Case Studies in Construction Materials 22 (2025) e04644

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Approaches to reduce cost and environmental impacts of UHPC production: A review

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ARTICLE INFO

Keywords:
Ultra-High Performance Concrete
Ultra-high performance geopolymer concrete
Recycled fibres
Recycled aggregates
Limestone calcined clay cement
Cost analysis
Environmental impacts

ABSTRACT

Ultra-High Performance Concrete (UHPC) is a special fibre-reinforced concrete with ultra-high compressive strength, high flexural strength, excellent toughness and durability. Typically, UHPC is formulated from Portland cement (PC), supplementary cementitious materials (SCMs), fine aggregates, fibres, water and admixtures. However, the current widespread application of UHPC is hampered by two major problems, i.e., high cost and high environmental impacts associated with UHPC production. To address these issues, this study provides a comprehensive review of approaches to reduce the cost and environmental impacts of UHPC production. The main approach discussed in detail is the substitution of PC with geopolymer as a sustainable PC-less binder to develop ultra-high performance geopolymer concrete (UHPGC). The other approaches covered in this article include the use of limestone calcined clay cement (LC^3) as a substitute for PC, the incorporation of recycled fibres in place of manufactured fibres, the utilisation of recycled fine aggregates as alternatives to natural sand, and the application of recycled agricultural and industrial wastes as replacements for the commonly used SCMs (i.e., silica fume, fly ash, and ground granulated blast furnace slag). Additionally, incorporating natural/recycled coarse aggregates into the production of UHPC can further reduce the material's cost and carbon emissions. The recommendations for future research are also highlighted for each strategy. The findings of this up-to-date article offer valuable insights for developing a more cost-effective and environmentally friendly UHPC, thereby facilitating its wider application in the construction industry.[1]

1. Introduction

Ultra-high performance concrete (UHPC) is a specialised fibre-reinforced concrete known for its ultra-high compressive strength (≥150 MPa), high flexural strength followed by deflection-hardening behaviour, as well as excellent durability [1]. UHPC is typically composed of Portland cement (PC), supplementary cementitious materials (SCMs), fine aggregates, fibres, water, and admixtures, and it undergoes curing using various methods (Fig. 1). The exceptional properties of UHPC and its advantages as a construction material for various structural and architectural applications have been widely reported. For instance, Nematollahi et al. [2] found that precast

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[1] The author Behzad Nematollahi is a guest editor of this journal. In accordance with policy, Behzad Nematollahi was blinded to the entire peer review process.

https://doi.org/10.1016/j.cscm.2025.e04644
Received 3 January 2025; Received in revised form 30 March 2025; Accepted 9 April 2025

cantilever retaining walls made of UHPC used 86 % less material, had 57 % lower embodied energy, and emitted 60 % less CO_2 compared to their normal-strength concrete (NSC) counterparts. Similarly, according to Lei et al. [3], a UHPC bridge required 14 % more material by weight than a conventional steel-composite girder bridge but consumed 66 % less embodied energy and reduced CO_2 emissions by 57 %. Additionally, the cost of the UHPC bridge superstructure was 27 % lower than that of the conventional bridge. Despite all these advantages, UHPC has yet to achieve widespread adoption in the construction industry. This is primarily due to its higher cost and greater environmental impact during production compared to NSC. A case study on bridge construction [4] reported that the cost of using UHPC as construction material is 830 USD/m^3, significantly higher than the 100 USD/m^3 for NSC. Similarly, the CO_2 emissions associated with UHPC production reached 877 kg-CO_2/m^3, more than double the 348.3 kg-CO_2/m^3 generated by NSC. This significant disparity highlights the necessity for effective strategies to mitigate both the economic and environmental burdens associated with UHPC production.

To address the above challenges, this review article aims to provide a comprehensive discussion of approaches to reduce the cost and environmental impacts of UHPC. The approaches covered in this article include the use of geopolymer/alkali-activated cement and limestone calcined clay cement (LC^3) as substitutes for PC, the use of recycled fibres instead of manufactured virgin fibres, the use of recycled fine aggregates to replace natural sand, and the use of recycled agricultural and industrial wastes as alternatives for commonly used SCMs. Additionally, the incorporation of coarse aggregates in UHPC production is explored. This review scientifically discussed the current progress of each approach and its effects on the mechanical properties, sustainability, and cost-effectiveness of UHPC.

