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REVIEWS

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A review on ultra high-performance fibre-reinforced concrete with nanomaterials and its applications

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Abstract

Ultra high-performance concrete (UHPC) is an advanced concrete which exhibits a higher performance mostly in all aspects and has a compressive strength higher than 150 MPa. The paper reviews the usage of different types of fibres, nanomaterials, mineral admixtures, preparation techniques and the utilization of UHPC. Improved microstructure, reduced porosity and homogeneous mixing are the basic requirements of the UHPC design. Though UHPC helps in the preparation of structural members at lesser size, it requires an enormous amount of cement which is accountable for a huge CO_2 emission, abrasion and cracks; hence, supplementary cementitious materials might be utilized as a limited alternative for cement without sacrificing the strength of concrete at lesser cost. The nanomaterials act as a nucleation site for the C-S–H gel formation by filling the voids and pores, thereby aiding to attain a denser microstructure for UHPC and also delaying the nucleation of the cracks at the nanoscale. The fibres used in the UHPC help in energy dissipation and also produce a bridging effect for micro- and macro-cracks. Based on the investigations, it has been found that the usage of medium hooked-end steel fibres and a hybrid combination of fibres with nanomaterials helps in improving several properties of the UHPC.

Keywords: Fibre-reinforced concrete, Nanomaterials, Sustainable supplementary cementitious components, Blast resistant concrete, Impact resistant concrete, Radiation shielding concrete

Introduction

Ultra high-performance concrete (UHPC) is a special concrete with superior properties and a high cement content, which exhibits a compressive strength which is at least three times more than conventional concrete. UHPC has extreme durability, which leads to higher service life and lesser maintenance of the structures. UHPC also has an enhanced resistance to abrasion and corrosion, which is more suitable for structures like bridge decks and industrial floors and for structures which are exposed to harsh environments [1, 2].

UHPC also produces a very good resistance against freeze–thaw and chloride due to its lower permeability because of its denser microstructure [3, 4]. UHPC has lesser weight due to the reduced size of the structural member with high strength compared to the conventional concrete of the same weight and hence can be used where lean structural members are required [5]. The usage of different fibres, nanomaterials and mineral admixtures makes a huge impact on the properties of UHPC. It has been suggested in many literatures that even different types of curing techniques have an impact on UHPC properties [6–10]. The incorporation of nanomaterials helps in preventing the initiation of cracks at the nanoscale, and the fibres are capable of mitigating the cracks when it reaches the micro-scale [11]. UHPC also provides excellent resistance against blast and impact loads, which is because of its enhanced mechanical properties [12–15]. It is also used in nuclear reactors in many countries due to its excellent radiation shielding capability [16].

The application of UHPC in various structures has been reported in different countries in the world. US Army engineers were the first to use UHPC in the late 1980s, and later, it was used in Canada for a Sherbrooke foot bridge around 1997. Although UHPC is extensively used in many countries with some design guidelines, it still lacks with proper framework of design and mix procedure [17]. Further development of a widely accepted design code might encourage the industry to implement UHPC in large-scale applications. Several investigations were being done to create a mix procedure for the UHPC, which is eco-friendly and cost-effective. UHPC has a very less water-cement ratio mostly lesser than 0.20, which leads to the usage of a large quantity of cementitious materials and superplasticizers to increase the workability of the concrete. UHPC is also manufactured without coarse aggregates, and in some studies, quartz sand was used instead of coarse aggregates [1, 3]. UHPC can be utilized with a variety of fibres to increase the concrete's tensile, flexural, shrinkage, toughness, ductility and post-cracking strength which enhances the properties of the UHPC greatly.

In India, the evolution of the UHPC is still in the early stage although there are some reported investigations from the researchers. The usage of various fibres on UHPC was also been reported by some academic researchers and is still in development for industrial use.

The objective of the work is to perform a detailed survey on the UHPC, their raw materials like different types of fibres, nanomaterials, supplementary cementitious materials and their field applications. The mechanism of each fibre and nanomaterial may be different due to their individual properties. The usage of fibres and nanomaterials on the UHPC is currently under investigation stage but will surely result in a major advancement in the near future.

Raw materials of UHPC

UHPC requires many special raw materials and mix procedures to attain an enhanced performance of the properties. The materials which can be used in UHPC are shown in Fig. 1.

Fibres in UHPC

The usage of fibres for construction has a long history back from the 1900s. Fibres tend to increase the structural strength, tensile strength, shrinkage, spalling resistance, toughness, ductility and post-cracking properties. UHPC also improves the performance in

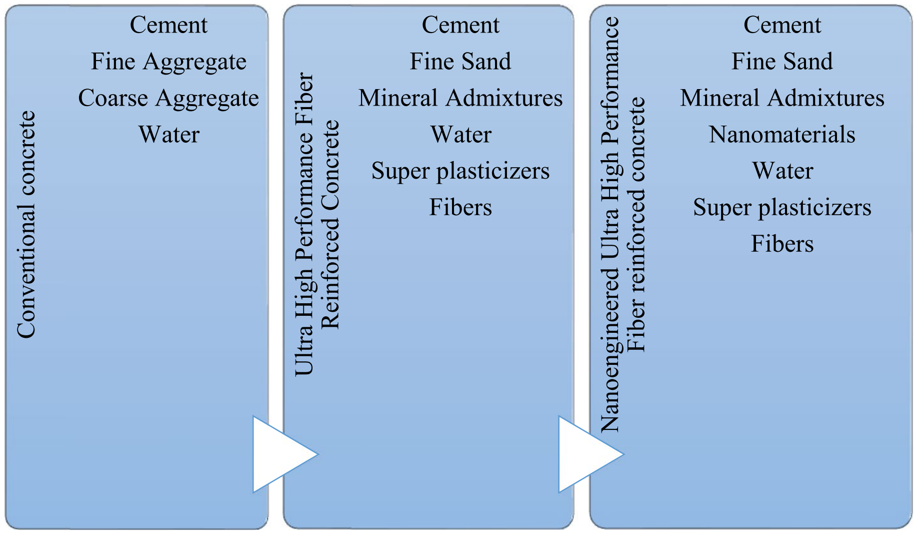


Fig. 1 Raw materials

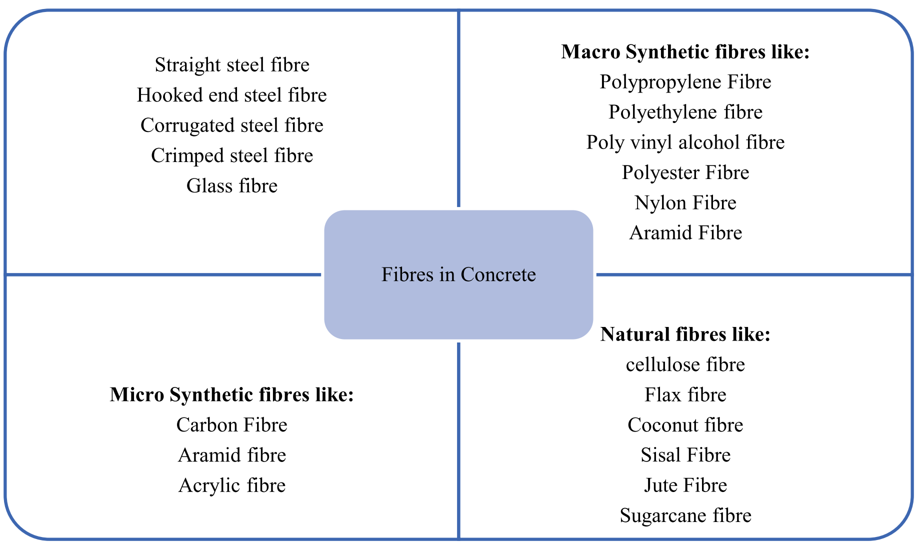


Fig. 2 Fibres utilized as a reinforcement in UHPC

terms of the durability of the concrete. Fibres are classified as micro- and macro-fibres based on their size, which creates a bridging effect on the concrete when the crack reaches micro- and macro-scale. The optimum volume fraction of fibres in concrete may also vary based on the density and size of fibres. Each fibre has a different effect on the concrete based on its aspect ratio and properties. Some of the fibres which are mostly used in concrete are detailed in Fig. 2.

Steel fibres

Steel fibres are available in diverse shapes and sizes. Properties of the steel fibre-reinforced concrete may differ based on their aspect ratio, size and shape. A higher aspect ratio steel fibre may reduce the workability, however increases the strength properties of the concrete. Steel fibres might create a linking effect on the concrete and prevent the development of cracks; however, smaller size fibres are effective at arresting smaller cracks at an earlier stage of cracking. A major disadvantage of steel fibre is corrosion; however, Valcuende et al. [1] performed a corrosion resistive analysis on UHPC reinforced with different fibres. The results reported that there was no corrosion even after 1 year of accelerated carbonation testing, which was achieved with the optimum usage of steel fibres and the denser microstructure of the UHPC. Steel fibres influence resistance against chloride in two ways, one is by controlling shrinkage cracking on the cement paste and the other is by creating weakened points with which the chlorides permeate easily through the interphases among the materials. Hence, more usage of fibres in concrete may create pores inside them. It was also revealed that even after exposure at 1000 °C, 69% of the original compressive strength was kept, and the split tensile strength began to fall after 400 °C exposure, however retained 41% of the split tensile strength even at 800 °C. Degradation of the steel fibre was reported above 600 °C and weighed largely on the drop of tensile strength at fibre-reinforced UHPC [18]. The triangular steel fibres when twisted provide better results than the straight steel fibres due to their better anchorage effect [19].

Steel fibres also prevent spalling by linking the plate and the UHPC cover. Abbas et al. [3] studied the effects of steel fibres in the concrete at varying lengths of 8 mm, 12 mm and 16 mm at dosages of 1%, 3% and 6% by mixture volume. The results show that incorporating short steel fibres of 8 mm and 12 mm at 6% of volume showed enhanced results in compressive, tensile and flexural strength than long steel fibres of the same volume. An increase in peak load carrying capacity of up to 37% was also noticed in UHPC. No deterioration in UHPC was reported due to the exposure of chloride ions solution.

Isa et al. [20] focussed on producing an eco-efficient UHPC with recycled tyre steel cords and recycled tyre steel fibres. Their performance was based on the length of the fibres. Recycled tyre steel cords with a length of 12 mm and 15 mm produced a superior strength and post-cracking stiffness while the recycled tyre steel cords with 9 to 15 mm produce 50% more flexural strength. They conclude that the recycled tyre steel fibres provide a better performance like manufactured steel fibres; however, the usage of recycled tyre steel fibre reduces the workability, fresh density, compressive strength and modulus of elasticity but offers significant cost and environmental benefits than recycled tyre steel cords or manufactured steel fibres.

Ashkezari et al. [21] analysed the effects of ultra high-performance concrete with the reinforcement of steel fibres. In the results 3% of 12-mm straight steel fibres produced a maximum compressive, split tensile and flexural strength at percentages of 81%, 228% and 180%, respectively, as shown in Fig. 3. Taekgeun et al. [22] aimed to enhance the interfacial bond and tensile performance of UHPC with steel fibres. So, they modified the fibre surface using ethylene diamine tetra acetic acid (EDTA) electrolyte solution and nanosilica coating. The surface roughness of the steel fibre increases due to the EDTA solution and nanosilica properties. He concluded that the EDTA-treated fibre provides the best tensile strength, strain capacity, pull-out resistance, bond strength and *g*-value.

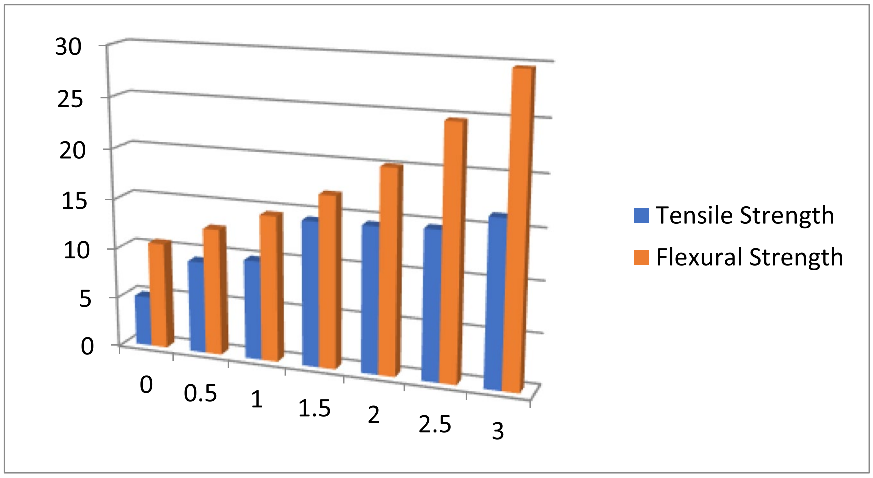


Fig. 3 Tensile and flexural strength at various steel fibre contents [21]

Glass fibres

Glass fibres used in concrete are in either continuous or discontinuous form. Various types of glass fibres are available to use; however, AR glass fibre is the most commonly used fibre due to its resistance against alkali attack. Mohammed et al. [23] worked with a high volume of micro-AR glass fibres. The behaviour of ultra high-performance fibre-reinforced concrete and their results concluded that a better mechanical performance was recorded for the mixtures with 1.5% of micro-glass fibres. Rigaud et al. [24] researched on UHPC with glass fibres as a reinforcement. Durability and ductility are well maintained during the accelerated ageing tests at 50 °C water. The flexural strength, elastic limit and maximum stress were enhanced with a glass fibre of 6 mm length and 0.15 mm diameter used in a quantity of 2.5% in concrete.

Meng et al. [25] present the mechanical performance of a glass fibre-reinforced polymer (GFRP). The utilization of glass fibre-reinforced polymer on UHPC enhanced the flexural properties of the panels. The use of GFRP in a single layer and double layer had made an increase in flexural capacity to almost 25% and 49%, respectively. A decrease in the first cracking load of 15% and 19% was observed due to the usage of single and double-layered GFRP, respectively. The energy dissipation was improved up to 12 and 17 folds because of the usage of single-layer GFRP and a double-layer GFRP, respectively.

Synthetic fibres

Synthetic fibres are polymer-based materials which are created by the process of polymerization. They are known for their long-term alkaline resistance in concrete. Zhau et al. [26] worked on UHPC by employing nanosilica particles to treat polyvinyl alcohol fibres using a sol–gel method. The physical friction and interlocking effect were improved, as the nanosilica particles improve the surface roughness of the polyvinyl alcohol fibres. New calcium silicate hydrate gels are also formed which fills the crack, which might be because of the reaction of nanosilica with calcium-containing phases in the cementitious matrix. The compressive and flexural strength was also

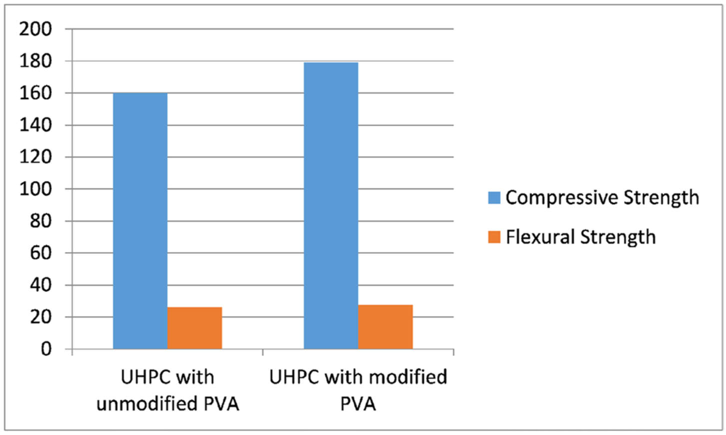


Fig. 4 UHPC with nanosilica-treated polyvinyl alcohol fibres [26]

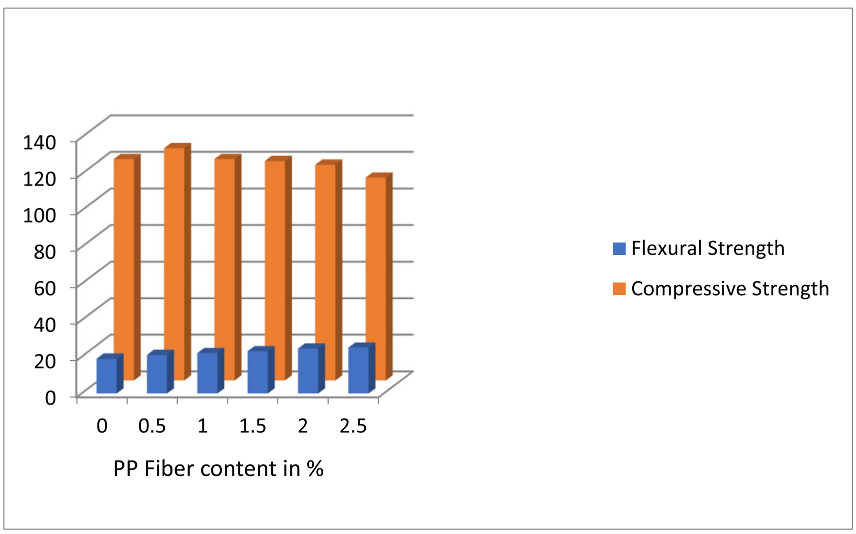


Fig. 5 Compressive and flexural strength of polypropylene fibre-reinforced UHPC [29]

improved based on the study as discussed in Fig. 4. The spalling resistance on the UHPC was also improved by the polymer fibres [27].

