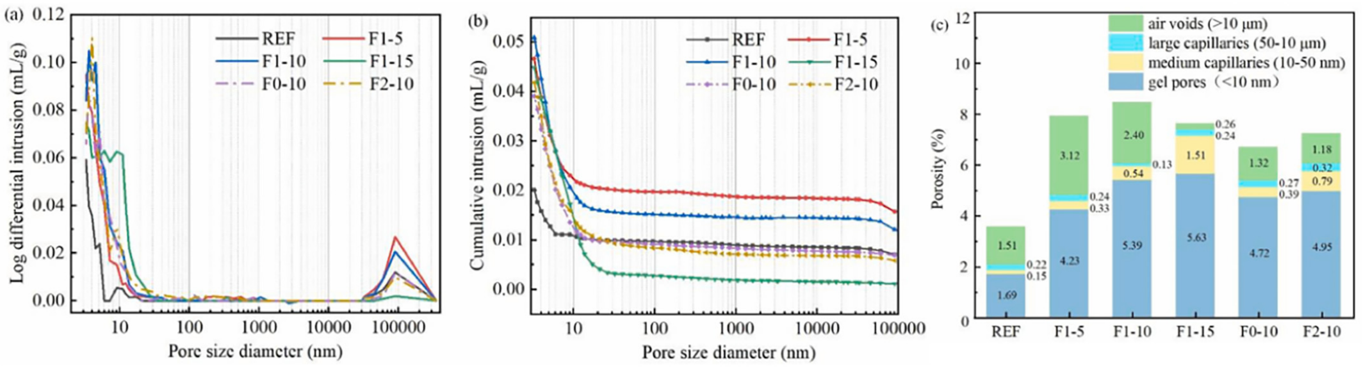


Fig. 14. Pore structures of UHPC containing various quantities of IBA, where F0-F2 represent different particle sizes of waste concrete powder, 5–15 represent the substitution level. F0: 0–150 μm, F1: 150–300 μm, and F2: 300–600 μm (reproduced under license number 5490561453546 from Zou et al., 2022).

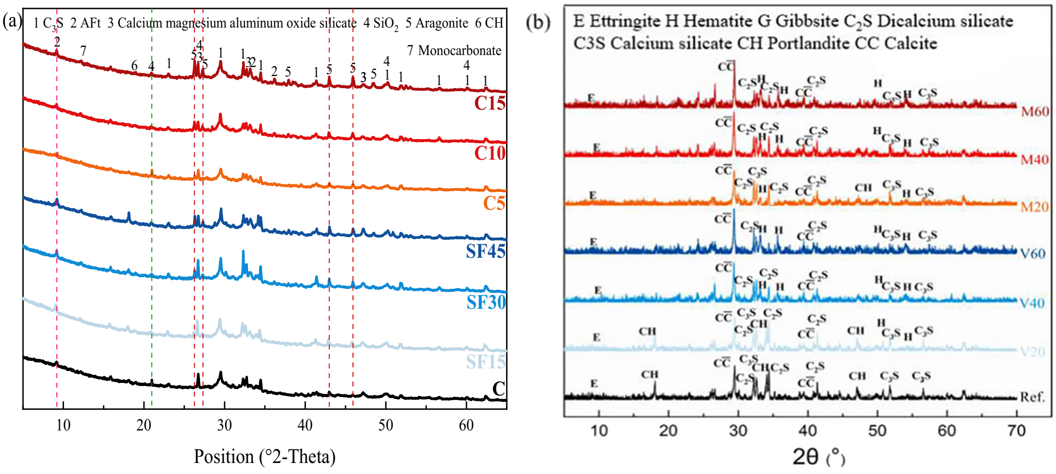


Fig. 15. The XRD patterns of UHPC with coral powder (a) and red mud (b). Coral powder to replace part of cement (C5-C15) and SF (SF15-SF45), V20-V60 & M20-M60: replacement by volume and mass, respectively (reproduced under license number 5490561142395 and 5490561319314 from He et al., 2022a; Hou et al., 2021).