Among the various components of UHPC, the PC content in a typical UHPC mixture is normally two to three times higher than that of NSC, which adversely affects the sustainability of the material and contributes to its high cost as well as high autogenous shrinkage, and heat of hydration [5,6]. Therefore, reducing the PC content in UHPC is crucial. One straightforward solution is to partially replace the PC with SCMs such as fly ash and ground granulated blast furnace slag (GGBFS). This approach has been extensively studied in the literature [7–9], and green UHPC has been developed with up to 60 wt% of PC replaced by fly ash or GGBFS [10]. Since this solution has been thoroughly discussed in previous review articles on UHPC [5,7], it will not be covered in detail in this review. A more sustainable approach to tackle the drawbacks associated with the high PC content in UHPC is the complete replacement of PC with a PC-free binder such as geopolymer, also known as alkali-activated cement. Geopolymer is synthesised through the alkali activation of aluminosilicate source materials (also known as feedstocks/precursors), which contain considerable amounts of aluminium and silicon, such as metakaolin, fly ash, silica fume and GGBFS [11]. The production of geopolymer has a significantly lower environmental footprint compared to PC. Yang et al. [12] reported that various types of geopolymers reduced carbon emissions by 55–75 % compared to PC. Similarly, Nematollahi et al. [13] found that the ambient-temperature cured geopolymer concrete emitted 76 % less carbon and consumed 36 % less embodied energy compared to typical concrete. Those findings, along with numerous other studies, have contributed to the growing interest in developing ultra-high performance geopolymer concrete (UHPGC) using geopolymer as the sole binder [11,14]. The existing studies on UHPGC are discussed in detail in Section 3. In addition, it is worth noting that limited studies have recently been conducted to develop green UHPC using “Limestone Calcined Clay Cement (LC^3)” [15,16]. LC^3 is a blended cement manufactured by a combination of limestone, calcined clay, and PC [17]. The production of LC^3 can provide a reduction of carbon emissions by at least 40 % compared to PC [18]. The available research on using LC^3 to develop green UHPC is briefly discussed in Section 4.

As a key component of UHPC, different types of fibres are frequently used to improve flexural and tensile properties and prevent brittle failure of the composite. Steel fibre is the most commonly used reinforcement strategy in UHPC due to its superb tensile strength (> 2000 MPa) and high modulus of elasticity (> 200 GPa). In addition to steel fibres, synthetic fibres such as polyvinyl alcohol (PVA)