The impact of ultra-fine palm oil fuel ash combined with shredded recycled waste bottle in the form of polyethylene terephthalate (PET) on UHPC was explored by Alani et al. [28]. It was discovered that a total cement binder with 1% PET fibre had the highest compressive strength. In addition to that lower porosity, water permeability and rapid chloride permeability were also recorded. With the inclusion of UPOFA, additional C-S–H gel was formed, which improves the adhesive strength between PET fibre and the constituents of the concrete by decreasing the void values.

Yan et al. [29] aimed to enhance the ductility characteristics of the UHPC with polypropylene fibres at various volumetric fractions. The compressive property of the concrete improves at 0.5% of polypropylene fibre by 5.78%. The flexural strength, modulus of rupture and toughness index was also improved by 26.9%, 24.92% and 4.75%, respectively. The effect of compressive and flexural strength at different proportions was discussed in Fig. 5. Rios et al. [30] suggest that the incorporation of polypropylene fibres significantly enhances the maximum pore size and porosity. The use of polypropylene fibre reduces the thermal damage due to the partial melting of the polypropylene fibres in combination with the rise in porosity.

Yu et al. [31] studied the effects of UHPC with polyethylene fibres and concluded that the tensile strength, modulus of rupture and compressive strength increased significantly. Spalling tests, permeability measurements, and microscopic characterizations on frequently used polymer fibres such as low-density polyethylene, ultra-high molecular polyethylene, polypropylene, polyamide and polyester fibres were conducted by Zhang and Tan [32] and concluded that the low-density polyethylene, polypropylene and polyamide could prevent spalling in UHPC, while ultra high molecular polyethylene and polyester fibres are not effective in spalling prevention. Thermal expansiveness of the polymer fibres is a major property which enhances the spalling resistance.

Carbon fibres

Raw carbon fibres are produced from either polyacrylonitrile or petroleum coal. Carbon fibres are lighter and stronger than steel. They can be used either directly with concrete or in the form of external wrapping sheets. The diameter of carbon fibres was mostly 5–10 µm, and they are composed mostly of at least 92% of carbon from its weight. Ferrier et al. [33] tried to make a type of UHPC which provides enhanced performance than the conventional. The aim is to create a light weight beam with high compressive strength, tensile strength, shear resistance and to be able to withstand significant bending moments. Their findings show that the using of carbon fibre-reinforced polymer rebar in concrete boosts carbon bending stiffness even in small rebar diameters by boosting the young's modulus.

Tian et al. [34] investigated prefabricated grid-reinforced UHPC and concluded that the use of carbon fibre-reinforced polymer grid could provide more sufficient lateral confinement to achieve a strain hardening behaviour, increasing the specimen's ductility and toughness.

Three distinct fibres were chemically processed with sodium hydroxide, nitric acid and ammonia acids by Yoo et al. [35]. The outcome states that increasing the carbon fibre content enhanced conductivity, while chemically treating the carbon fibre resulted in slightly better conductivity. The UHPC with 0.1% by weight of nitric acid processed carbon fibres achieved the best shielding efficacy, compressive and tensile performance. Figure 6 discusses the shielding effectiveness of different acids in UHPC.

Natural fibres

The effect of nanocellulose fibres, which are manufactured from cellulose obtained from plants, was studied. The maximum compressive value of UHPC was found at 0.05% nanocellulose, according to the findings. At peak load, nanocellulose in concrete also improves ductility, energy absorption capacity, toughness index and flexural strength. It was also determined that the cellulose fibre improves flexural strength [36, 37]. The shrinkage value was also reduced with an optimum content of cellulose fibres. The degree of hydration in cellulose fibre is the absorption of water at an earlier stage, but the absorbed water in the cellulose fibre was released at a later age, promoting a continuous

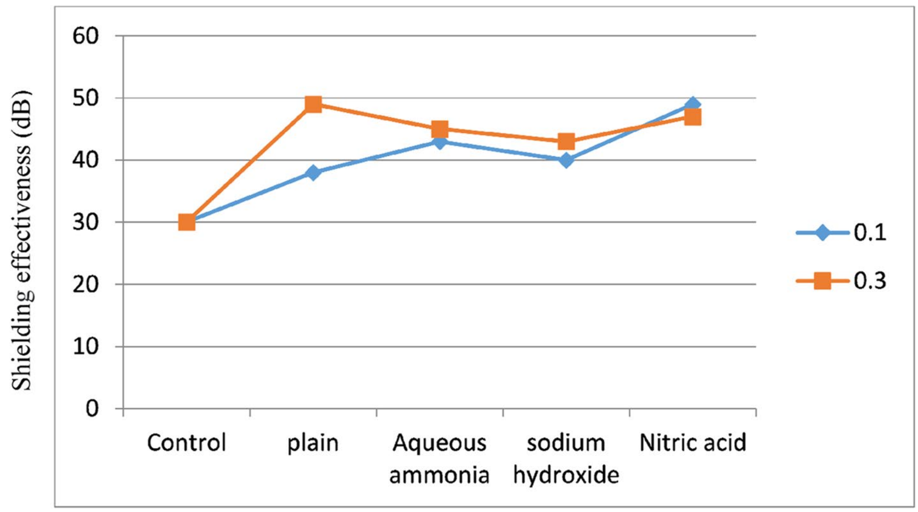


Fig. 6 Shielding effectiveness of carbon fibre-reinforced UHPC [35]

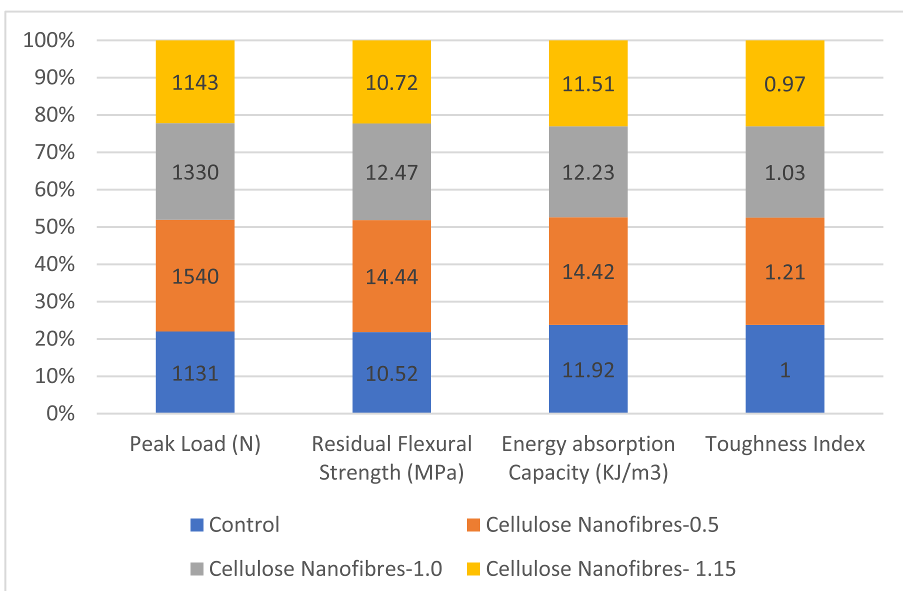


Fig. 7 Ultimate load, flexural strength, energy absorption capacity and toughness index of UHPC with cellulose nanofibres [36]

hydration response. The hydration level was greater than in the control sample, peaking at 0.9 kg/m^3. Cellulose fibres also mitigate autogenous shrinkage by a twofold mechanism and produce a matrix bridging effect due to the nano-reinforcing effect, which also improves the volumetric stability [38]. The effect of nanocellulose fibres with respect to conventional concrete was discussed in Fig. 7.

Zhang et al. [39] explore the implementation of natural fibres like jute fibre at different volumes on UHPC for the enhancement of compressive properties, permeability and resistance to spalling. Natural fibres have the tendency of swelling due to the absorbing water and shrinking due to exposure to warm and high temperatures. Due to the deswelling and shrinkage of natural fibres at varying temperatures, permeability was influenced by the space between the fibres and the concrete. The results conclude that jute fibres when used at an application of 10 kg/m^3, eliminate the spalling. The compressive strength and flexural strength was also increased in all dosages.

Natural Sisal fibres were obtained from sisal leaves in the form of vascular bundle fibres. Ren et al. [40] studied UHPC with varying lengths (6, 12 and 18 mm) and volume contents of sisal fibres (1.0%, 2.0% and 3.0%). The workability of the UHPC mixture declines as the length and volume of the sisal fibres rise, according to the experimental data. Flexural strength and toughness were both improved by 16.7% and 540.0%, respectively, as discussed in Fig. 8. The length of sisal fibres also enhanced the pull-out energy and pull-out load. UHPC with 6 mm, 12 mm and 18 mm of sisal fibres at 1% by volume increases the compressive strength at around 3.7%, 8.5% and 15.5% from the reference specimens. The flexural property and the toughness were improved to the best at 2.0% of sisal fibres with a span of 18 mm at a percentage of 16.7% and 540.0%.

Hybrid fibres

The combination of the two different types of fibres or a fibre of different shape or size is called as hybrid fibre. The inclusion of hybrid fibre enhances the energy dissipation capacity in the concrete than the usage of single-sized fibres. Yu et al. [41] and Kamal et al. [42] used steel and polypropylene fibres in UHPC to evaluate the behaviour and effect of concrete beams. They analysed with special focus on the deflection at various levels of loading, as well as initial cracking, cracking pattern and ultimate load. The steel fibres are more potent than the polypropylene fibres in raising initial and ultimate loads. The results concluded that the hybrid combination of polypropylene and steel fibres increases the compressive strength for 28 days up to 2.5% and 6%. An increase in ultimate load was also reported for both steel and polypropylene fibres at around 48 and 15 percentage, respectively, than the conventional concrete as shown in Fig. 9.

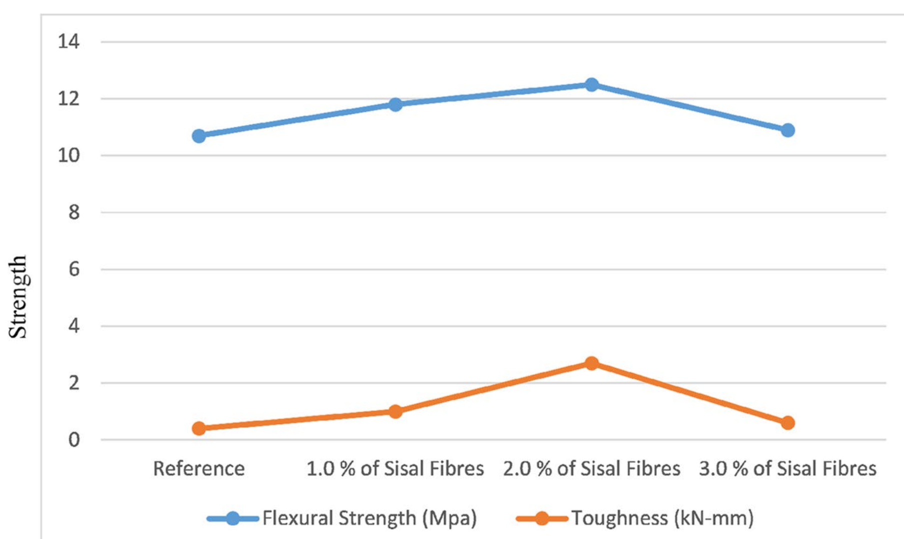


Fig. 8 Flexural strength and toughness of 18-mm sisal fibre reinforced UHPC [40]

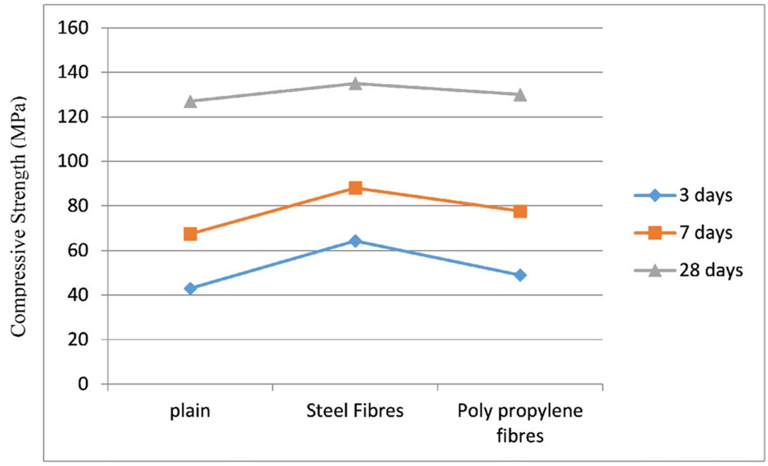


Fig. 9 Compressive strength of steel and polypropylene fibre-reinforced UHPC [42]

Zhang et al. [43] studied the integrated response of steel and flax fibres in resisting spalling on UHPC. The flax fibre increases the permeability, and the steel fibre provides a bridging effect on UHPC under elevated temperatures. Natural fibres like flax will not melt at high temperatures, and the degradation starts well over 300 °C; further, there might be an interfacial separation due to the expanding responses of flax fibres. Therefore, the UHPC with only flax fibre provides a passageway for vapour at extreme temperatures and increases the permeability. The reports suggest that the steel fibre increases the strength, and the flax fibre works in reverse by decreasing the strength.

Li et al. [44] explored the utilization of polypropylene fibres, steel fibres and aggregate size both in the individual and combined forms. Polypropylene fibre helps in preventing spalling and increases the permeability much more than steel fibres. Higher permeability was recorded with the combined use of steel fibre, polypropylene fibre and larger aggregates. It was also reported that an increase in the length and dosage of the polypropylene fibres has more effects on permeability than the diameter of the fibres.

Yan et al. [45] aimed to investigate the ductility characteristics of UHPC with hybrid fibre combinations. Fibres are added in various dosages, and the observed outcomes state that the type and amount of included fibres influence the performance of the UHPC mixtures. With the inclusion of 2.5% fibres, the flexural strength in basalt fibre, polypropylene fibre and glass fibre was increased by 20.8%, 26.9% and 27.9%, respectively; there was also an increase in modulus of rupture for about 20.4% for the basalt fibre, 24.92% in polypropylene fibre and 26.05% for glass fibre. When compared with reference specimens, there was a considerable decrease in fluidity due to the addition of fibres. The toughness index was also increased in all fibre-reinforced concrete. Improvement in the compressive strength was recorded with the volume of all the fibre content, less than 0.5%. Glass fibre resulted in the highest peak load and then polypropylene fibre followed by basalt fibre at the volume of 2.5% based on the load–deflection curve.

Li, Yang and Tan [46] investigated the flexural performance of a hybrid polyethylene–steel fibre-reinforced UHPC. The hybrid combination of polyethylene and steel fibres significantly improves the limit of proportionality, modulus of rupture and toughness index of UHPC. The best flexural performance was demonstrated by UHPC, which contains 0.5% polyethylene and 2.0% steel fibres. Polyethylene fibre produces unfavourable results on compressive strength, and hence, combined usage of steel and polyethylene fibre provides a better result.

Sbia et al. [47] incorporate nano- and micro-scale reinforcement in UHPC. They used carbon nanofibre for nano-reinforcement and polyvinyl alcohol fibre for micro-reinforcement. The results indicate that the combined usage of carbon nanofibre and polyvinyl alcohol fibre improves flexural strength, maximum deflection, energy absorption capacity, resistance to impact and abrasion and compressive strength. Feng et al. [48] aim to study the properties of the hooked-end steel fibre and macro-polypropylene fibre in concrete. The results concluded that 1.0% of hooked-end steel (HES) fibre with 0.5% of macro-polypropylene (MPP) fibre shows better results in all terms than the conventional concrete.

Nanomaterials in UHPC

These are the materials of size 0.1 to 100 nm. Nanomaterials increase the longevity of concrete and resistance to fire and improve the quality of concrete such as self-healing and self-cleaning. Nanomaterials also improve the flexural and compressive strength in concrete at an early age; however, dispersion of nanomaterials is a major concern, and various techniques were followed to disperse the nanomaterials. The different nanomaterials which are used in concrete are nanosilica, nanotitanium oxide, nanoaluminium dioxide, nanocalcium carbonate, nanoclays, nanocellulose, nanorice husk ash, nanoiron, nanoferrous oxide and carbon nanomaterials like graphene, carbon nanotubes and carbon nanofibres (Table 1).