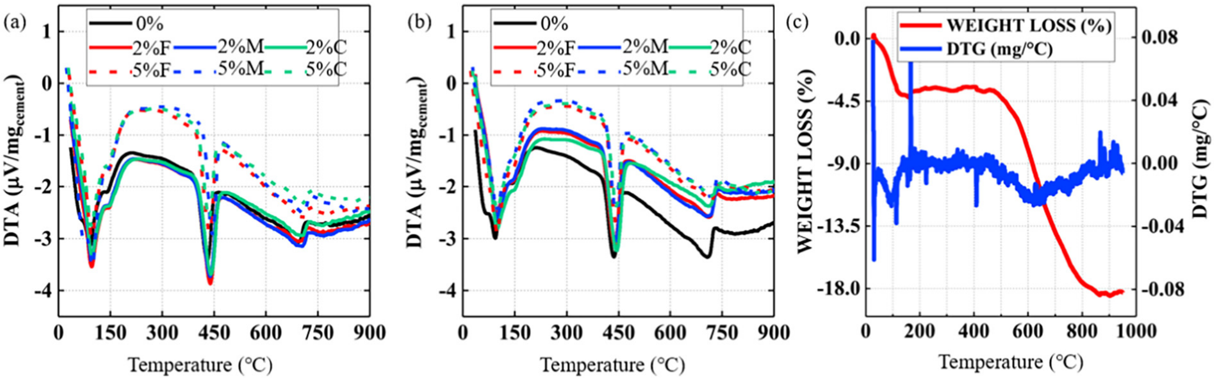


Fig. 16. Thermo-gravimetric analysis (TGA) for UHPC mixture containing biochar at 7 (a) and 28 d (b), biochar (c), where coarse biochar is (C), medium biochar is (M), and fine biochar is (F) (reproduced under license number 5490560983022 from Dixit et al., 2019).

could enhance the microstructure of UHPC owing to the internal curing effect. Meanwhile, the incorporation of extra quantity of IBA would decrease the strength considerably. From the microstructure analysis, the hydration of UHPC was enhanced by using IBA, resulting in a denser microstructure and a higher hydration degree of the UHPC compared to the control specimen. The cumulative pore volume increased with the increasing quantity of IBA owing to its porous structure. The cumulative pore volume increased from 0.028 to 0.068 mL/g when the content of IBA was increased from 0 % to 100 %. Gu et al. (2022) evaluated the effect of SSA as a cement replacement on the pore structure of UHPC. The results showed that the pore volume of UHPC paste increased significantly due to addition SSA into UHPC mixtures. Addition of SSA as a cement replacement also increased the pozzolanic reactivity of SSA and the actual water to cement ratio of UHPC mixtures. Moreover, Lv et al. (2022) investigated the influence of high temperature-treated MSWIFA on the microstructure of UHPC. The addition of MSWIFA was helpful to the improvement of the pore structure, increasing the number of harmless pores and reducing the number of harmful pores. Zou et al. (2022) used recycled concrete powder as a cement replacement when preparing UHPC and found that although it increased the porosity of the sample, its internal curing effect also increased the content of gel products (See Fig. 14).