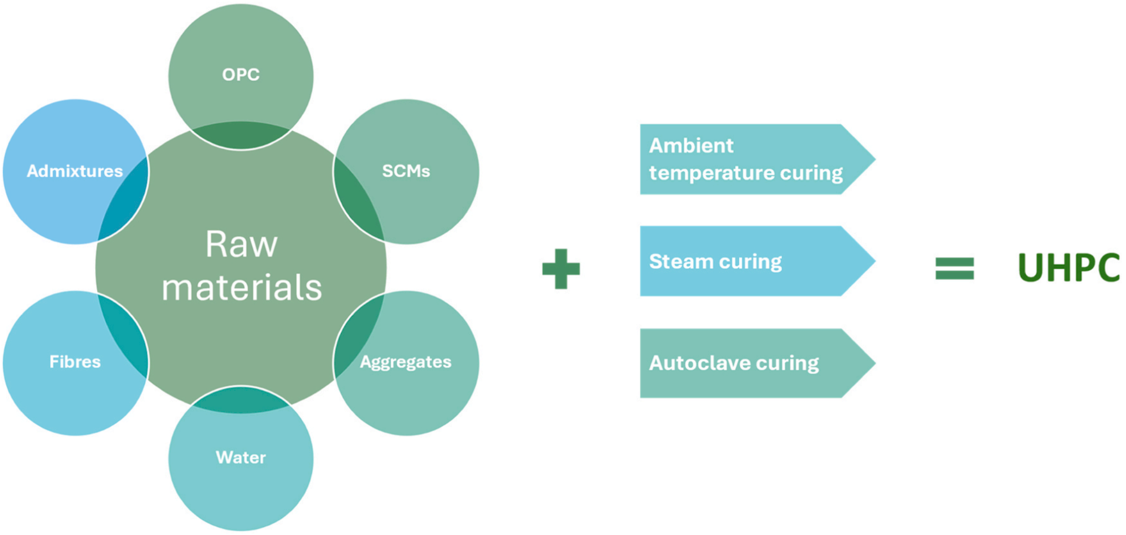

Fig. 1. Typical composition of UHPC.

[19], polyethylene (PE) [20] and polypropylene (PP) [21] fibres are also used to reinforce the UHPC matrix. The typical physical and mechanical properties of PVA, PE and PP fibres can be found in [22]. However, the manufactured fibres used in UHPC are costly, and their production is energy- and carbon-intensive [4]. To reduce the environmental impact and overall cost of UHPC production, some studies have used recycled fibres from various waste streams as alternatives to manufactured steel or synthetic fibres. For example, Isa et al. [23] developed an economical UHPC by using recycled tyre steel cords and recycled tyre steel fibres. A detailed discussion of related research advancements will be presented in Section 5.

In addition, due to the increasing scarcity of natural resources, the potential application of recycled fine aggregates as an alternative to natural sand in UHPC has been explored in some studies [24,25]. To further enhance the sustainability and cost-effectiveness of UHPC, researchers have investigated the incorporation of alternative SCMs, such as bagasse ash, palm oil shell ash, waste clay, and steel slag, as substitutes for commonly used SCMs like silica fume, fly ash, and GGBFS [26,27]. Furthermore, some studies have attempted to incorporate coarse aggregates into UHPC mixtures to reduce the use of powder materials, thereby reducing the overall cost [28,29]. This article provides a brief overview of the existing studies on using recycled fine aggregates, alternative SCMs, and coarse aggregates in UHPC, with a focus on their potential to reduce costs and minimize environmental impact (See Sections 6, 7, and 8).

It is expected that the findings of this state-of-the-art review will promote the development of a more cost-effective and environmentally friendly UHPC, thereby facilitating its wider application in the construction industry, including infrastructure, residential, and commercial projects. By identifying sustainable material alternatives and cost-reduction strategies, the review provides key insights and outlines future research directions to further enhance the sustainability and performance of UHPC.

2. Data collection, methods and approach

The Web of Science database was used in this article for literature statistics. The collected articles contain the specified search terms either in their titles, keywords or abstracts. Articles included in the search results are reviewed in a second round to eliminate irrelevant articles, and some relevant articles that are not included in the search results are also manually added for statistical purposes. It is necessary to note that the cut-off date for this literature search at Web of Science was November 2024, therefore, any studies published after that date were out of statistical scope for this review.

3. Ultra-high performance geopolymer concrete

UHPGC is an emerging greener UHPC that combines the advantages of geopolymer and UHPC as mentioned in Section 1 to meet the demand for ultra-high performance and eco-friendly building materials [14]. This section focuses on recent advancements in UHPGC research, providing a summary and analysis of existing studies on its environmental impacts, mechanical performance, key parameters affecting both the fresh and hardened properties of UHPGC. Furthermore, it provides a comparative analysis of the production costs associated with UHPGC and UHPC.