Carbon nanotubes

Carbon nanotube (CNT) is a one-dimensional nanocarbon material which was found out in 1991, with the structure resembling a rolled-up sheet of graphene, which has a cylinder cap-like seal on both sides and a hollow interior [49]. They are of two types, which are single-walled carbon nanotubes and multi-walled carbon nanotubes. Vianna et al. [50] stated that 0.05 to 0.10% of carbon nanotubes in the weight of cement can reduce the spalling due to exposure and increase the compressive and split tensile strength. Carbon nanotubes dispersed in a solution of 0 to 2.0% also improve the electrical resistivity and mechanical properties by pore filling and densification of concrete. The highest percentage of carbon nanotube was recorded as 0.10% in dispersed solution [59]. It also improves the hydration properties and bridges the cracking services as shown in Fig. 10.

Carbon nanofibre

Carbon nanofibre (CNF) is a recent carbon material between graphene and carbon 60. It has a tensile strength of 2.7 GPa and a modulus of elasticity around 400 GPa with a diameter around 0.5 to 100 nm [49]. Carbon nanofibres when compared to carbon nanotubes offer substantially higher performance and geometric attributes at low cost. Based on the performance, the optimum percentage of carbon nanofibre in UHPC was 0.04%. Carbon nanofibre was dispersed with water in the presence of polyacrylic acid at a polymer-to-nanomaterial weight ratio of 0.1 to 1.0% and should be sonicated for 30 min. A

Table 1 Comparison of different nanomaterials and their properties

References	Nanomaterial	Size (nm)	Specific surface area (m^2/g)	Optimal percentages (%)	Advantages	Disadvantages
Changjiang Liu et al. [49] T. M. Vianna et al. [50]	Carbon nanotube	10 to 20	165 to 205	0.10 to 0.50	Improves the electrical resistivity and the mechanical performance of the concrete CNTs also improve the hydration process and help in the bridging effect of the cracks	Dispersion of the carbon nanotube is difficult, and the cost of the material is also expensive
Changjiang Liu et al. [49] Libya Ahmed Sbia et al. [51]	Carbon nanofibre	0.5 to 200	50 to 60	0.04	Improvements in the energy absorption capacity, resistance to impact and abrasion, compressive strength, flexural strength and maximum deflection	The dispersion of carbon nanofibre is still difficult due to the influence of surface energy and van der Waals force; hence, surface modifications and ultrasonication are required for proper sonication
Changjiang Liu et al. [49] Hongyan chu et al. [52] Van Dac Ho et al. [53]	Graphene	2 to 10 nm	60 to 255	0.05 to 0.1	Boosts the hydration properties of the concrete by improving the calcium silicate hydration gel with its nucleation effect Improves the strength and durability properties of the concrete and also reduces the voids and pores with its nanosize Prevents the development of nanocracks with its high tensile strength	Manufacturing of graphene is expensive and consumes a lot of time, however can be compensated with reduced usage in concrete Dispersing of graphene in concrete is difficult and may require complex techniques to mix it with concrete. Excessive usage of the material may also cause an agglomeration effect, which may reduce the performance of the concrete
R. Yu et al. [54]	Nanosilica	12 to 200	200 to 220	3 to 4	Improvements in the C-S–H gel formation, mechanical performance, durability, permeability and porosity	Excessive usage of nanosilica than the optimum percentage may create negative effects
Jessica Camiletti et al. [55] Zemie Wu et al. [56] Wengui Li et al. [57] Wengui Li et al. [58]	Nanocalcium carbonate	15 to 80	45	2 to 5	Accelerates hydration and enhances the mechanical properties Aids in increased shorter setting time and denser microstructure	Workability of the concrete may be reduced, and the autogenous shrinkage of the concrete will be increased

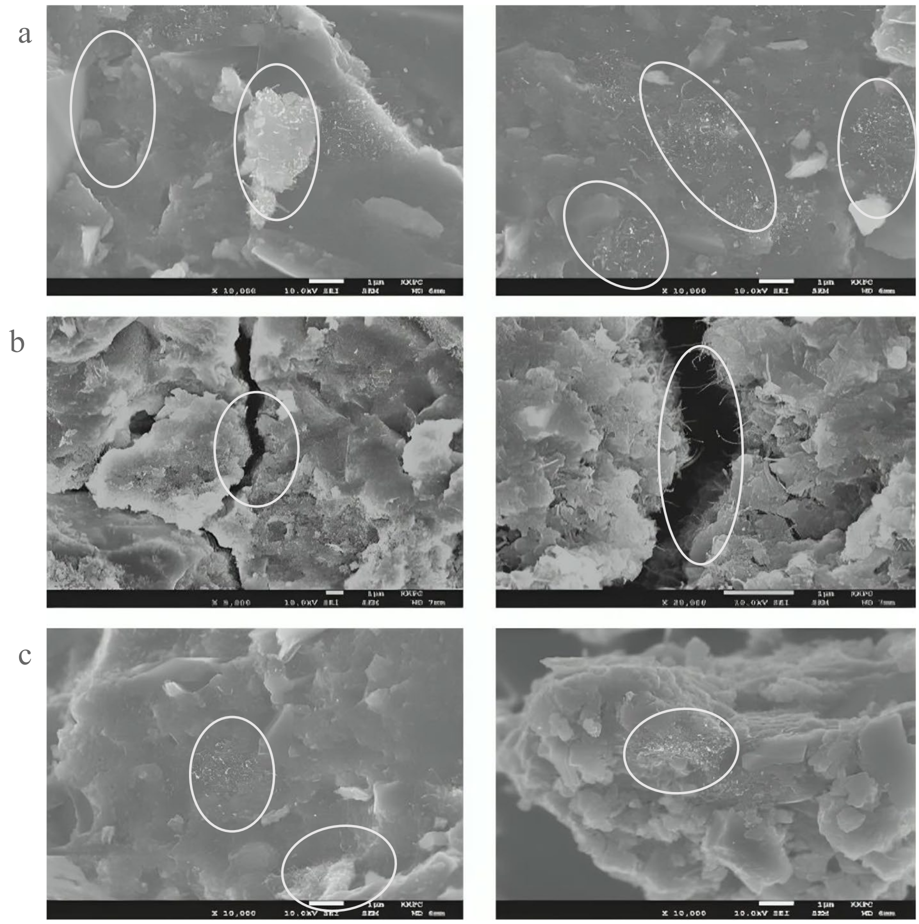


Fig. 10 SEM images of UHPC with carbon nanotubes. **a** CNTs embedded in the hydration products. **b** CNTs bridged the cracking surfaces. **c** CNTs agglomerated on the surface of cement [59]

well-dispersed carbon nanotubes will have a uniform dispersion in the microstructural analysis as shown in Fig. 11. Carbon nanofibre surfaces form a bond with C-S–H as it is highly hydrophilic and effectively combines with the cementitious matrix [51].

Graphene

A single-layer stripping approach was used first to make graphene by Novoselov and Geim in the University of Manchester in 2004. Graphene is a type of 2D honeycomb crystal framework carbon material made with single-layer carbon atoms. An optimum mixing concentration with 0.05–0.07% of graphene by volume of cementitious materials improves the performance of the concrete in all mechanical and durability aspects. It was also concluded that graphene-reinforced UHPC possesses outstanding properties like high electrical conductivity, high thermal conductivity and high mechanical strength at an optimum percentage of 0.07% of graphene by volume; however, higher usage of graphene on concrete limits the enhancement of mechanical properties due to the impact of the van der Waals force on the sedimentation of the suspension which steers to the bad dispersion and also decreases the fluidity of the concrete. The microstructural analysis of the UHPC with graphene nanoplatelets presented in Figs. 12 and 13 also ensures

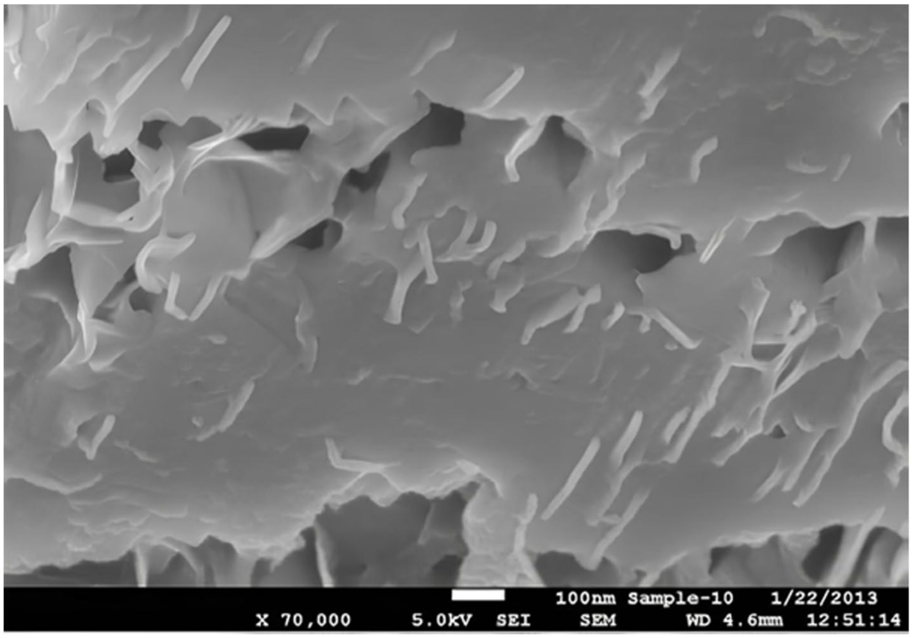


Fig. 11 Scanning electron microscopy (SEM) of the carbon nanofibre reinforced concrete [51]

Fig. 12 Graphene nanoparticles

the enhancement of the calcium silicate hydrate gel into petal-like hydration products; however, increased usage of graphene nanoplatelets may lead to extremely high concentrations of graphene nanoplatelets dispersion, and so, it cannot be effectively dispersed in the concrete [49, 52, 53, 60, 61]. The porosity and electrical resistivity of the UHPC at 0.05% of graphene nanoplatelets in volume were lower than the conventional UHPC as in Fig. 14.

Nanosilica

It is an organic chemical compound, which is non-poisonous, flavourless and devoid of pollutants. It has a larger surface area which absorbs more water and thus reduces

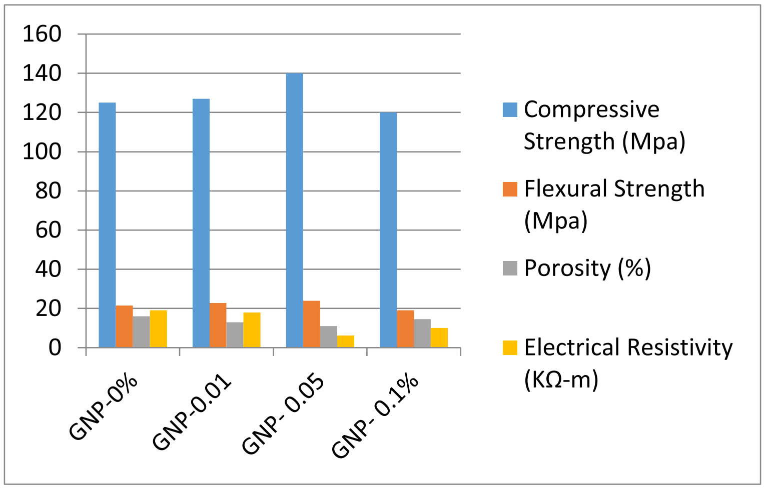


Fig. 13 Compressive strength, flexural strength, porosity and electrical resistivity of UHPC with graphene nanoparticles [60]

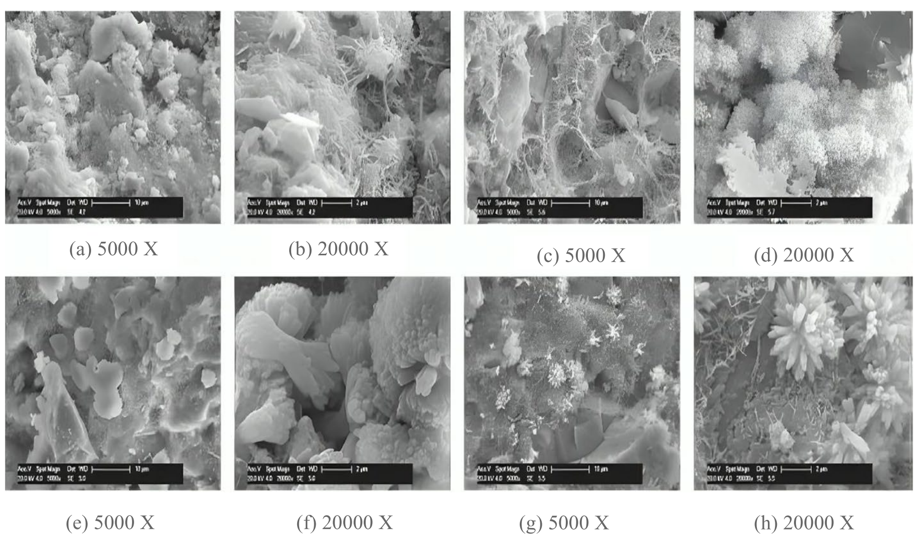


Fig. 14 SEM images of UHPC with graphene nanoplatelets (GNP): UHPC with GNPs of 0% (**a**, **b**), UHPC with GNPs of 0.01% (**c**, **d**), UHPC with GNPs of 0.05% (**e**, **f**) and UHPC with GNPs of 0.1% (**g**, **h**) [60]

the fluidity of the concrete. Yu et al. [54] reported that the inclusion of nanosilica significantly creates an improvement in the viscosity of UHPC. Nanosilica creates a nucleation effect which promotes more C-S–H gel, and so, finding an optimum amount is necessary. In the microstructural analysis of the UHPC with a nanosilica of 4%, it was observed to have a dense structure with only few air pores, but in the UHPC with 5% nanosilica, more pores were observed as shown in Fig. 15. The outcome of the compressive and split tensile properties was observed to be maximum at around 3.74% (Fig. 16). Sujay et al. [62] studied the properties of nanosilica used at a combination with ultra-fine fly ash for cement and concluded that 15% of ultra-fine fly ash as an alternative for cement with 3% nanosilica achieves the highest durability

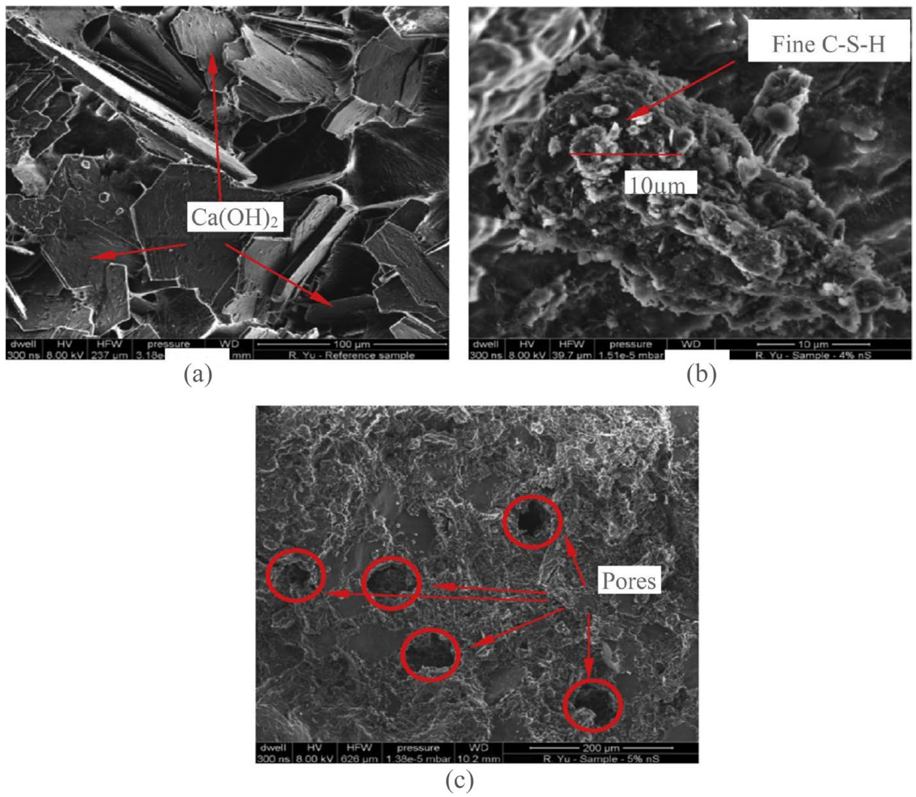


Fig. 15 SEM images. **a** Control sample. **b** UHPC with 4% of nanosilica. **c** UHPC with 5% of nanosilica [54]

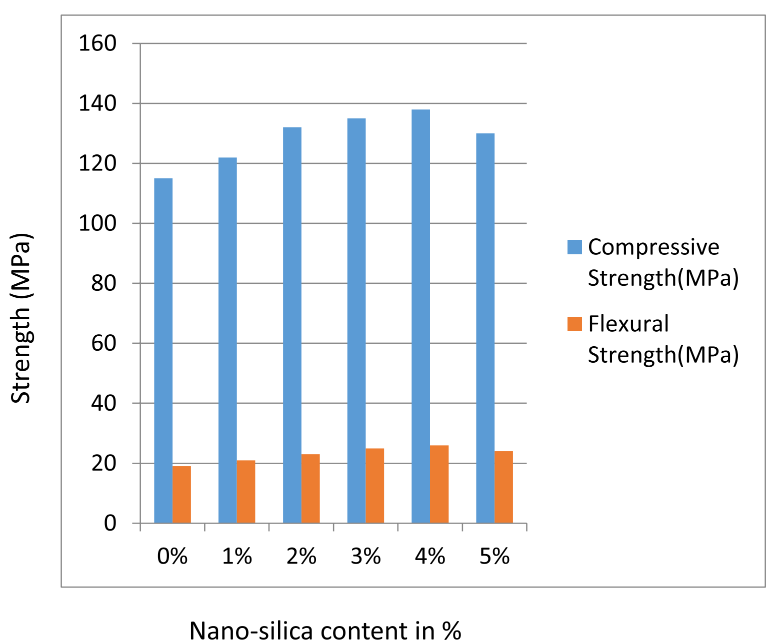


Fig. 16 Compressive and flexural strength of nanosilica-reinforced UHPC [54]

and reduced porosity and permeability, due to the improved micro- and macrometer densities of the concrete. A considerable reduction in chloride ion penetration was also noticed.