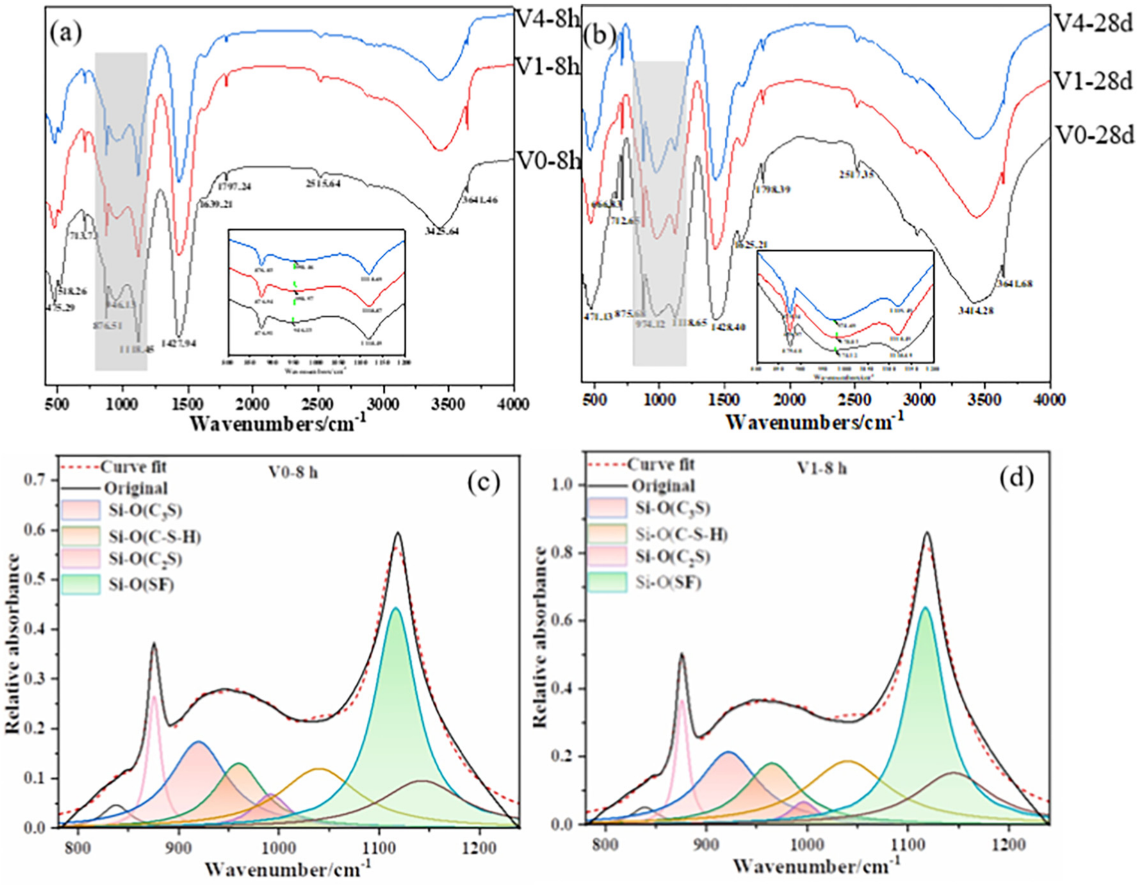


Fig. 17. FTIR spectra of UHPC with SF, limestone powder and SSP. V0: Microwave curing for 0 h, V1: Microwave curing for 1 h, and V4: Microwave curing for 4 h (reproduced under license number 5490560861227 from Feng et al., 2022b).

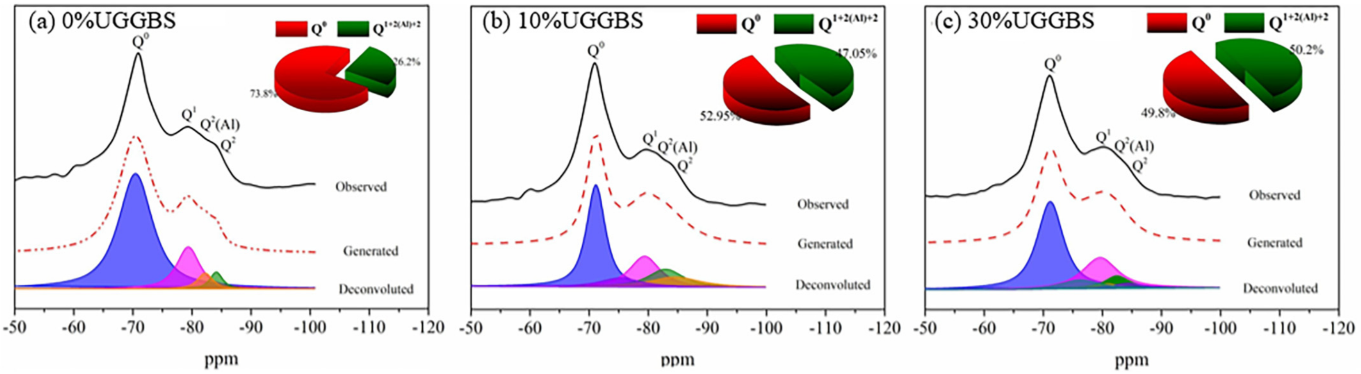


Fig. 18. ^{29}Si NMR of 28-d UHPC with wet-grinded ultrafine GGBS slurry (UGGBS) (reproduced under license number 5490560742728 from Yang et al., 2021).

4.3. Reaction product

X-ray diffraction (XRD) is one of the important tests that should be conducted to determine the type of reaction product. de Matos et al. (2020) used huge quantities of waste powders with quarry wastes, granite, adiabase, and basalt as alternatives to limestone and quartz conventional fillers. The XRD diffractogram of the UHPC samples show the main peaks related to ettringite and calcium hydroxide. The pozzolanic reactions of the SF partially consume this phase. The use of different materials did not significantly affect the CH peaks at all curing ages. He et al. (2022a) used coral powder to replace part of cement and SF to prepare eco-friendly UHPC, and its XRD pattern is shown in Fig. 15(a). They found that the cement clinker in UHPC was not fully hydrated at 28 d and the addition of coral powder made the aragonite peaks stronger. Monocarbonate was also produced with increasing substitution levels of coral powder, mainly due to the reaction of coral powder with C_3A (He et al., 2022a). Hou et al. (2021) used red mud as a partial cement replacement to produce UHPC and found that it had little effect on the type of reaction products, as shown in Fig. 15(b). Meanwhile, due its low W/B, UHPC contained unreacted phases such as C_2S and C_3S. Furthermore, the addition of red mud also reduced the peak of calcium hydroxide, which indicated that red mud has potential pozzolanic activity.

TG is one of the effective means to judge the content of hydration products. Dixit et al. (2019) used a biochar as a cement replacement at different replacement levels in the production of UHPC. The results indicated that the hydration degree increased to 42 % and 59 % for the control sample and 5 % replacement level, respectively. The DTG curves presented a discernable fluctuation from plain sample to biochar samples, with significant rising change for the 5 % replacement specimen at 7 d (See Fig. 16). Meanwhile, DTG curves for 2 % replacement level presented a considerable rising change at 28 d. These changes might be due to the large amount of dehydration of chemically-bound water generated from the C-S-H gels. This indicated that even at low W/B ratios, biochar still exerted a significant internal curing function. Hou et al. (2021) used red mud as cement replacement to evaluate the microstructure of UHPC. They concluded that the addition of red mud into the UHPC led to increases in calcite, hematite, and gibbsite; however, it reduced C-S-H gels and the peaks of ettringite.