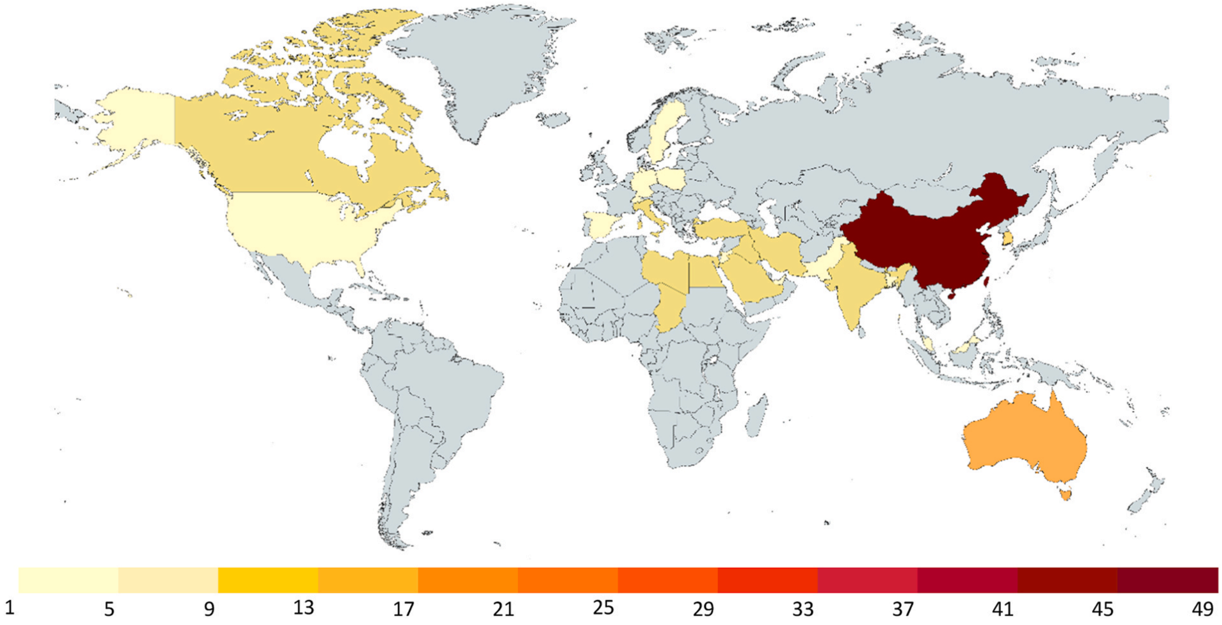

Fig. 2. Global distribution of publications on UHPGC till November 2024 (based on the national affiliation of the researcher).

3.1. Up-to-date research progress

The search keywords used to retrieve publications in the field of UHPGC include “UHPGC”, “ultra-high performance geopolymer concrete”, “GP-based UHPC”, “geopolymer-based UHPC”, “geopolymer-based ultra-high-performance concrete”, “alkali-activated ultra-high-performance concrete”, “alkali-activated UHPC” and “UHP-GPC”. The inception of published articles in the field of UHPGC can be traced back to 2012, and this topic has witnessed notable growth in the last three years. From 2012–2020, only a few studies have been conducted. As of November 2024, a total of 95 publications have been contributed to this topic. Fig. 2 shows the global distribution of publications on UHPGC based on the affiliation of the researchers. As shown in this figure, China stands as the leading contributor (48 articles), followed by Australia (15 articles), and other countries including South Korea, Egypt, Saudi Arabia, etc., contribute one to ten articles based on the national affiliation of researchers. Of those 95 publications, 92 % are original research articles, with the remaining fall into the category of review articles (Fig. 3).

Table 1 summarises the raw materials and mixture designs employed in the production of UHPGC, and their corresponding mechanical strengths. The formulation of UHPGC involves systematic optimization of constituent materials including precursors systems, alkali activators, aggregates, fibre reinforcements, and chemical admixtures. The prominent binary or ternary aluminosilicate precursors for UHPGC production include silica fume/GGBFS, fly ash/GGBFS or silica fume/fly ash/GGBFS. Additionally, some studies have explored the use of agricultural waste materials, such as wheat straw ash [30] and rice husk ash [31], as alternative precursors to enhance sustainability. Furthermore, the selection and dosage of alkaline activators are crucial in the geopolymerisation reaction and have a significant impact on the fresh and hardened properties of UHPGC. In general, a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) is the most frequently used alkali activator, while only limited studies utilised potassium-based activators, likely due to their higher cost [32]. Key parameters such as alkali silicate modulus, alkali molarity, and the ratio of alkali silicate to alkali hydroxide have significant effects on the setting behaviour [33], workability [34] and mechanical strength [35] of UHPGC. As summarized in Table 1, previous studies have explored a wide range of activator compositions, with alkali silicate solution modulus varying from 0.85 to 3.38 [34,36], alkali hydroxide solution molarities ranging from 2.5 to 16 M [37,38], and the alkali silicate to alkali hydroxide ratios (M_s) ranging from 1.0 to 3.5 [39,40].