Nanocalcium carbonate

Nanocalcium carbonate is a low-cost material, which is made from natural calcite, marble and limestone. Camiletti et al. [55] used nanocalcium carbonate in the study as a partial replacement for cement at various percentages. From performance and economic points of view, efficient improvement in concrete properties was attained at 5% by volume and not more than 10% was advised. Wu et al. [56] reported that the optimum dosage of nanocalcium carbonate to amplify the compressive and flexural strength was 1.6 to 4.8% by the mass of cementitious materials. Nanocalcium carbonate reacts with C_3A to form calcium aluminates which is a substance with high permeability in fresh state, which makes ions and water diffuse into internal structure more easily and reduces the concentration of Ca^{2+}, thus accelerating the hydration. Nanocalcium carbonate accelerates the hydration reaction of UHPC because of its nucleation effect, decreases flowability and increases the amount of autogenous shrinkage of the UHPC. It also enhances the mechanical properties and produces a denser microstructure. Li et al. [57] blended nanosilica and nanocalcium carbonate and concluded that the optimum combined usage of nanosilica and nanocalcium carbonate was 1.0% and 3.0% as discussed in Fig. 17. Nano-$CaCO_3$ reduces the initial and final setting time which also aids in increased shorter setting time. The microstructural analysis in Fig. 18 states that the nanocalcium carbonate can enhance the packing density and fill the hollow space leading to a dense microstructure [58].

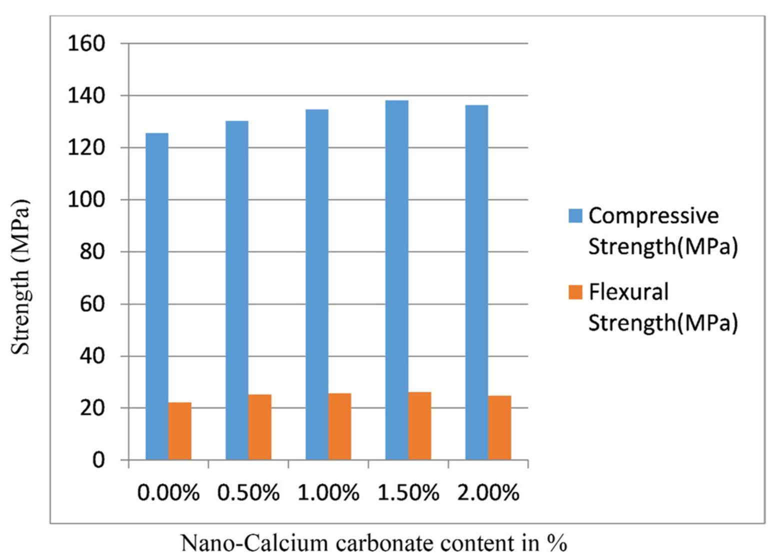


Fig. 17 Compressive and flexural strength of nanocalcium carbonate-reinforced UHPC [57]

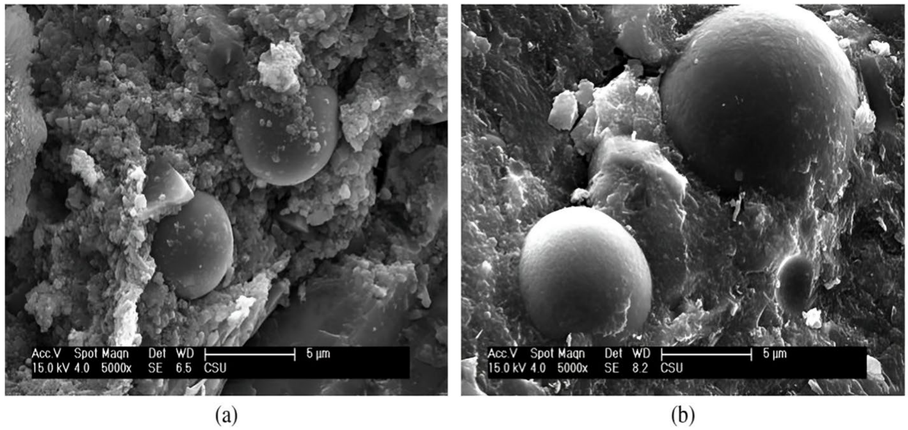


Fig. 18 **a** UHPC with 0% nanocalcium carbonate content. **b** UHPC with 2% nanocalcium carbonate content [58]

Nanowaste materials

Nanowaste materials include fly ash, silica fume, coal, metakaolin, glass waste and rice husk ash in nanoform that might be utilized in concrete. High-energy ball milling techniques were used to change the waste materials from micro- to nanosize. Faried et al. [4, 63] used nanorice husk ash, which was burned at different temperatures and concluded that nanorice husk ash burned at 700 °C for 5 h shows the best results when used at 3% by mass of cementitious materials. Tawfik et al. [64], with the utilization of nanoclay, nanofly ash, nanosilica and nanosilica fume at 2%, 4%, 3% and 4%, respectively, by weight of cementitious materials concluded that there was a considerable improvement in mechanical and non-destructive properties in concrete. The results concluded that there was an enhancement in compressive strength by 17%, 24%, 14% and 13% and a decrease in sorptivity by 48%, 60%, 60% and 84% for nanoglass waste, nanorice husk ash, nanometakaolin and nanosilica fume, respectively. Nanometa clay shows lower workability due to the clay properties and ultrafine size as compared to the OPC to metakaolin. Nanometaclay also produces a retardation effect at early ages, however increases more than the conventional at later ages [65, 66].

Supplementary cementitious components in UHPC

UHPC consumes a large amount of cement, which is mostly around 800–1100 kg/m^3. The huge usage of cement in UHPC influences the production cost, hydration and dimensional stability. Hence, alternatives to lessen the usage of cement content are of main concern. The most commonly used cementitious components and their impact on UHPC will be explored in the following sections.

Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBFS) is used as a substitute for cement for many decades to reduce environmental issues and production costs in the concrete industry. GGBFS has a particle size of 31–50 µm. GGBFS is one of the materials which possess mechanical and durability performance in UHPC. The hardened

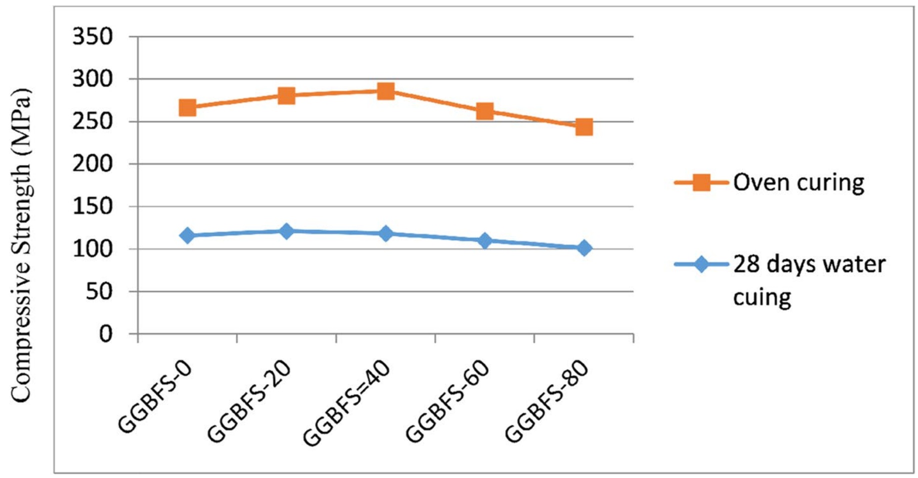


Fig. 19 Compressive strength of UHPC with GGBFS under standard water curing and oven curing [67]

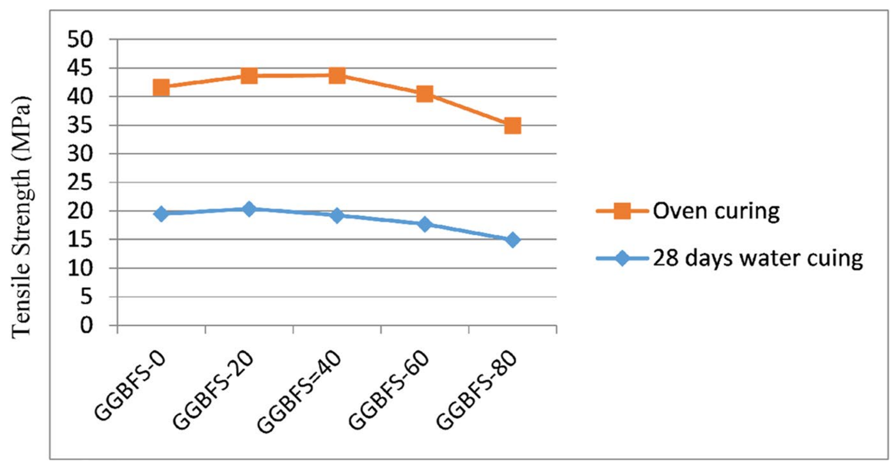
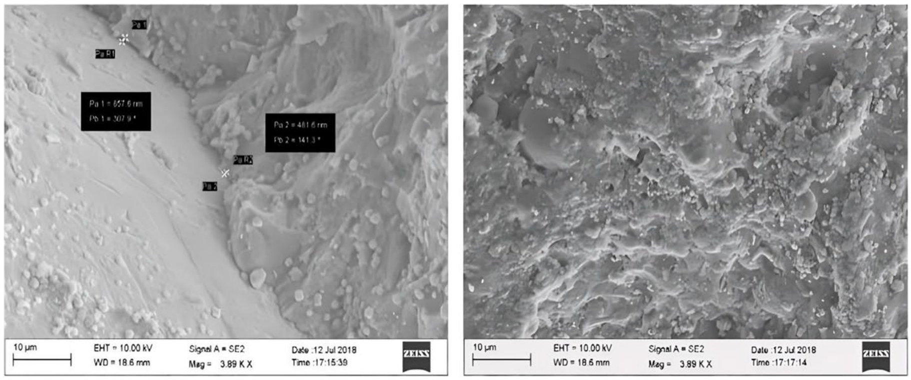


Fig. 20 Tensile strength of UHPC with GGBFS at various proportions under standard water curing and oven curing [67]

properties of GGBFS were significant up to 40% replacement for cement in standard curing conditions and up to 60% replacement for cement in the case of elevated temperature curing. The microstructural properties presented in Fig. 21 also confirm that the denser microstructure of the UHPC was due to the high volume of GGBFS. The hydraulic and pozzolanic activity of GGBFS creates more C-S–H gel formation than conventional, as noticed in the SEM images. GGBFS also significantly improves the fracture energy up to 60% replacement for cement. Durability properties are improved due to the enhanced pore structure by the incorporation of GGBFS in UHPC, which also produces a better resistance for chloride ingress and water absorption [67]. The improvement of the strength properties at various proportions of GGBFS was discussed in Figs. 19, 20, and 21.



(a) (b)

Fig. 21 SEM images of UHPC (**a**). Conventional (**b**) with 60% of GGBFS [67]

Fly ash

Fly ash is a spherical particle, which is a by-product of the coal industry. Fly ash is mostly used in combination with other materials like GGBFS, silica fume, metakaolin and steel slag. Hasan et al. [68] targeted to produce an eco-friendly reactive powder concrete (RPC) with 50% of the cement replaced by cementitious components and concluded that the fresh properties of the concrete were improved. Yazici et al. [69] used fly ash, GGBFS and silica fume at the UHPC and concluded that the strength improves at an optimum percentage of 10% fly ash and 10% GGBFS with 35% silica fume. The microstructural analysis also concluded a denser microstructure, which is suitable for the improvement in strength properties. Tahwia et al. [70] studied the impacts of fly ash and silica fume as a partial substitution for cement and concluded that the 30% substitution of cement by fly ash and 15% by silica fume improves the compressive performance, sulphate and chloride resistance in concrete.

Granite powder

Ground granite powder is an industrial waste produced from a stone processing plant. It was then processed in the laboratory to attain in a dry powder form. The particle size of granite powder utilized in the study mainly ranges from 10 to 100 µm. It has a very low CaO (2.31%) compared to the cement (53.32%); however, SiO_2 in granite powder is three times more than the SiO_2 in cement. Zhang et al. [71] experimentally investigated the granite powder as a substitute for cement. They studied the hydration products, pore structure, strength properties and chloride permeability at the macro-scale. Studies concluded that the optimum replacement of ground granite powder for cement was 5%, 10% and 15% under various curing conditions like standard curing, curing by warm water and autoclaved curing.

Nanocotton stalk

Nanocotton stalk is an agricultural ash made from the process of combustion, which yields an ultra-fine material suitable for supplementary cementitious components. The nanocotton stalk ash and palm leaf ash, when used as an alternative for cement in

UHPC, a reduction in slump flow was recorded. The largest slump flow was observed at 30% of palm leaf ash and 10% of nanocotton stalk, when used as a partial substitute for cement. The mixture containing 20% of palm leaf ash with 5% of nanocotton stalk ash achieves the highest strength properties and elastic modulus [72].

Limestone powder

It is a non-pozzolanic material which improves the fluidity of the concrete and produces a positive effect on C-S–H gel. Limestone powder was also effective in mitigating autogenous shrinkage [62]. It was also concluded based on past studies that an appropriate content of limestone powder at around 50% might contribute to higher properties. A secondary pozzolanic hydration, which can boost the potentiality of the concrete's development of strength at a later age, was noticed. Limestone powder also helps in making an eco-friendly and minimal-cost UHPC. Based on the investigations, around 20% of limestone powder gives the best result compared to conventional concrete as studied in Fig. 22, which also helps in making an eco-friendly and minimal-cost UHPC [73].

Silica fume

Silica fume is a waste product from the industries, which produces ferro silicon alloys, with a diameter of around 0.2 μm and is an essential constituent for UPHC. Liu et al. [74] concluded that the replacement of 20 to 30% of silica fume for cement possess superior mechanical and fracture properties on the UHPC. The influence of silica fume in concrete depends on the amount in concrete. Various other researchers also conclude that the optimum percentage of silica fume in UHPC was around 20 to 35%; however, it was extremely based on the water-cement ratio in concrete. Figure 23 explains the reaction of silica fume at various contents in concrete.

Phosphorous slag

Phosphorous slag is a by-product of the industries involved in the production of yellow phosphor. The primary constituents of the phosphorous slag are silicon dioxide and calcium carbonate, which states that phosphorous slag has a potential reactivity.

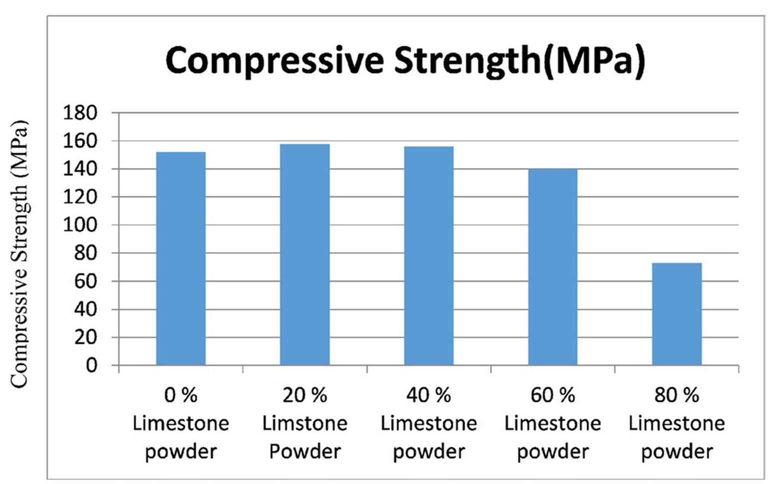


Fig. 22 Compressive strength of UHPC with limestone powder [73]

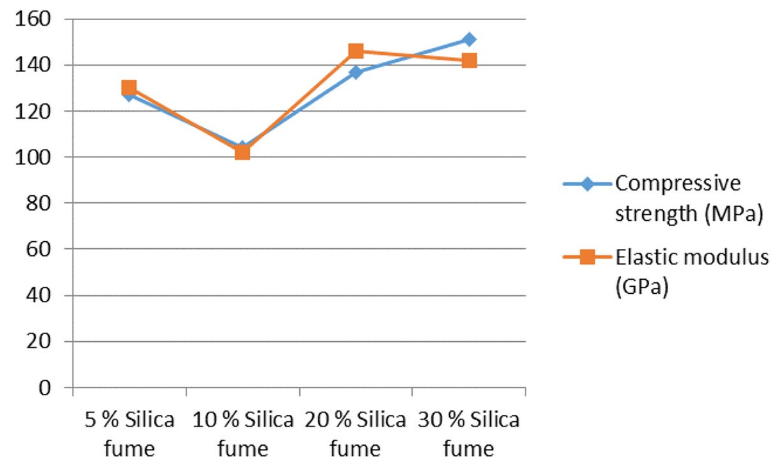


Fig. 23 Compressive performance and elastic modulus of UHPC with silica fume [74]

A study on UHPC by incorporating high-volume phosphorous slag with a particle size of around 10 μm was done, which states that the addition of phosphorous slag reduces the autogenous shrinkage at an early age and enhances the flowability. Phosphorous slag also improves the compressive strength up to 40% of the replacement for cement and above that reduces the strength below the reference. The early age strength development was also less though it produces a comparable compressive performance at 28 days. The microstructural analysis also validated that the phosphorous slag lengthens the inert period of cement hydration in UHPC [75].