FTIR is an effective means to judge the bond type in the reaction product. In general, waste products retard the early reaction progress of UHPC mixtures due to their low reactivity. In order to improve the early-age performance development of UHPC mixed with various solid wastes (SF, limestone powder and SSP) and stimulate the reactivity of solid wastes (SSP), Feng et al. (2022b) used microwave curing to effectively increase the content of early-ages reaction products of UHPC, as shown in Fig. 17(a and c). For the 28-d sample, the intensity of the O—H characteristic peak at 1625 cm^{-1} decreased with the prolongation of the microwave curing time, which indicated that the generated C-S-H decreased or the moisture inside the crystal was insufficient (See Fig. 17(b)). Very long microwave curing times would lead to water loss of UHPC, which in turn decreases the C-S-H content in the long-term. The results showed that brief microwave curing decreased the content of the unreacted phase and increased the degree of polymerization of C-S-H.

^{29}Si NMR is the main means to characterize the molecular structure of C-S-H in the reaction product of UHPC. When ordinary GGBS was replaced by wet-grinded ultrafine GGBS slurry, the chain length of C-S-H increased significantly, as shown in Fig. 18 (Yang et al., 2021). This indicates that wet milling enhanced the reactivity of GGBS and enhanced the hydration degree of UHPC. Meanwhile, the Al/Si ratio of UHPC mixed with wet-milled GGBS also increased, which indicated that more aluminates were leached from GGBS. Therefore, using appropriate modification and activation methods to improve the reactivity and filling effect of solid waste is the key to improving its utilization value in UHPC.

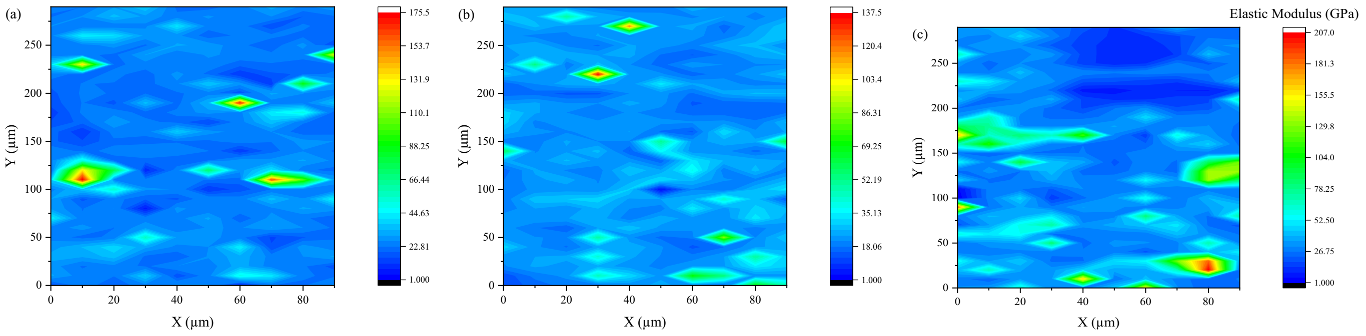


Fig. 19. Nanomechanical properties of recycled concrete powder-modified UHPC matrix. (a) 0 % concrete powder, (b) 15 % concrete powder, and (c) 30 % concrete powder (reproduced under license number 5490560591631 from He et al., 2022b).

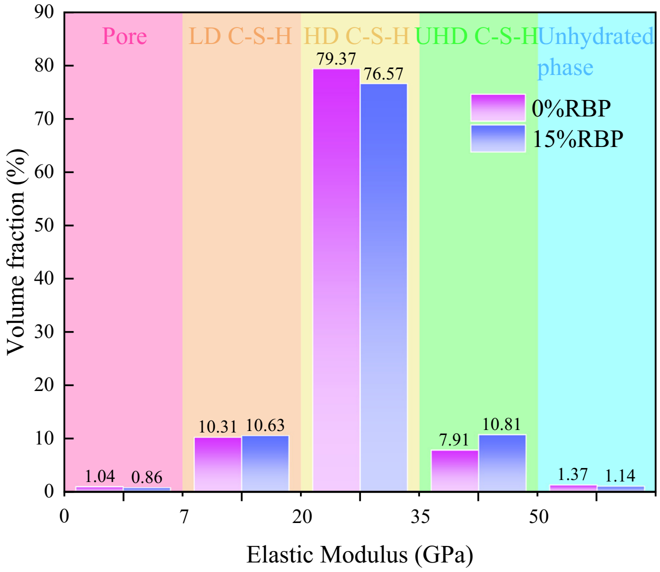


Fig. 20. The volume fractions of constituent phases of UHPC mixed with recycled brick powder (reproduced under license number 5490560469240 from He et al., 2021).