Metakaolin

Metakaolin is manufactured by the dehydroxylation of the clay mineral kaolinite, which has a reduced particle measure and a higher surface area, when compared to Portland cement. Alharbi et al. [76] investigated the response of metakaolin as an available alternative for silica fume, which is a typical constituent of UHPC. The results concluded that the metakaolin can be replaced by up to 50% of silica fume in concrete. A reduction in mechanical performance was noticed due to the usage of metakaolin; however, the easy availability and the low cost of metakaolin would favour its usage in UHPC. Combined usage of metakaolin and nanomaterials can enhance the compressive strength, elastic modulus, sorptivity, porosity and absorption properties of the UHPC.

Expanded perlite powder

It is an amorphous volcanic glass, formed by the hydration of the obsidian. Wang et al. [77] investigated the effects of UHPC containing expanded perlite powder as a substitution for cement. The results indicated that a significant durability and a slightly lesser strength were obtained up to 60% of expanded perlite powder as a substitution for cement. The replacement of cement with expanded perlite powder results in an increased slump flow and reduces the viscosity of the UHPC. Microstructural analysis indicated that expanded perlite exhibits a pozzolanic activity and promotes the early hydration process.

Aggregates

Generally, coarse aggregates are not used in UHPC, in order to produce a denser microstructure. Fine river sand, quartz sand, recycled glass powder, artificial aggregates, crushed basalt, marine clay, steel slag and Aeolian sand are mostly used in investigations.

In most of the studies, two types of river sand from 0 to 0.6 mm and 0.6 to 1.25 mm were utilized as fine aggregates [74, 78, 79]. Shi et al. [80] used quartz sand of three types, which were coarser particles with 0.4–0.8 mm, average particles with 0.18–0.8 mm and small sand with 0.1 to 0.18 mm. Refined quartz with a size lower than 0.6 mm was mostly used in various studies. Very fine quartz sand from 0.1 mm to 50 μm was also used by some researchers [70]. Alharbi et al. [76] used quartz sand of size ranging from 150 to 600 μm as fine aggregates in their research.

Amin et al. [72] used recycled coarse aggregates of 4.75 to 19 mm and concluded better results. Crushed granite of 6 mm diameter was also used in some studies [81]. Dixit et al. [82] used marine clay and quartz as an aggregate in the investigation. Reduction in compressive strength was noticed in his work; however, addition of biochar compensates the degradation in strength due to the usage of marine clay. Li et al. [83] used coarse basalt aggregates with a maximal size of 8 and 16 mm for the analysis. Reduction in strength properties was observed high if the size of basalt aggregates was increased. Jankovic et al. [84] stated that the combination of quartz and barite aggregates at 50:50 will produce better results than the concrete made only with quartz sand or barite aggregates.

Jiao et al. [85] evaluated the effective utilization of glass sand as aggregates in UHPC. The results concluded that the glass sand when replaced with quartz sand up to 75% results in improved compressive strength; however, there is no significant effect on split tensile and flexural strength. The usage of waste glass as aggregates in concrete might also reduce the environmental pollution due to landfill. It also increases the workability and the rheological properties. Chu et al. [86] address the possibility of utilizing Aeolian sand in UHPC. The findings noted that the UHPC with Aeolian sand produces around 163.9 MPa, 18 MPa and 49.3 MPa of compressive strength, flexural strength and young's modulus, respectively. This suggests that the Aeolian sand can also be used in UHPC as a fine aggregate.

Superplasticizers in UHPC

Water plays a major role in concrete by initiating a reaction when it is added to cement. It also establishes bonds and reduces the abrasion between the cement, aggregates and the admixtures. It is also responsible for the process of hydration which generates the hardening process of the concrete to form structures for various utilizations. Water is also responsible for the fluidity in the concrete, which makes the concrete easy to mix with less abrasion in the machines and mould into different shapes. However, excessive usage of water in concrete may reduce the performance of the concrete and increase the chances of bleeding, drying shrinkage, loss of abrasive resistance, permeability, dusting and scaling. In the case of UHPC, developing an exceptionally dense interfacial transition zone with less porosity and voids is required, which leads to the diminished usage of water in UHPC. The low water-cement ratio in the range of around 0.20 has made superplasticizers a major typical constituent at UHPC to improve the workability and to minimize the negative effects due to the excessive usage of water. In most of the studies superplasticizers were used in the range of 0.5 to 2.0% by the weight of the total cement; however, the usage of superplasticizers depends on various materials and requirements in UHPC. Polycarboxylic-based superplasticizers were the most commonly used superplasticizer in various studies. The dispersing ability of the superplasticizers was mainly dependent on the chemical structure and absorption ability of the particles in UHPC [87]. Schrofl et al. [88] demonstrate that allylethal-based polycarboxylic ether (PCE) sample preferably absorbs on silica fume whereas methacrylic acid-based PCE sample strongly interacts with the surfaces of the hydrating cement. Due to the different particulate matter, different surfaces occur, which provides anchoring sites for the superplasticizers. The type of surface which provides the best match with the molecular configuration of the PCE will attract more PCE than others. Hence, blends of chemically different polycarboxylates exhibit more performance than individual polycarboxylates. Superplasticizers also have some disadvantages, which should be considered during the construction. The usage of superplasticizers will certainly add some additional costs to the concrete. They might also tend to make the concrete mix stickier, which may create a problem while finishing the concrete. The slump loss and air entrainment will also be higher in the concrete with superplasticizer than the conventional concrete and hence optimum usage of Superplasticizer is also necessary.

Mix procedure

A mix of UHPC should be done by considering the requirements of the UHPC like workability and strength. As of now, UHPC does not have any framed guidelines for mix procedure. In some studies, mix proportions were made using the experimental trial and error method because of no standard procedure. Ozersky et al. [89] suggested a mixing process where all the dry components are dispersed and uniformly distributed within the mixture succeeded by the inclusion of water and chemical additives. The altered Andreasen and Andersen model equation which might be used to design the UHPC is shown as follows:

$$\mathrm{p}(\mathrm{D_i}) = \mathrm{D_i}^{\mathrm{q}} - \mathrm{D^q}_{\mathrm{min}}/\mathrm{D^q}_{\mathrm{max}} - \mathrm{D^q}_{\mathrm{min}}$$

where $P(Di)$ is the fraction of the total solids being smaller in size than Di, Di is the size of the particle (μm), D_{max} is the maximum size of particles (μm), D_{min} is the minimum size of particles (μm) and q is the distribution modulus [90].

Hunger et al. [91] recommend a q value of 0.22–0.25 and determine that it is a proportion between the finer and coarser particles. The proportions of each type of material in the mixture are done by an optimization algorithm, which was based on the least square method (LSM) to obtain a perfect fit within the created mixture and target curves as follows.

$$RSS = \sum_{i=1}^{n} \left(P_{mix}\left(\mathrm{D_i^{i+1}}\right) - P_{tar}\left(\mathrm{D_i^{i+1}}\right)\right)^2$$

where P_{mix} is the possessed mix, and P_{tar} is the target grading measured from the equation.

The mixture design technique can even be done using software such as Matlab, and then it can be verified by experiments. Yu et al. [90] created a close-packed and homogeneous skeleton of UHPC using the defined Andreasen and Andersen particle packing model with comparatively low binder content. The packing density can be increased by the reduction in the proportion of the little to massive particles. Most of the empirical findings conclude that the real filling response of RPC was relatively effective with low water-cement ratio only.

Curing techniques

It is clearly known by various studies that the properties of concrete were also based on the temperature, duration of curing and the techniques used for curing. Autoclave curing produces the ultimate strength followed by warm curing, curing by heated water, curing by hot air and standard curing. The following sections briefly discuss the curing techniques used in UHPC.

Standard room curing

This is the usual and inexpensive process which is very practical to use; however, researchers suggest that when the curing was at room temperature, the pozzolanic activity was weak. The compressive property of the UHPC may even go higher up to 200 MPa if there is a prolonged curing age [6].

Heat curing

It has been reported in studies that a 15–30-MPa compressive strength might be further attained at 24 h, when compared to the 28-day strength test at standard room temperature curing [6]. The temperature of steam curing in several literature studies varies up to 90 °C, and the duration of the steam curing varies from 12 h to 7 days. The best strength was achieved with the steam curing at 90 °C for 12 days, as compared to normal room temperature curing [7]. The increase in curing temperature can influence the microstructure and the chemical reactions of the mineral admixtures used in UHPC.

Autoclave curing

Autoclave curing was mostly applied from 8 to 24 h, which produces results superior to both standard and steam curing. An 8-h autoclave curing of UHPC with fibres can increase the compressive strength up to 200 MPa [8]. The compressive and flexural strength of the UHPC with mineral admixtures were reported as higher even in a time limit of 8 h and 3 h of curing with high-pressure steam at a temperature of 210 °C, when compared to the standard room temperature curing [7]. Shrinkage and creep of the UHPC were also influenced by the curing regimes. With the accelerated rate of early hydration at enhanced temperatures, autogenous shrinkage occurs up to 87% during the thermal treatment [9]. Autoclave curing produces higher strength properties than other types of curing; however, there is a limitation on its application during practice due to the difficulty in operation and high energy consumption of autoclave curing [10].

Applications of the UHPC

UHPC has various applications in the field of the construction industry like blast and impact load-resistant structures, radiation shielding structures, dams, bridges, multi-storeyed buildings, prefabricated structures, marine structures, treatment plants, seismic-resistant structures and prefabricated structures.

Blast-resistant concrete

Xu et al. [12] tested concrete beams of ultra high-performance concrete reinforced with fibres in a series of explosion tests. From each of the specimens, reflected overpressures and deflections at the column in the centre and near the supports were among the data acquired. The results of the study revealed that fibre-reinforced UHPC columns exhibited an outstanding performance, when subjected to blast load resistance. The results also showed that $CaCO_3$ particles could improve the material's performance. UHPC with the reinforcement of fibres and $CaCO_3$ can effectively resist overpressure and shockwaves due to the high explosives than other concrete.

Aoude et al. [13] present an analysis of the performance of ultra high-performance fibre-reinforced concrete under blast loads. The specimens were evaluated under stimulated blast loading and a variety of blast pressure combinations by using shock tubes. The findings show that the fibre characteristics, content, seismic details and longitudinal reinforcement ratio are all key aspects that can affect the blast-resistant performance and breakdown of UHPC columns. Up to 4% fibre content in concrete increases blast performance and the capacity to maintain high blast pressure before failure. The use of fibres with optimal qualities, such as enhanced aspect ratio and tensile strength, improves the UHPC's blast performance. The usage of fibre-reinforced UHPC with 15-M bars prevents the tension steel from rupturing. The fibre-reinforced UHPC with seismic detailing improves blast performance by reducing displacement at an equivalent blast pressure and allowing for higher blast pressures to be sustained.

Li et al. [92, 93] have done an investigation into the response of a set of reinforced concrete slabs to explosive loading conditions. The explosive charges were tested at scaled distances, and the UHPC slabs were found to be effective against blast load in tests. To replicate the field blast testing on UHPC slabs, numerical models were created in LS-DYNA. The field test results and numerical results were compared, demonstrating the possibility and validity of numerical forecasts in the UHPC slab reactions. It was also found that 70% of the loading capability was retained after a TNT detonation of 35 kg at a standoff distance of 1.5 m in a UHPC column reinforced with 2.5% nanocalcium carbonate and with the reinforcement of micro-steel fibres. With advancements in nanotechnology, steel fibre-reinforced concrete can be re-engineered through nanoscale particle addition. According to the findings of field tests and numerical calculations, the UHPC material with nanoadditions has a strong blast load-resisting capacity.

Yi et al. [94] conducted an experiment to see if ultra high-strength concrete (UHSC) and reactive powder concrete (RPC) might be used in concrete structures that are vulnerable to accidental impacts. The blast damage and failure modes of reinforced panel specimens were recorded. The results reveal that UHSC and RPC are much more resistant to blast explosions than conventional strength concrete, which might be due to the presence of rebar and steel fibres, which offer enough ductility, energy absorption capability and crack control to the UHSE and RPC.

The dynamic increase factor (DIF) of both flexural and shear high-speed loading of ultra high-performance fibre-reinforced blast-resistant concrete was examined by Millard et al. [95]. The findings demonstrate that at high loading rates, no DIF should be utilized for boosting shear strength. With the usage of 6.0% hybrid steel fibres, the highest static flexural tensile strength and quasistatic shear strength were achieved. The dynamic increase factor was recorded as lowest, when using the combination of hybrid long and short steel fibres. Studies also revealed that, when the fibre percentage grows from 0 to 6%, the strain rate for the flexural strength of UHPC decreases. By establishing a bridging effect on the low-strength locations, the fibres in the UHPC restrict the lateral growth of microcracks.

Impact-resistant concrete

Cao et al. [14] used repeated low-velocity drop load impacts to study the dynamic resistance of layered UHPC with fibres. The outcome indicates that a superior resistant capacity was achieved at double-layered fibre-reinforced UHPC, when compared to its single-layered counterpart. Double-layered beams absorbed more impact force because of the improved fibre utilization efficiency. With the usage of hooked-end steel fibres and hybrid fibres on both one- and two-layered UHPC, which improves the peak response force and resistance to impact, the impact energy in the double-layered beam was up to 28% more than in the similar single-layered UHPC with the same quantity of steel fibres. Liu et al. [96] experimentally examined the UHPC with 3% ultra-high-molecular-weight polyethylene (UHMWPE) fibres and 3% by volume of steel fibres for their impact responses. UHPC reinforced with fibres outperformed plain concrete without fibres in terms of DOP, crater diameter, volume loss, tensile strength, toughness and bridging effect. Steel fibre-reinforced UHPC provides superior results than the UHPC reinforced with UHMWPE fibres.

Li et al. [46] analysed the flexural responses of a hybrid steel-polyethylene fibre-reinforced ultra high-performance concrete. Results indicate that, there was an enhancement in the limit of proportionality, modulus of rupture and toughness index at UHPC due to the combination of hybrid polyethylene (PE) and steel fibres. The best flexural performance and toughness were shown in the UHPC with 0.5% of polyethylene fibres by volume and the steel fibres of 2.0% by volume in the study. The flexural performance of PE-steel hybrid fibre-reinforced UHPC was drastically degraded due to exposure to extreme temperatures. Figure 24 explains the toughness of concrete reinforced with polyethylene and steel fibres at different proportions, when subjected to varying temperatures.