4.4. Nanomechanical properties

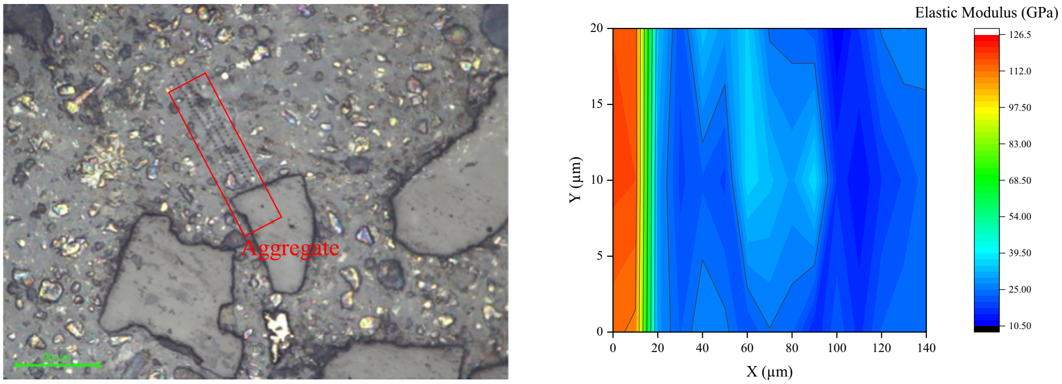
Nanoindentation is a nanoscale means to distinguish the phase composition of matrix and ITZ characteristics of UHPC. He et al. (2022b) used recycled concrete powder to replace 15 %–30 % of SF to prepare UHPC and study its nanoscale features, as shown in Fig. 19. The results showed that the content of non-hydrated phase and pore phase in the matrix increased significantly with the increase of the replacement ratio of waste concrete powder. Meanwhile, the waste concrete powder improved the nanomechanical properties of C-S-H gels by diluting the cement and changing the free water filling space. When the content of waste concrete powder was 30 %, the average elastic modulus of C-S-H gel in the matrix increased by 12.66 % compared with the plain paste.

He et al. (2021) used recycled brick powder to replace part of SF to prepare UHPC and used nanoindentation technology to characterize the phase of matrix and the width of ITZ (See Figs. 20 and 21). Using recycled brick powder to replace 15 % of SF to prepare UHPC increased the total amount of C-S-H gel, in which the content of high-density (HD) C-S-H decreased by 3.53 %, but the content of ultra-high-density (UHD) C-S-H increased by 36.71 %, as shown in Fig. 20.

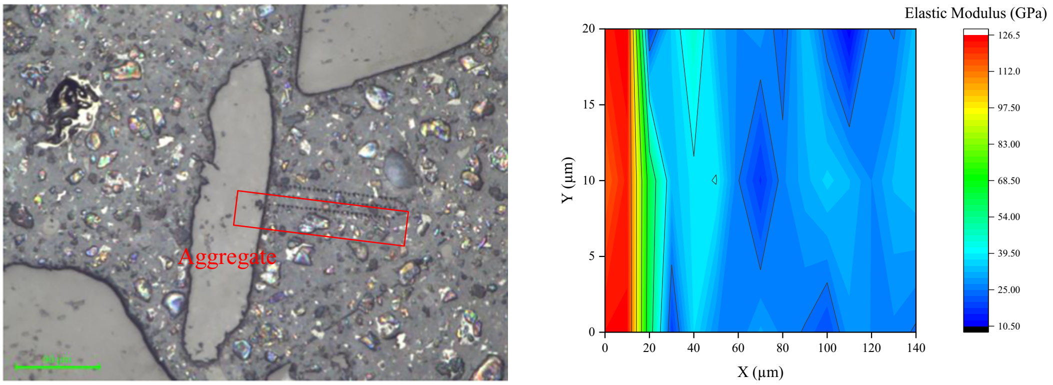
He et al. (2021) also tested the ITZ performance of UHPC modified with recycled brick powder; they found that the addition of 15 % recycled brick powder could significantly improve the ITZ performance of UHPC, which was not only manifested as a decrease in width, but also an increase in the average elastic modulus (See Fig. 21). This was not only due to the filling effects of recycled brick powder, but also its internal curing effect. Hence, the proper use of solid waste in UHPC can improve its nanoscale characteristics.

5. Environmental benefits

In general, solid waste contains trace amounts of heavy metals, especially waste incineration ash and metal tailings. Landfilling these hazardous solid wastes will cause potential harm to the surrounding environment and human health. However, UHPC has a dense microstructure, which can



(a) 0% brick powder



(b) 15% brick powder

Fig. 21. The nano mechanical properties of ITZ of UHPC mixed with recycled brick powder (reproduced under license number 5490560469240 from He et al., 2021).