Wei et al. [97] explored hybrid fibre-reinforced UHPC to enhance its performance, particularly its crack restraint capability and flexural property. The test results revealed that all the specimens suffered minor damage as a result of the flexural reaction. UHPC beams reinforced with hybrid fibres outperform single long fibre reinforcement in terms of impact resistance. A mixture of hybrid long and medium fibres has a residual displacement which was 16.08% and 23.95% below that of long fibre reinforcement alone. Improved flexural strength, fracture energy and impact resistance were observed with

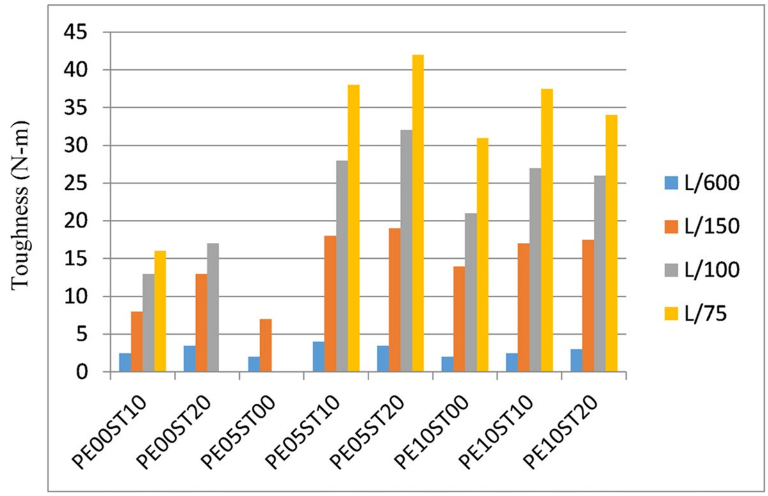


Fig. 24 Toughness of UHPC with polyethylene and steel fibres at various proportions in different deflections [46]

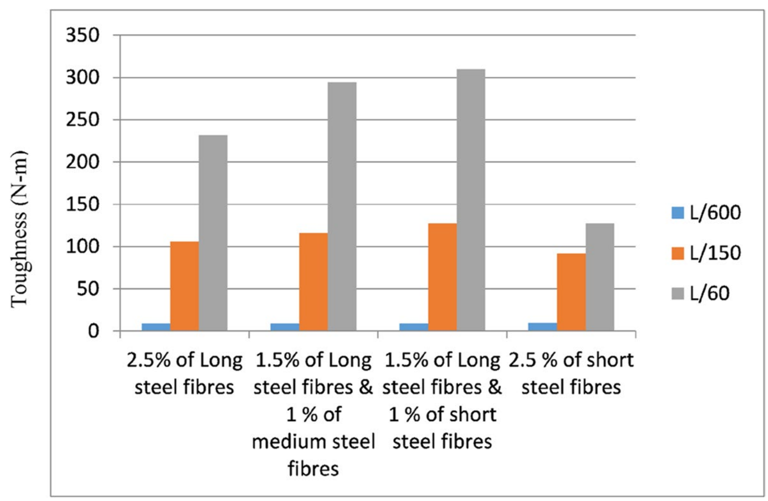


Fig. 25 Toughness of hybrid fibre-reinforced UHPC [97]

steel fibres of long and short sizes at a percentage of 1.5 and 1, when compared to the other proportions of fibres. UHPC reinforced with long steel fibres of 1.5% and medium steel fibres of 1% gives the maximum toughness as discussed in the Fig. 25.

Yu et al. [98] deal with the green UHPHFRC for their static and impact-resistant properties. It was reported that, with the usage of an enhanced packing model, UHPHFRC with comparably less binder amount can be generated, making the concrete more eco-friendly. The interaction with long and short steel fibres results in improved workability, increased static mechanical performance and resistance to impact. Though long steel fibres dominate in terms of resistance to impact, a combination of steel fibres of long size at 1.5 percentage and steel fibres of short size at 0.5 percentage results in the best overall performance. The principle behind the enhanced impact resistance is the bridging ability of the short steel fibres for microcracks and the long steel fibres for macrocracks.

The hooked-end medium steel fibres in combination with long steel fibres also improve the energy dissipation capacity of UHPHFRC than conventional concrete or the UHPC reinforced with single fibres [99]. Lee et al. [100] examined the static and dynamic flexural performance of ultra high-performance fibre-reinforced concrete and concluded that with the inclusion of steel fibres and stirrups, an enhancement in the static and resistance to impact for the fibre-reinforced UHPC beams in terms of greater load withstanding capacity, higher energy dissipation capacity and lower maximum and residual displacements as discussed in Fig. 26 was noticed. Brittle shear failure was seen on specimens without steel fibres and stirrups under static and impact loading conditions.

Li et al. [99] investigated the impact performance of UHPC with three types of steel fibres and coarse aggregates. The results concluded that fibre-reinforced UHPC with coarse aggregates has somewhat lower mechanical strength than fibre-reinforced UHPC with only fine aggregates; however, lesser cement was utilized. Because of the reduction in flexural toughness and impact resistance, coarse aggregate sizes should not exceed 25 mm, and steel fibre lengths should not be more than 2 to 5 times the size of the maximum aggregate. By observing the flexural and impact properties, it was assured that the medium and long steel fibres contribute excellent properties than short ones. The medium fibres are more compatible with fine aggregate and the long fibres with coarse aggregate produce a more harmonious response on flexural and impact properties. The hooked-end steel fibres of 30 mm achieved the best flexural, tensile and impact performance followed by 60-mm-long 5D fibre and 13-mm short steel fibres; however, short fibres due to their homogeneous mix in UHPC produce a good performance on compressive strength.

Rong et al. [101] investigated UHPC with waste residues like fly ash, silica fume and slag as a substitution for a large quantity of cement and by substituting ground fine quartz sand instead of river sand with different steel fibre quantity fraction. The results concluded that, with the improvement of steel fibre quantity, the impact resistance of

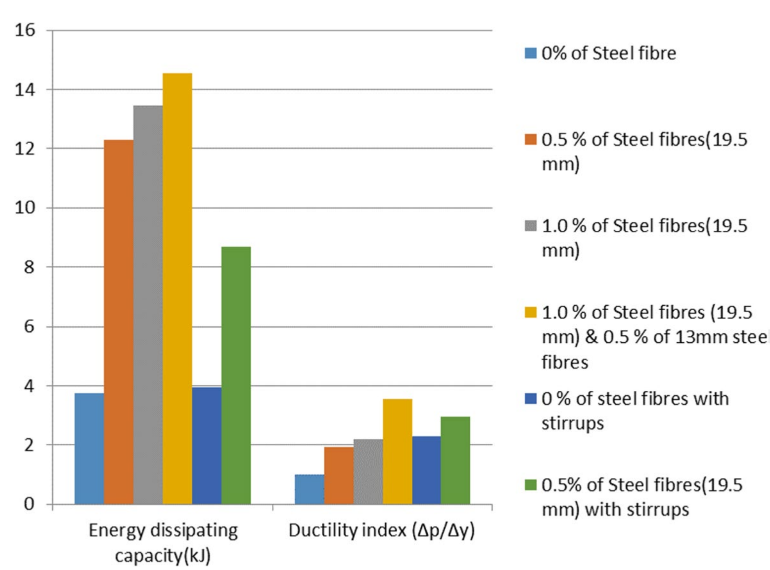


Fig. 26 Energy dissipation capacity and ductility index of UHPC with fibres [100]

concrete was improved. Four per cent of steel fibre performs the best with enhanced impact resistance, dynamic compression behaviour and toughness. According to ACI recommendations, Liu et al. [102] used a hammer of 10 kg to evaluate the drop load impact resistance of the UHPC. The researchers created 40 cylindrical specimens of three different mixture types: conventional concrete, nonfibrous UHPC matrix and UHPC-containing fibres. Under impact loads, UHPC without fibres failed at a lower rate than regular concrete with coarse particles. The test results concluded that the steel fibres with 2% by volume produce a first crack impact resistance which is 23 times and 36 times greater than the conventional concrete and the UHPC without fibres. The reason for the greater resistance to impact in the conventional concrete with coarse aggregates, when compared to the UHPC without fibres is the coarse aggregates in conventional concrete will create a torturous path for the crack to move around the aggregate to the weaker portion. The UHPC with fibres reached triple the quantity of loading drops than the number of initial crack drops, which shows the ductile behaviour of the UHPC with fibres; however, the post-crack impact response is negligible in the case of conventional and the non-fibrous UHPC due to only two or three drops to complete failure from the initial crack. Steel fibres also improve the quasi-static tensile properties, post-peak ductility and dynamic flexural strength when it was improved from 1.0 to 3.0% by volume [103].

Liu et al. [96] target the usage of ultra-high molecular polyethylene fibres and steel fibres at UHPC. It was concluded that the steel fibres by volume of 3% perform well in compressive, flexural, toughness, absorption of energy capacity and resistance to impact than the concrete reinforced with ultra-high molecular polyethylene fibres. Jabir et al. [104] explored the capability of UHPC reinforced with fibres against impact performance by drop mass impact test with three types of fibres at a volumetric content of 2.5%. According to the findings of the tests, 15-mm micro-steel fibres at 2.5% produced the strongest impact resistance, followed by a combination of 2.0% of 15-mm steel fibres with 0.5% of polypropylene fibres as shown in Fig. 27. In the hybrid usage of 6-mm steel fibres and 15-mm steel fibres at a quantity of 1.25% each obtained, the maximum

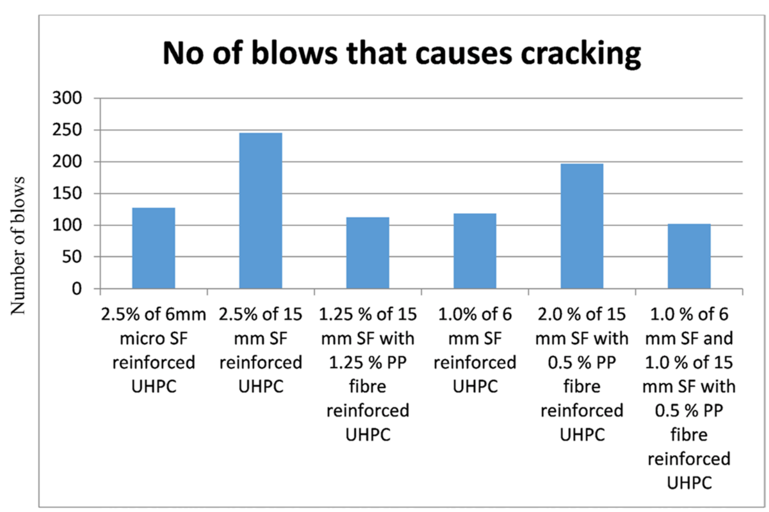


Fig. 27 Impact-resistant performance of the fibre-reinforced UHPC [104]

compressive strength than the 15-mm steel fibres and the hybrid fibres with polypropylene and micro steel fibres. The highest split tensile strength was obtained at 2.0% of 15-mm steel fibres, when combined with 0.5% polypropylene fibres.

Li et al. [105] develop an UHPC, which was functionally graded by implementing the composite concepts. The composite beam, which was functionally graded has a lower layer with slurry-infiltrated fibrous concrete and a top layer with conventional concrete in two stages. The bottom layer consists of steel fibres, and the top two layers are filled with coarse aggregates as seen in Fig. 28. Gravity pressure was employed to cast inject UHPC slurry into the voids. The results show that FGCB has better flexural characteristics and impact resistance than the other materials. The maximum efficiency was achieved by using 3% of 30-mm hooked-end steel fibres. An excellent interfacial bond, lesser cement consumption, huge efficiency in the usage of steel fibre, flexural bearing capacity and an excellent impact resistance were achieved by the anchorage effect of hooked-end shape in steel fibres, preplaced stiff skeleton of the steel fibres and coarse aggregates with less shrinkage.

Su et al. [106] developed a UHPC with nanomaterial additions, due to the advancements in nanotechnology, and it was discovered that the strength improves as strain rates and nanomaterial dosage increase in UHPC. Nanotitanium dioxide has the highest dynamic compressive strength at 3% by volume, whereas nanocalcium carbonate has the highest dynamic tensile strength at 3% by volume. Wei et al. [15, 107] proposed three designs to enhance the impact-resistant performance of the UHPC. A reinforced concrete (RC) beam with layers of UHPC retrofitted on the tension sides, on both the

Fig. 28 Cross-section of the FGCB with layers [105]

compression and tension sides, the UHPC layers attached with a gap of 5 mm between the interfaces and are not directly to the tension surface are the three designs. The results concluded that the UHPC layers with nano-addition and steel fibre-reinforced beams produce a better impact performance. The impact resistance was also significantly increased if the spacing is not more than 5 mm between the RC beam and the UHPC layer, and more than 10 mm spacing is not advised between the reinforced concrete beam and the UHPC layer. A better impact resistance can also be achieved if the thickness of the UHPC layer was increased. Wei et al. [15] performed a dynamic analysis on the UHPC loaded axially and ordinary concrete against the impact loading with low velocity. The specimens were casted in square and circular cross-sections. Brittle failure and shear plug development were detected in the RC columns, while flexure response and minimum damage were found in the UHPC columns at severe impact loads. Nanoparticles used in the study produce a nanoscale filling and a pozzolanic effect. The results concluded that the reinforced UHPC columns with steel fibres and nanoparticles show the highest impact resistance. In the impact scenario, a minimal flexural damage was noticed in the square and circular columns made by UHPC, whereas a brittle shear failure was experienced in the case of RC columns.

Othman et al. [108] investigated six doubly reinforced concrete plates with uniform top and bottom orthogonal steel reinforcement mats. All plates were reinforced longitudinally with 10-mm CSA standard deformed steel bars of grade 400. In comparison with high-strength concrete (HSC), UHPC with fibres has a stronger compressive and tensile response. Improvement in post-peak ductility was noticed by the rise in the quantity of short steel fibres. The concluded results indicate that the UlHPC with fibre-reinforced concrete plates produces better damage-resistant characteristics in comparison with the high-strength concrete. Steel fibres at an optimum of 3% in the same impact loads increase the ability to withstand impact load before failure. It also increases dynamic performance with lower peak and residual displacements even when the impact loads are the same. No spalling, scrabbing and significant large fragmentations were observed. The largest cumulative residual displacement of 65 mm with only bending cracks and significant punching shear cracks were observed under all ultra high-performance fibre-reinforced concrete plates at repeated impact forces, regardless of the fibre volume dosage.

Smith-Gillis et al. [109] attempted to revamp the flexural and impact performance by the external reinforcement, which was applied in two different ways. The first was one-directional E-glass fibre-reinforced (PETG) tapes that are organized in layers and thermoformed to the panels made with UHPC, and the next was E-glass fibre woven fabrics that are bonded by methyl methacrylate with vacuum diffusion and are positioned on the panel faces. The results concluded a 150 to 180% improvement in peak load capacity and toughness for both thermoplastic composite reinforcements. Continuous fibre-reinforced thermoplastic composite (CFRTP) additions reduced both the residual deformation by 60% and the change in specimen compliance by up to 80 to 95%, which indicates an enhancement in damage resistance. The thermoforming method can be more preferred due to its simplicity, though both the reinforcement fabrication techniques provide good performance. The results suggest that a better characterization with an appropriate material model of the concrete and CFRTP bond is required, which grant us to fine-tune both CFTRP fibre layups and processing parameters for even better resistance in further development.

Radiation shielding concrete

Rashid et al. [16] investigated the UHPC's radiation shielding capabilities after being exposed to high temperatures. Both types of UHPC examined exhibited a 76–82% improvement in the half-value layer and tenth-value layer that was attributable to the significant spalling and cracking involved. The results conclude that for radiation shielding, magnetite was slightly better than silica sand and the utilization of steel and polyvinyl alcohol fibres reduces the Excessive spalling. Khalaf et al. [110] conducted an experiment with eight concrete proportions that were created with an aggregate of steel furnace slag as the essential aggregate and a nanosilica slurry of 3% in blend with (0–3%) nanocalcium carbonate as additive materials. The mechanical analysis, fluid transport and C-ray shielding capabilities of hardened concrete samples were assessed. With the impact of 3% nanosilica and 2.0% nanocalcium carbonate, the compressive and gamma-ray defending capabilities of conventional concrete were improved by 10.3% and 3.4%, respectively. The concrete's other mechanical and fluid transport qualities were also greatly improved. The results also concluded that there was an enhancement in the mechanical performance and C-ray defending potentiality of the concrete due to the utilization of nanomaterials in the concrete.

Gokce et al. [111] investigated the reactive powder concrete (RPC) on their gamma ray and neutron mitigation, when the standard aggregates were supplemented with heavy weight aggregate barite. The optimal RPC mix for concurrently defending against neutrons and gamma rays was discovered to comprise 40% barite aggregates of total aggregate volume in combination with 60% quartz sand. As the study object, Azreen et al. [112] chose steel fibre-reinforced UHPC specimens with various inert components, such as silica sand, amang and lead glass, which were evaluated experimentally. Even though it was adequate as a gamma ray shield, UHPC with lead glass lost compression strength with time, while UHPC with amang caused a problem with radiological safety. Because of the availability and cost-effectiveness of the material, the usage of UHPC with silica sand is furthermore practicable for the erection of nuclear plants.

Khan et al. [113] investigated heavy-weight ultra high-performance concrete (HWUHPC) by substituting sand instead of haematite powder with ultrafine particles, which was heavier than sand roughly two times. The dry density of HWUHPC mixes ranges between 2600 and 2900 kg/m^3, meeting the criteria for a minimum dry density to be classified in the heavy-weight category. Despite the fact that the HWUHPC combinations had various densities, the mechanical characteristics did not change appreciably and indicated no damaging consequences owing to the substitution of sand. Due to the enhancement in the dry density of HWUHPC, an increase in radiation shielding capability was noticed. The radiation shielding in the HWUHPC was reported to be 40% greater than that of ordinary concrete with the equivalent dry density, demonstrating that the density of the microstructure, in addition to the density of concrete, increases the radiation shielding.

Jankovic et al. [84] evaluated the usage of nanosilica as a substitution for cement (2% or 5%) and the aggregates in the combination of 50:50 by volume of quartz and barite on the study of UHPC. The radiation shielding capabilities of UHPC were further improved by combining nanosilica, barite and quartz aggregate as a composite with better pore size distribution, which further improves the potential usage of UHPC in hospitals and nuclear facilities.

Conclusions

A detailed study on UHPC and its effects on fibres, nanomaterials and the supplementary cementitious components were made. The utilization of the UHPC in the construction industry with various techniques, which were used to improve further the properties according to the requirements, was also investigated. Based on the previous works, the following conclusions were made.