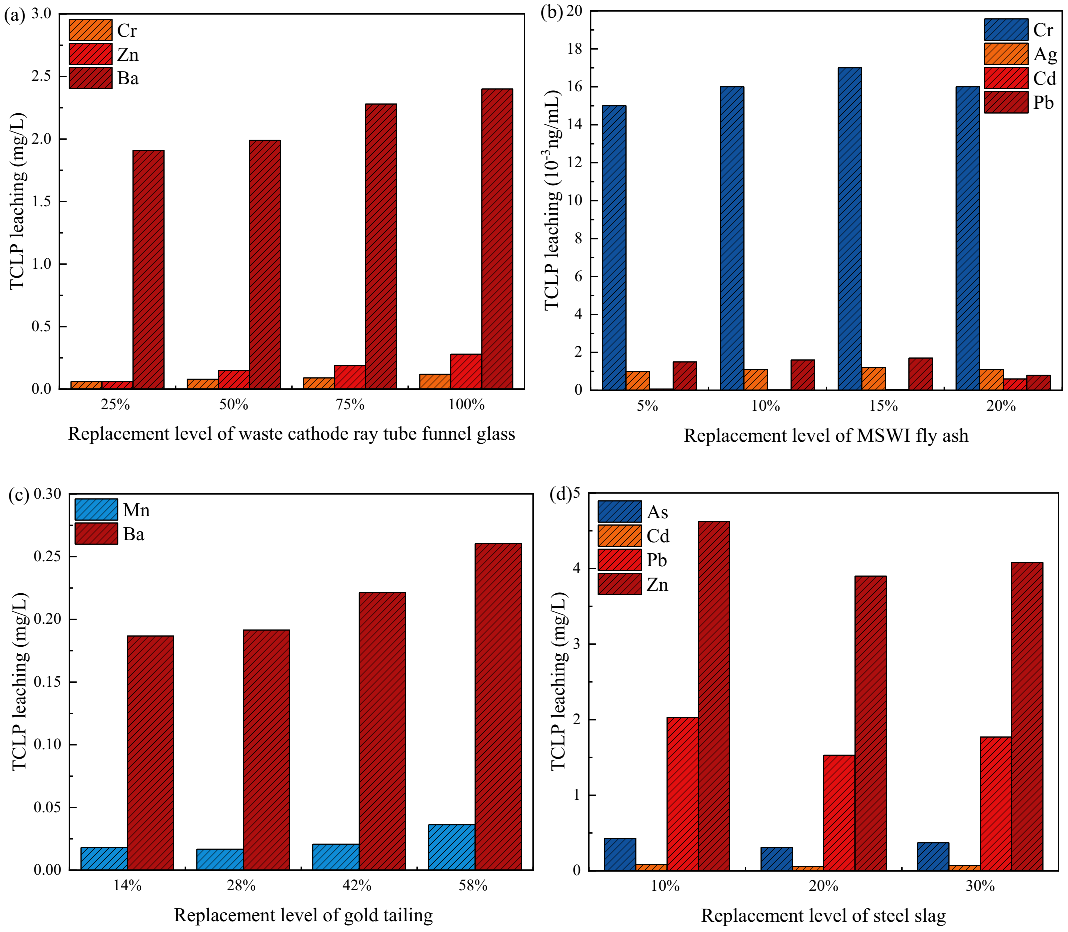


Fig. 22. Heavy metal leaching of UHPC with waste (Liu et al., 2020; Lv et al., 2022; Zhang et al., 2019; Wang et al., 2021).

effectively alleviate the leaching of these heavy metal ions, making it meet service standards, as shown in Fig. 22. Liu et al. (2020) used waste CRT funnel glass to replace part of the river sand to produce UHPC and found that there were leaching risks of Cr, Zn, and Ba. Although leaching concentrations of heavy metals increased with increasing substitution levels, they remained below United States Environmental Protection Agency limits, as shown in Fig. 22(a). Lv et al. (2022) also used MSWIFA to produce UHPC and found that the leached concentrations of Cr, Cd, and Pb were high, but they were still lower than the requirements of GB 5085.3-2007 (See Fig. 22(b)). The leaching of heavy metals in metal tailings is also serious, as shown in Fig. 22(c and d). However, it must be admitted that the dense microstructure and low permeability of UHPC can effectively solidify heavy metal ions through physical barrier and chemical action.

Zhang et al. (2019) used SS as a partial cement replacement during UHPC production and performed a life cycle assessment, as shown in Fig. 23(a). When the replacement level of SS was 10 %–30 %, the global warming potential value was reduced by 10.8 %–32.5 % and the fossil fuel usage was reduced by 7.8 %–22.7 %. For UHPC mixed with solid waste, the carbon footprint of the mixture tends to increase with the increase of compressive strength, as shown in Fig. 23(b). To further compare the carbon footprint of UHPC at the same strength, the ratio of total carbon emission to compressive strength is calculated and shown in Fig. 23(c). In general, adding solid waste to UHPC can effectively reduce the carbon emission per unit strength of the mixture. Xu et al. (2021) used ceramic tile waste powder to replace 15 %–55 % of cement in UHPC and found that its carbon emission was reduced from 7.95 to 5.69 kg/m^3·MPa. Yang et al. (2020a) found that the carbon emission of full-volume rock dust-based UHPC was reduced by 13.4 % compared to plain UHPC. Therefore, proper incorporation of solid waste into UHPC has significant environmental benefits.