The usage of fibres in UHPC clearly enhanced the strength properties especially the tensile and flexural strength. The UHPC with fibre reinforcement also improves the property of energy dissipation, which further increases the impact resistance and exhibited a better residual performance after impact damage. Based on the various reviews, hooked-end steel fibre produces the best bonding and anchorage effect than the other types of steel fibres due to its shape.

The hybrid usage of fibres provided a greater performance than the single usage of fibres. The combination of various fibres with different properties may create a concrete with enhanced properties. The combined usage of high-modulus fibres like steel and low-modulus fibres like basalt produces an outstanding impact resistance in many studies. The usage of long and short steel fibres also helps in the bridging effect of micro and macro cracks at many investigations.

Nanomaterials aid in providing reinforcement at a nanoscale filling effect by the densification of concrete. It also helps in upgrading the strength and durability performance of the concrete with a reduction in porosity and permeability. It also interacts with the cement particles and creates a nucleation effect to improve the C-S–H gel formation.

The various supplementary cementitious materials used in UHPC mostly improve the properties of the concrete up to some extent and aid in the reduction of the usage of cement at the UHPC, thereby assisting in producing a sustainable concrete without compromising on their properties.

UHPC with the usage of fibres, nanomaterials and some limited supplementary cementitious materials improves the blast load resistance, impact load resistance and the radiation shielding capability of the concrete structures. Spalling or crushing was not noticed, and the ultimate deflection was also recorded less in the UHPC with fibres and nanomaterials.

Scope for future work

As UHPC is a recently developed material, it still lacks proper mix procedure and framed rules; hence, framing a proper mix procedure with various special materials is essential. Detailed research on the utilization of nanomaterials, fibres, aggregates and the alternative cementitious materials in the UHPC is required to lower the usage of cement and sand and to amplify the properties of UHPC.

The fibres mostly used in UHPC are of various types of steel fibres; however, studies related to the usage of hybrid fibre reinforcement and other types of fibres like glass, polymer, carbon and natural fibres are very less and the improvement of the UHPC with the various types of fibres and hybrid fibres can also be investigated. In-depth research on UHPC related to their improvement of impact, radiation shielding and durability properties can also be done as the UHPC has a very good performance in all aspects.

The investigations related to the usage of discarded or waste steel, polypropylene and plastic fibres in UHPC are mostly unavailable, and hence, the usage of waste fibres on UHPC should be investigated more to lessen the environmental pollution and initial expense of the structure. Studies on the ultra high-performance concrete with steel mesh, glass mesh, rubber mesh and carbon fibre-reinforced polymer mesh in layered concrete is also very limited; however, the usage of various types of mesh and layered concrete might increase the properties of the UHPC. Limited investigations are only available on wrapping with various types of external sheets like steel and glass with epoxy resin on UHPC; hence, investigations on UHPC with different meshes, layered concrete and external sheeting might also be done.

Limitations

As with the majority of the studies, there might be some possible limitations to be considered as follows:

- Mix proportioning of the UHPC with various special materials is a big question because of the limited design codes and no standard procedure.
- The initial cost of manufacturing the UHPC might be costlier because of the special constituent materials used for the performance enhancement in the UHPC.
- Skilled workmanship and quality control are required as the manufacturing of the UHPC is complicated and requires special attention.

Abbreviations

UHPC	Ultra high-performance concrete
RTSC	Recycled tyre steel cords
EDTA	Ethylene diamine tetra acetic acid
GFRP	Glass fibre-reinforced polymer
C-S-H	Calcium silicate hydrate
HES	Hooked end steel
MPP	Macro-polypropylene fibre
CNT	Carbon nanotube
CNF	Carbon nanofibre
GNP	Graphene nanoplatelets
GGBFS	Ground granulated blast furnace slag
PCE	Polycarboxylic ether
UHMWPE	Ultra high-molecular-weight polyethylene
UHPHFRC	Ultra high-performance hybrid fibre-reinforced concrete
FGCB	Functionally graded composite beam
RPC	Reactive powder concrete
HWUHPC	Heavy weight ultra high-performance concrete

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Authors' contributions
Conceptualization, methodology, formal analysis, investigation and original draft preparation—V. Anish. Supervision, review and editing—J. Logeshwari.

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Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Valcuende M, Lliso-Ferrando JR, Ramón-Zamora JE, Soto J (2021) Corrosion resistance of ultra-high performance fibre-reinforced concrete. Constr Build Mater 306:1–10. https://doi.org/10.1016/j.conbuildmat.2021
2. Li J, Zemei Wu, Shi C, Yuan Q, Zhang Z (2020) Durability of ultra-high performance concrete – a review. Constr Build Mater 255:119296. https://doi.org/10.1016/j.conbuildmat.2020.119296
3. Abbas S, Soliman AM, Nehdi ML (2015) Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fibre lengths and dosages. Constr Build Mater 75:429–441. https://doi.org/10.1016/j.conbuildmat.2014.11.017
4. Serag Faried A, Mostafa SA, Tayeh BA, Tawfik TA (2021) Mechanical and durability properties of ultra-high performance concrete incorporated with various nano waste materials under different curing conditions. J Build Eng 43:102569. https://doi.org/10.1016/j.jobe.2021.102569
5. Sritharan S (2015) Design of UHPC structural members: lessons learned and ASTM test requirements. Adv Civil Eng Mater 4(2):113–131
6. Yunsheng Z, Wei S, Sifeng L, Chujie J, Jianzhong L (2008) Preparation of C200 green reactive powder concrete and its static–dynamic behaviours. Cement Concr Compos 30(9):831–838. https://doi.org/10.1016/j.cemconcomp.2008.06.008
7. Yazici H (2007) The effect of curing conditions on compressive strength of ultra high strength concrete with high volume mineral admixtures. Build Environ 42(5):2083–2089. https://doi.org/10.1016/j.buildenv.2006.03.013
8. Yang SL, Millard SG, Soutsos MN, Barnett SJ, Le TT (2009) Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC). Constr Build Mater 23(6):2291–2298. https://doi.org/10.1016/j.conbuildmat.2008.11.012
9. Yanni VYG (2009) Multi-scale investigation of tensile creep of ultra-high performance concrete for bridge applications. Dissertation, Georgia Institute of Technology
10. Shi C, Wu Z, Xiao J, Wang D, Huang Z, Fang Z (2015) A review on ultra high performance concrete: part I. Raw materials and mixture design. Constr Build Mater 101(part 1):741–751. https://doi.org/10.1016/j.conbuildmat.2015.10.088
11. Ramezani M, Dehghani A, Sherif MM (2022) Carbon nanotube reinforced cementitious composites: a comprehensive review. Constr Build Mater 2022:315. https://doi.org/10.1016/j.conbuildmat.2021:125100
12. Juechun Xu, Chengqing Wu, Hengbo Xiang YuSu, Li Z-X, Fang Q, Hao H, Liu Z, Zhang Y, Li J (2016) Behaviour of ultra high performance fibre reinforced concrete columns subjected to blast loading. Eng Struct 118:97–107. https://doi.org/10.1016/j.engstruct.2016.03.048
13. Aoude H, Dagenais FP, Burrell RP, Saatcioglu M (2015) Behaviour of ultra-high performance fibre reinforced concrete columns under blast loading. Int J Impact Eng 80:185–202. https://doi.org/10.1016/j.ijimpeng.2015.02.006
14. Cao YYY, Liu G, Brouwers HJH, Qingliang Yu (2020) Enhancing the low-velocity impact resistance of ultra-high performance concrete by an optimized layered-structure concept. Compos B Eng 200:108221. https://doi.org/10.1016/j.compositesb.2020.108221
15. Wei J, Li J, Chengqing Wu (2019) An experimental and numerical study of reinforced conventional concrete and ultra-high performance concrete columns under lateral impact loads. Eng Struct 201:109822. https://doi.org/10.1016/j.engstruct.2019.109822
16. Rashid RSM, Mohammed Salem S, Azreen NM, Voo YL, Haniza M, Shukri AA, Yahya M-S (2020) Effect of elevated temperature to radiation shielding of ultra-high performance concrete with silica sand or magnetite. Constr Build Mater 262:120567. https://doi.org/10.1016/j.conbuildmat.2020.120567
17. Ye Y-Y, Smith ST, Zeng J-J, Zhuge Y, Quach W-M (2021) Novel ultra-high-performance concrete composite plates reinforced with FRP grid: development and mechanical behaviour. Compos Struct 269:114033. https://doi.org/10.1016/j.compstruct.2021.114033
18. Liang X, Chengqing Wu, Yang Y, Cheng Wu, Li Z (2019) Coupled effect of temperature and impact loading on tensile strength of ultra-high performance fibre reinforced concrete. Compos Struct 229:1–9. https://doi.org/10.1016/j.compstruct.2019
19. Yoo DY, You I, Zi G (2021) Effects of waste liquid–crystal display glass powder and fibre geometry on the mechanical properties of ultra-high-performance concrete. Constr Build Mater 266 (Part B). https://doi.org/10.1016/j.conbuildmat.2020.120938

20. M.N. Isa, Kypros Pilakoutas, Maurizio Guadagnini, Harris Angelakopoulos (2020) Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. Constr Build Mater 255. https://doi.org/10.1016/j.conbuildmat.2020.119272
21. Ghasem Dehghani Ashkezari, Farzan Fotouhi, Mehrdad Razmara (2020) Experimental relationships between steel fibre volume fraction and mechanical properties of ultra-high performance fibre-reinforced concrete. J Build Eng 32. https://doi.org/10.1016/j.jobe.2020.101613
22. Oh T, You I, Banthia N, Yoo DY (2021) Deposition of nanosilica particles on fibre surface for improving interfacial bond and tensile performances of ultra-high-performance fibre-reinforced concrete. Compos Part B Eng 221. https://doi.org/10.1016/j.compositesb.2021.109030
23. Mohammed BH, Aryan FH, Sherwani RH, Faraj HH, Qadir KH, Younis, (2021) Mechanical properties and ductility behaviour of ultra-high performance fibre reinforced concretes: effect of low water-to-binder ratios and micro glass fibres. Ain Shams Eng J 12(2):1557–1567. https://doi.org/10.1016/j.asej.2020.11.008
24. Rigaud S, Chanvillard G, Chen J (2012) Characterization of bending and tensile behaviour of ultra-high performance concrete containing glass fibres. In: Parra-Montesinos GJ, Reinhardt HW, Naaman AE, editors. High performance fibre reinforced cement composites 6. RILEM State of the Art Reports. Springer 2. p. 373–380. https://doi.org/10.1007/978-94-007-2436-5_45
25. Meng W, Khayat KH, Bao Yi (2018) Flexural behaviours of fibre-reinforced polymer fabric reinforced ultra-high-performance concrete panels. Cement Concr Compos 93:43–53. https://doi.org/10.1016/j.cemconcomp.2018.06.012
26. Zhou Y, Huang J, Yang X, Dong Y, Feng T, Liu J (2021) Enhancing the PVA fibre-matrix interface properties in ultra-high performance concrete: an experimental and molecular dynamics study. Constr Build Mater 285. https://doi.org/10.1016/j.conbuildmat.2021.122862
27. Zhang D, Dasari A, Tan KH (2018) On the mechanism of prevention of explosive spalling in ultra-high performance concrete with polymer fibres. Cem Concr Res 113:169–177. https://doi.org/10.1016/j.conbuildmat.2021.122862
28. Alani AH, Muhamad Bunnori N, Noaman AT, Majid TA (2019) Durability performance of a novel ultra-high-performance PET green concrete (UHPPGC). Constr Build Mater 209:395–405. https://doi.org/10.1016/j.conbuildmat.2019.03.088
29. Yan P, Chen B, Afgan S, Haque MA, Wu M, Han J (2021) Experimental research on ductility enhancement of ultra-high performance concrete incorporation with basalt fibre, polypropylene fibre and glass fibre. Constr Build Mater 279. https://doi.org/10.1016/j.conbuildmat.2021.122489
30. Ríos JD, Cifuentes H, Leiva C, Ariza MP, Ortis M (2020) Effect of polypropylene fibres on the fracture behaviour of heated ultra-high performance concrete. Int J Fract 223:173–187. https://doi.org/10.3989/mc.2018.00717
31. Ke-Quan Yu, Jiang-Tao Yu, Dai J-G, Zhou-Dao Lu, Shah SP (2018) Development of ultra-high performance engineered cementitious composites using polyethylene (PE) fibres. Constr Build Mater 158:217–227. https://doi.org/10.1016/j.conbuildmat.2017.10.040
32. Zhang D, Tan KH (2020) Effect of various polymer fibres on spalling mitigation of ultra-high performance concrete at high temperature. Cem Concr Compos 114. https://doi.org/10.1016/j.cemconcomp.2020.103815
33. Ferrier E, Michel L, Zuber B, Chanvillard G (2015) Mechanical behaviour of ultra-high-performance short-fibre-reinforced concrete beams with internal fibre reinforced polymer bars. Compos B Eng 68:246–258. https://doi.org/10.1016/j.compositesb.2014.08.001
34. Tian H, Zhou Z, Zhang Yi, Wei Y (2020) Axial behaviour of reinforced concrete column with ultra-high performance concrete stay-in-place formwork. Eng Struct 210:1–13. https://doi.org/10.1016/j.engstruct.2020.110403
35. Yoo D-Y, Kang M-C, Choi H-J, Shin W, Kim S (2020) Influence of chemically treated carbon fibres on the electromagnetic shielding of ultra-high-performance fibre-reinforced concrete. Arch Civil Mech Eng 20(123):1–15. https://doi.org/10.1007/s43452-020-00117-y
36. Supit SWM, Nishiwaki T (2019) Compressive and flexural strength behaviour of ultra-high performance mortar reinforced with cellulose nano-fibres. Int J Adv Sci Eng Inf Technol 9(1):365–372. https://doi.org/10.18517/ijaseit.9.1.7506
37. Ma R, Guo L, Ye S, Sun W, Liu J (2019) Influence of hybrid fibre reinforcement on mechanical properties and autogenous shrinkage of an ecological UHPFRCC. J Mater Civil Eng 31(5). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002650
38. Hisseine OA, Soliman NA, Tolnai B, Tagnit-Hamou A (2020) Nano-engineered ultra-high performance concrete for controlled autogenous shrinkage using nanocellulose. Cem Concr Res 137. https://doi.org/10.1016/j.cemconres.2020.106217
39. Zhang D, Tan KH, Dasari A, Weng Y (2020) Effect of natural fibres on thermal spalling resistance of ultra-high performance concrete. Cem Concr Compos 109. https://doi.org/10.1016/j.cemconcomp.2020.103512
40. Ren G, Yao B, Huang H, Gao X (2021) Influence of sisal fibres on the mechanical performance of ultra-high performance concretes. Constr Build Mater 286. https://doi.org/10.1016/j.conbuildmat.2021.122958
41. Yu R, Van Beers L, Spiesz P, Brouwers HJH (2016) Impact resistance of a sustainable ultra-high performance fibre reinforced concrete (UHPFRC) under pendulum impact loadings. Constr Build Mater 107:203–215. https://doi.org/10.1016/j.conbuildmat.2015.12.157
42. Kamal MM, Safan MA, Etman ZA, Salama RA (2014) Behaviour and strength of beams cast with ultra high strength concrete containing different types of fibres. HBRC Journal 10(1):55–63. https://doi.org/10.1016/j.hbrcj.2013.09.008
43. Zhang D, Tan GY, Tan KH (2021) Combined effect of flax fibres and steel fibres on spalling resistance of ultra-high performance concrete at high temperature. Cem Concr Compos 121. https://doi.org/10.1016/j.cemconcomp.2021.104067
44. Li Ye, Pimienta P, Pinoteau N, Tan KH (2019) Effect of aggregate size and inclusion of polypropylene and steel fibres on explosive spalling and pore pressure in ultra-high-performance concrete (UHPC) at elevated temperature. Cement Concr Compos 99:62–71. https://doi.org/10.1016/j.cemconcomp.2019.02.016