6. The interaction mechanism between solid waste and UHPC

Fig. 24 presents the interaction mechanism between solid waste and UHPC. In general, solid waste is rich in silicon, aluminum and calcium elements, which may dissolve and participate in the reaction in an alkaline environment. For active solid waste with smaller size, the dissolution rate of internal elements is faster, which can react with calcium hydroxide to form a gel product. The large-sized solid waste is generally used as an aggregate and is more reactive than river sand/limestone aggregate. This makes solid waste consume the weak components (calcium hydroxide) at the ITZ and strengthens the performance of the ITZ through pozzolanic reactions. Meanwhile, for large-sized aggregates, cement paste may be anchored on it due to the rough surface of the aggregates. For UHPC, tight particle packing is critical. When the size of solid waste particles is small enough, it can play a filling role thereby improving the packing state of the UHPC mixture. In addition, some porous solid wastes have the function of water storage. The porous aggregate has an internal curing function, which not only promotes the further hydration of the non-hydrated phase, but also improves the performance of ITZ. In addition to the hydration of Si, Ca, Al, Fe, etc., the interaction between solid waste and UHPC matrix may also cause heavy metal ions leaching. The hydration

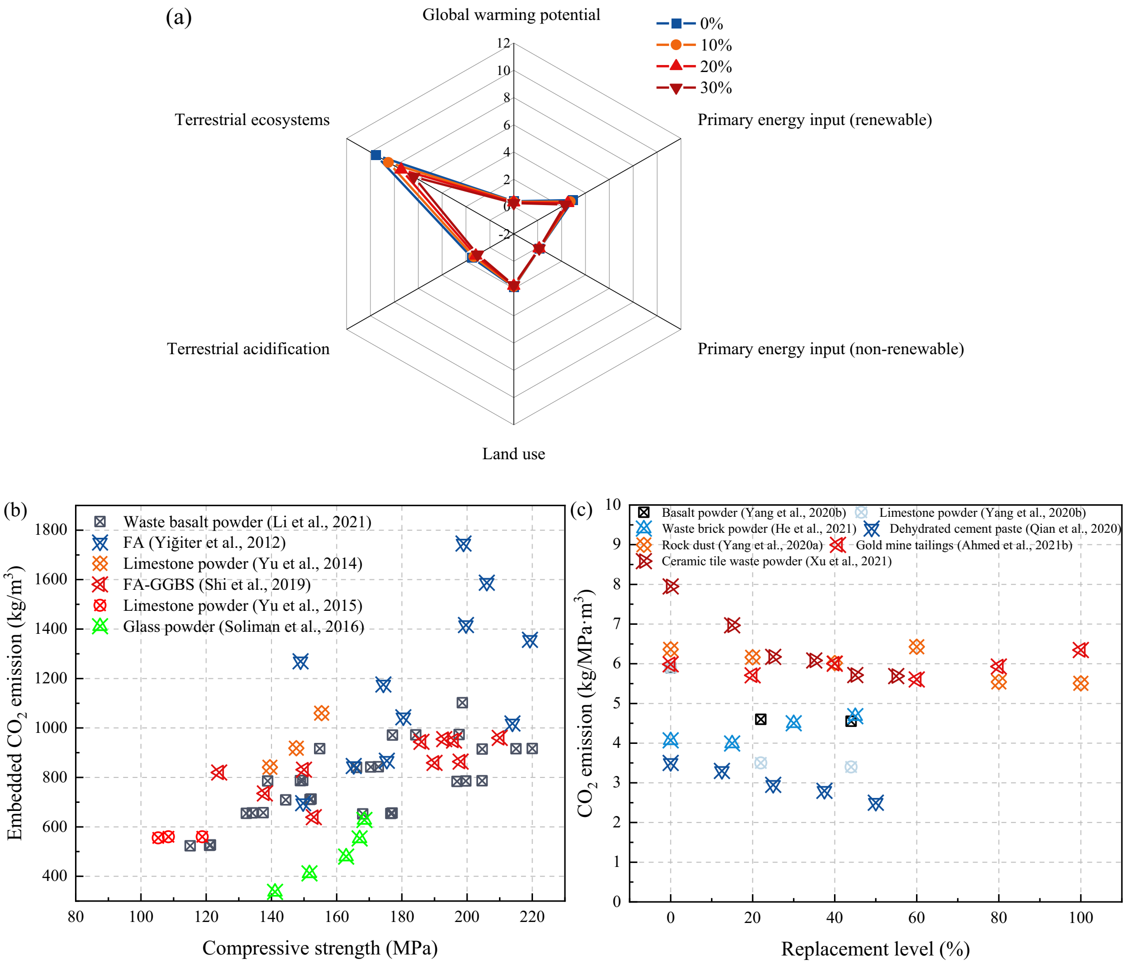


Fig. 23. Environmental benefit (a) and CO_2 emission (b and c) of UHPC with solid waste (Zhang et al., 2019; Li et al., 2021; Yiğiter et al., 2012; Yu et al., 2014; Shi et al., 2019; Yu et al., 2015; Soliman and Tagnit-Hamou, 2016; Yang et al., 2020b; He et al., 2021; Qian et al., 2020; Yang et al., 2020a; Ahmed et al., 2021b; Xu et al., 2021).