45. Yan P, Chen B, Afgan S, Haque MA, Wu M, Han J (2021) Experimental research on ductility enhancement of ultra-high performance concrete incorporation with basalt fibre, polypropylene fibre and glass fibre. Constr Build Mater 279.https://doi.org/10.1016/j.conbuildmat2021.122489
46. Li Ye, Yang E-H, Tan KH (2020) Flexural behaviour of ultra-high performance hybrid fibre reinforced concrete at the ambient and elevated temperature. Constr Build Mater 250:118487. https://doi.org/10.1016/j.conbuildmat.2020.118487
47. Sbia LA, Peyvandi A, Soroushian P, Balachandra AM (2014) Optimization of ultra-high-performance concrete with nano- and micro-scale reinforcement. Cogent Eng 1(1). https://doi.org/10.1080/23311916.2014.990673
48. Feng J, Yin G, Tuo H, Wen C, Liu Z, Liang J, Zhang Y (2021) Uniaxial compressive behaviour of hook-end steel and macro-polypropylene hybrid fibres reinforced recycled aggregate concrete. Constr Build Mater 304:124559. https://doi.org/10.1016/j.conbuildmat.2021.124559
49. Liu C, He X, Deng X, Yuyou Wu, Zheng Z, Liu J, Hui D (2020) Application of nanomaterials in ultra high performance concrete: a review. Nanotechnol Rev 9(1):1427–1444. https://doi.org/10.1016/j.cemconres.2020.106017
50. Viana TM, Bacelar BA, Coelho ID, Ludvig P, Santos WJ (2020) Behaviour of ultra-high performance concretes incorporating carbon nanotubes under thermal load. Constr Build Mater 263:120556. https://doi.org/10.1016/j.conbuildmat.2020.120556
51. Sbia LA, Peyvandi A, Soroushian P, Jue Lu, Balachandra AM (2014) Enhancement of ultrahigh performance concrete material properties with carbon nanofibre. Adv Civil Eng 2014:1–10. https://doi.org/10.1155/2014/854729
52. Hongyan Chu Yu, Zhang FW, Feng T, Wang L, Wang D (2020) Effect of graphene oxide on mechanical properties and durability of ultra-high-performance concrete prepared from recycled sand. Nanomaterials 10(9):1718. https://doi.org/10.3390/nano10091718
53. Ho VD, Ng C-T, Coghlan CJ, Goodwin A, Guckin CM, Ozbakkaloglu T, Losic D (2020) Electrochemically produced graphene with ultra large particles enhances mechanical properties of Portland cement mortar. Constr Build Mater 234:117403. https://doi.org/10.1016/j.conbuildmat.2019.117403
54. Yu R, Spiesz P, Brouwers HJH (2014) Effect of nano-silica on the hydration and microstructure development of ultra-high performance concrete (UHPC) with a low binder amount. Constr Build Mater 65:140–150. https://doi.org/10.1016/j.conbuildmat.2014.04.063
55. Camiletti J, Soliman AM, Nehdi ML (2013) Effect of nano-calcium carbonate on early-age properties of ultra-high-performance concrete. Mag Concr Res 65(5):297–307. https://doi.org/10.1680/macr.12.00015
56. Zemei Wu, Caijun Shi KH, Khayat SW (2016) Effects of different nanomaterials on hardening and performance of ultra-high strength concrete (UHSC). Cement Concr Compos 70:24–34. https://doi.org/10.1016/j.cemconcomp.2016.03.003
57. Li W, Huang Z, Cao F, Sun Z, Shah SP (2015) Effects of nano-silica and nano-limestone on flowability and mechanical properties of ultra-high-performance concrete matrix. Constr Build Mater 95:366–374. https://doi.org/10.1016/j.conbuildmat.2015.05.137
58. Wengui Li MASCE, Huang Z, Tianyu Zu, Shi C, Duan WH, Shah SP, M.ASCE, (2016) Influence of nanolimestone on the hydration, mechanical strength and autogenous shrinkage of ultra high-performance concrete. J Mater Civ Eng 28(1):1–9. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001327
59. 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). Cem Concr Res 131:106017
60. Guo L, Jiandong Wu, Wang H (2020) Mechanical and perceptual characterization of ultra-high-performance cement-based composites with silane-treated graphene nano-platelets. Constr Build Mater 240:117926. https://doi.org/10.1016/j.conbuildmat.2019.117926
61. Lanzhen Yu, Rongxing Wu (2020) Using graphene oxide to improve the properties of ultra-high-performance concrete with fine recycled aggregate. Constr Build Mater 259:120657. https://doi.org/10.1016/j.conbuildmat.2020.120657
62. Sujay HM, Nair NA, Sudarsana Rao H, Sairam V (2020) Experimental study on durability characteristics of composite fibre reinforced high-performance concrete incorporating nanosilica and ultra fine fly ash. Constr Build Mater 262:120738. https://doi.org/10.1016/j.conbuildmat.2020.120738
63. Serag Faried A, Mostafa SA, Tayeh BA, Tawfik TA (2021) The effect of using nano rice husk ash of different burning degrees on ultra-high-performance concrete properties. Constr Build Mater 290:123279. https://doi.org/10.1016/j.conbuildmat.2021.123279
64. Taher A. Tawfik, Magdy A. Abd EL-Aziz, S. Abd El-Aleem and A. Serag Faried (2018) Influence of nanoparticles on mechanical and non-destructive properties of high-performance concrete. J Chin Adv Mater Soc 6(4):409-433. https://doi.org/10.1016/j.conbuildmat.2021.123279
65. Muhd Norhasri MS, Hamidah MS, Mohd Fadzil A (2019) Inclusion of nano metaclayed as additive in ultra high performance concrete (UHPC). Constr Build Mater 201:590–598. https://doi.org/10.1016/j.conbuildmat.2019.01.006
66. Muhd Norhasri MS, Hamidah MS, Mohd Fadzil A, Megawati O (2016) Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC). Constr Build Mater 127:167–175. https://doi.org/10.1016/j.conbuildmat.2016.09.127
67. Ganesh P, Ramachandra Murthy A (2019) Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material. Constr Build Mater 197:667–680. https://doi.org/10.1016/j.conbuildmat.2018.11.240
68. Hasan ZA, Nasr MS, Abed MK (2021) Properties of reactive powder concrete containing different combinations of fly ash and metakaolin. Mater Today Proc 42(5):2436–2440. https://doi.org/10.1016/j.matpr.2020.12.556
69. Yazıcı H, Yigiter H, Karabulut AS, Baradan B (2008) Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete. Fuel 87(12):2401–2407. https://doi.org/10.1016/j.fuel.2008.03.005

70. Tahwia AM, Elgendy GM, Amin M (2021) Durability and microstructure of eco-efficient ultra-high-performance concrete. Constr Build Mater 303:124491. https://doi.org/10.1016/j.conbuildmat.2021.124491
71. Zhang H, Ji T, He B, He L (2019) Performance of ultra-high performance concrete (UHPC) with cement partially replaced by ground granite powder (GGP) under different curing conditions. Constr Build Mater 213:469–482. https://doi.org/10.1016/j.conbuildmat.2019.04.058
72. Amin M, Zeyad AM, Tayeh BA, Agwa IS (2021) Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates. Constr Build Mater 302:124196. https://doi.org/10.1016/j.conbuildmat.2021.124196
73. Li PP, Brouwers HJH, Chen W, Qingliang Yu (2020) Optimization and characterization of high-volume limestone powder in sustainable ultra-high performance concrete. Constr Build Mater 242:118112. https://doi.org/10.1016/j.conbuildmat.2020.118112
74. Liu Y, Shi C, Zhang Z, Li N, Shi Da (2020) Mechanical and fracture properties of ultra-high performance geopolymer concrete: effects of steel fibre and silica fume. Cement Concr Compos 112:103665. https://doi.org/10.1016/j.cemconcomp.2020.103665
75. Yang R, Rui Yu, Zhonghe Shui Xu, Gao XX, Zhang X, Wang Y, He Y (2019) Low carbon design of an ultra-high performance concrete (UHPC) incorporating phosphorous slag. J Clean Prod 240:118157. https://doi.org/10.1016/j.jclepro.2019.118157
76. Alharbi YR, Abadel AA, Mayhoub OA, Kohail M (2021) Effect of using available metakaolin and nano materials on the behaviour of reactive powder concrete. Constr Build Mater 269:121344. https://doi.org/10.1016/j.conbuildmat.2020.121344
77. Wang X, Di Wu, Geng Q, Hou D, Wang M, Li L, Wang P, Chen D, Sun Z (2021) Characterization of sustainable ultra-high performance concrete (UHPC) including expanded perlite. Constr Build Mater 303:124245. https://doi.org/10.1016/j.conbuildmat.2021.124245
78. Qian D, Rui Yu, Zhonghe Shui Yu, Sun CJ, Zhou F, Ding M, Tong X, He Y (2020) A novel development of green ultra-high performance concrete (UHPC) based on appropriate application of recycled cementitious material. J Clean Prod 261:121231. https://doi.org/10.1016/j.jclepro.2020.121231
79. Wang JN, Yu R, Xu WY, Hu CY, Shui ZH, Qian D, Leng Y, Liu KN, Hou DS, Wang XP (2021) A novel design of low carbon footprint ultra-high performance concrete (UHPC) based on full scale recycling of gold tailings. Constr Build Mater 304:124664. https://doi.org/10.1016/j.conbuildmat.2021.124664
80. Shi Ye, Long G, Ma C, Xie Y, He J (2019) Design and preparation of ultra-high performance concrete with low environmental impact. J Clean Prod 214:633–643. https://doi.org/10.1016/j.jclepro.2018.12.318
81. Reddy GGK, Ramadoss P (2020) Influence of alccofine incorporation on the mechanical behaviour of ultra-high performance concrete (UHPC). Mater Today Proc 33(part 1):789–797. https://doi.org/10.1016/j.matpr.2020.06.180
82. Dixit A, Verma A, Pang SD (2021) Dual waste utilization in ultra-high performance concrete using biochar and marine clay. Cement Concr Compos 120:104049. https://doi.org/10.1016/j.cemconcomp.2021.104049
83. Li PP, Yu QL, Brouwers HJH (2018) Effect of coarse basalt aggregates on the properties of ultra-high performance concrete (UHPC). Constr Build Mater 170:649–659. https://doi.org/10.1016/j.conbuildmat.2018.03.109
84. Jankovic K, Stankovic S, Bojovic D, Stojanovic M, Antic L (2016) The influence of nano-silica and barite aggregate on properties of ultra high performance concrete. Constr Build Mater 126:147–156. https://doi.org/10.1016/j.conbuildmat.2016.09.026
85. Jiao Y, Zhang Y, Guo M, Zhang L, Ning H, Liu S (2020) Mechanical and fracture properties of ultra-high performance concrete (UHPC) containing waste glass sand as partial replacement material. J Clean Prod 277:123501. https://doi.org/10.1016/j.jclepro.2020.123501
86. Chu H, Wang F, Wang L, Feng T, Wang D (2020) Mechanical properties and environmental evaluation of ultra-high-performance concrete with aeolian sand. Materials 13(14):3148. https://doi.org/10.3390/ma13143148
87. Li PP, Yu QL, Brouwers HJH (2017) Effect of PCE-type superplasticizer on early-age behaviour of ultra-high performance concrete (UHPC). Constr Build Mater 153:740–750. https://doi.org/10.1016/j.conbuildmat.2017.07.145
88. Schrofl Ch, Gruber M, Plank J (2012) Preferential adsorption of polycarboxylate superplasticizers on cement and silica fume in ultra-high performance concrete (UHPC). Cem Concr Res 42(11):1401–1408. https://doi.org/10.1016/j.cemconres.2012.08.013
89. Ozersky A, Khomyakov A, Peterson K (2021) Novel ultra high performance concrete mixing technology with preliminary dry forced packing. Constr Build Mater 267:120934. https://doi.org/10.1016/j.conbuildmat.2020.120934
90. Yu R, Spiesz P, Brouwers HJH (2014) Mix design and properties assessment of ultra-high performance fibre reinforced concrete (UHPFRC). Cem Concr Res 56:29–39. https://doi.org/10.1016/j.cemconres.2013.11.002
91. Hunger M (2010) An integral design concept for ecological self-compacting concrete. Dissertation, Eindhoven University of Technology, Eindhoven, p 240
92. Li J, Chengqing Wu, Hao H (2015) An experimental and numerical study of reinforced ultra-high performance concrete slabs under blast loads. Mater Des 82:64–76. https://doi.org/10.1016/j.matdes.2015.05.045
93. Li J, Chengqing Wu, Hao H, Liu Z (2017) Post-blast capacity of ultra-high performance concrete columns. Eng Struct 134:289–302. https://doi.org/10.1016/j.engstruct.2016.12.057
94. Yi N-H, Kim J-H, Han T-S, Cho Y-G, Lee JH (2012) Blast-resistant characteristics of ultra-high strength concrete and reactive powder concrete. Constr Build Mater 28(1):694–707. https://doi.org/10.1016/j.conbuildmat.2011.09.014
95. Millard SG, Molyneaux TCK, Barnett SJ, Gao X (2010) Dynamic enhancement of blast-resistant ultra high performance fibre-reinforced concrete under flexural and shear loading. Int J Impact Eng 37(4):405–413. https://doi.org/10.1016/j.ijimpeng.2009.09.004
96. Liu J, Chengqing Wu, Yu Su, Li J, Shao R, Chen G, Liu Z (2018) Experimental and numerical studies of ultra-high performance concrete targets against high-velocity projectile impacts. Eng Struct 173:166–179. https://doi.org/10.1016/j.engstruct.2018.06.098
97. Wei J, Li J, Chengqing Wu, Liu Z-X, Li J (2021) Hybrid fibre reinforced ultra-high performance concrete beams under static and impact loads. Eng Struct 245:112921. https://doi.org/10.1016/j.engstruct.2021.112921

98. Yu R, Spiesz P, Brouwers HJH (2014) Static properties and impact resistance of a green ultra-high performance hybrid fibre reinforced concrete (UHPHFRC): experiments and modelling. Constr Build Mater 68:158–171. https://doi.org/10.1016/j.conbuildmat.2014.06.033
99. Li PP, Cao YYY, Sluijsmans MJC, Brouwers HJH, Qingliang Yu (2021) Synergistic effect of steel fibres and coarse aggregates on impact properties of ultra-high performance fibre reinforced concrete. Cement Concr Compos 115:103866. https://doi.org/10.1016/j.cemconcomp.2020.103866
100. Lee J-Y, Yuan T, Shin H-O, Yoon Y-S (2020) Strategic use of steel fibres and stirrups on enhancing impact resistance of ultra-high-performance fibre-reinforced concrete beams. Cement Concr Compos 107:103499. https://doi.org/10.1016/j.cemconcomp.2019.103499
101. Rong Z, Sun W, Zhang Y (2010) Dynamic compression behaviour of ultra-high performance cement based composites. Int J Impact Eng 37(5):515–520. https://doi.org/10.1016/j.ijimpeng.2009.11.005
102. Yalin Liu MASCE, Ya Wei MASCE (2021) Drop-weight impact resistance of ultrahigh-performance concrete and the corresponding statistical analysis. J Mater Civ Eng 34(1):04021409. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004045
103. Othman H, Marzouk H, Sherif M (2019) Effects of variations in compressive strength and fibre content on dynamic properties of ultra-high performance fibre-reinforced concrete. Constr Build Mater 195:547–556. https://doi.org/10.1016/j.conbuildmat.2018.11.093
104. Jabir HA, Abid SR, Murali G, Ali SH, Klyuev S, Fediuk R, Vatin N, Promakhov V, Vasilev Y (2020) Experimental tests and reliability analysis of the cracking impact resistance of UHPFRC. Fibres 8(12):74. https://doi.org/10.3390/fib8120074
105. Li PP, Sluijsmans MJC, Brouwers HJH, Yu QL (2020) Functionally graded ultra-high performance cementitious composite with enhanced impact properties. Compos B Eng 183:107680. https://doi.org/10.1016/j.compositesb.2019.107680
106. Yu Su, Li J, Chengqing Wu, Pengtao Wu, Li Z-X (2016) Influences of nano-particles on dynamic strength of ultra-high performance concrete. Compos B Eng 91:595–609. https://doi.org/10.1016/j.compositesb.2016.01.044
107. Wei J, Li J, Chengqing Wu, Liu Z-X, Fang J (2021) Impact resistance of ultra-high performance concrete strengthened reinforced concrete beams. Int J Impact Eng 158:104023. https://doi.org/10.1016/j.ijimpeng.2021.104023
108. Hesham O, Hesham M (2016) Impact response of ultra-high-performance reinforced concrete plates. ACI Struct J. 113(6):1325–1334
109. Smith-Gillis R, Lopez-Anido R, Rushing TS, Landis EN (2021) Development of thermoplastic composite reinforced ultra-high-performance concrete panels for impact resistance. Materials 14(10):2490. https://doi.org/10.3390/ma14102490
110. Khalaf MA, Cheah CB, Ramli M, Ahmed NM, Al-Asady AMA, Ali AMA, Al-Shwaiter A, Tangchirapat W (2021) Engineering and gamma-ray attenuation properties of steel furnace slag heavyweight concrete with nano calcium carbonate and silica. Constr Build Mater 267:120878. https://doi.org/10.1016/j.conbuildmat.2020.120878
111. Suleyman Gokce H, Yalcinkaya C, Tuyan M (2018) Optimization of reactive powder concrete by means of barite aggregate for both neutrons and gamma rays. Constr Build Mater 189:470–477. https://doi.org/10.1016/j.conbuildmat.2018.09.022
112. Azreen NM, Rashid RSM, Haniza M, Voo YL, Mugahed Amran YH (2018) Radiation shielding of ultra-high-performance concrete with silica sand, amang and lead glass. Constr Build Mater 172:370–377. https://doi.org/10.1016/j.conbuildmat.2018.03.243
113. Khan MU, Ahmad S, Naqvi AA, Al-Gahtani HJ (2020) Shielding performance of heavy-weight ultra-high-performance concrete against nuclear radiation. Prog Nucl Energy 130:103550. https://doi.org/10.1016/j.pnucene.2020.103550

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