products of cement can effectively solidify these heavy metal ions through chemical bonding and physical adsorption/encapsulation; heavy metal ions also affect the precipitation of hydration products and may replace the ions in the hydration products (Chen et al., 2007).

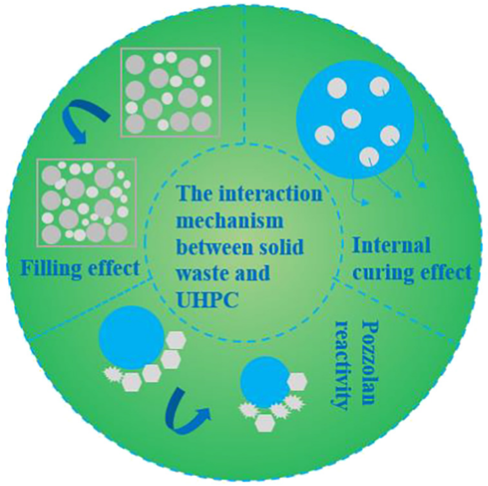


Fig. 24. The interaction mechanism between solid waste and UHPC.

7. Conclusions and recommendations

This study systematically reviews the durability and microstructure of environmentally friendly UHPCs in order to provide guidance for the production of low-carbon UHPCs. According to the results obtained from the previous studies, the subsequent conclusions can be drawn:

1. Even if the binder or aggregate is replaced by solid waste, eco-friendly UHPC still has a dense microstructure, which excels in impermeability, carbonation resistance, and high temperature resistance.
2. For small size solid waste, its pozzolanic activity and filling effect reduce its negative impact on the performance of UHPC, and even have an enhancement effect. Meanwhile, the internal curing effect of the porous admixture further contributes to the increased hydration degree of the binder.
3. Using an appropriate amount of solid waste to replace traditional aggregates is beneficial to improve the performance of UHPC, which benefits from the rough surface and water storage capacity of aggregates.
4. Using solid waste to replace part of the binder or aggregate to produce UHPC is an economical and eco-friendly strategy, which can effectively reduce carbon emissions, global warming potential, and fossil fuel usage of UHPC.
5. In general, metallurgical slag, metal tailings, radioactive solid waste, and municipal solid waste incineration fly ash have potential hazards of heavy metal leaching. UHPC has a dense matrix, which enables it to effectively mitigate the risk of heavy metal leaching in solid waste.

The high durability of UHPC is responsible for its widespread use in infrastructure projects, particularly those exposed to aggressive environments. As a result of this work, the following aspects should be considered in future research.

1. More research on aggressive environments, such as acid and sulfate attack, needs attention, especially for systems with different UHPC compositions. More importantly, the performance evolution under the coupling effect of multiple erosion environments also needs to be further studied.
2. Due to the low W/B ratio and high cementitious material content of UHPC, it is prone to shrinkage cracking, which is not conducive to its durability development. Porous solid waste has an internal curing function, which can be exploited to improve the volume stability of UHPC. However, at extremely low water-binder ratios, the water storage and lose characteristics of saturated porous solid wastes need to be further studied to ensure their internal curing effect in UHPC.
3. It is crucial to enhance the reactivity of solid waste in UHPC by process and composition, and the related grinding process, activator, and combined enhancement process need to be further developed.
4. In the evaluation of durability, the experimental design should consider the characteristics of solid waste. For example, metal tailings are conductive, which affects the accuracy of accelerated chloride tests.
5. With the development of new technologies and combination methods such as 3D printing concrete, engineered cementitious composites, fiber-reinforced polymeric composites, etc., the innovative combination of UHPC should be further studied.
6. In order to further understand the impact of solid waste doping on UHPC, it is necessary to study the multi-scale behavioral characteristics of eco-friendly UHPC, especially the microstructural evolution of the main reaction products.

CRediT authorship contribution statement

Hussein M. Hamada: Formal analysis, Writing – original draft. **Jinyan Shi:** Conceptualization, Writing – review & editing. **Farid Abed:** Writing – review & editing. **Mohammed S. Al Jawahery:** Investigation, Writing – review & editing. **Ali Majdi:** Methodology, Writing – review & editing. **Salim T. Yousif:** Validation, Visualization.

Data availability

Data will be made available on request.

Declaration of competing interest

None.

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