From Table 1, the most commonly used aggregates in UHPGC production are silica and natural sands, while there is a growing trend towards integrating recycled materials, such as waste glass [41,42], marble waste [30], waste ceramic balls [42], waste nickel slag [31] and waste rubber [30,41,43] to fully or partially replace sand in UHPGC manufacturing to mitigate the environmental impact. Notably, the use of recycled aggregates as a substitute for natural sand has demonstrated satisfactory mechanical performance, as summarised in Table 1. In terms of material proportions, most researchers have employed the extra water to precursor ratios in the range of 0.1–0.3 [20,21] and aggregate to precursor ratios in the range of 0.3–1.3 [11,19].Furthermore, steel fibres with different shapes, sizes and dosages have been the primary focus of extensive research to enhance the mechanical properties and prevent brittle failure in UHPGC. In addition to steel fibres, various other fibre types such as PVA, PE, PP and polyethylene terephthalate (PET) fibres have also been explored, as summarized in Table 1.

3.2. Environmental impacts

Due to the limited availability of detailed compositional data for UHPGC, the findings of Lao et al. [56], Ghasemzadeh Mousavinejad and Sammak [59] were selected as representative UHPGC mixes for comparing environmental impacts with UHPC, while the study by Wu et al. [72] served as a reference for a typical UHPC mixture. Table 2 presents an inventory of energy consumption and carbon emissions for the ingredients of UHPGC and UHPC. It should be mentioned here that the mixture proportions studied by Lao et al. [56] were based on weight ratios, therefore, a mean bulk density of 2507.3 kg/m^3 [44] was employed to calculate the weight proportions. Moreover, the environmental impact of water is minimal and has therefore been excluded from the calculations.

As shown in Fig. 4, steel fibres represent the predominant source of embodied energy in UHPGC production, accounting for at least half of the total energy consumption. In the UHPGC mixture with superplasticiser (Mix 1), the superplasticizer ranks second in energy

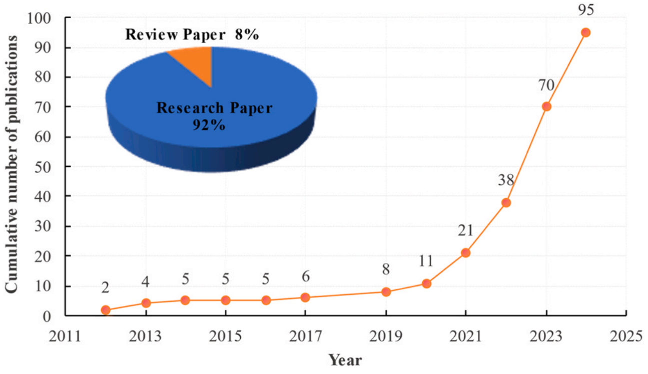

Fig. 3. Trends of publications on UHPGC till November 2024.

Table 1
Summary of raw materials and mixture design from available studies on UHPGC.

Ref.	Precursors	Activator	Aggregate (A/P ratio)	Fibre (d, L, V_f)	Admixture	Extra water-to-precursor ratio by weight	Mechanical performance
[44]	GGBFS, SF	Na_2SiO_3, NaOH (4 M)[b], (R = 3)[c]	Silica sand (0.16, 0.32, 0.48, 0.64, 0.8)	Straight steel fibres (d = 0.2 mm, L = 19.5 mm, V_f = 2 %)	SP	0.3	f_c = 139.0–160.7 MPa f_t = 7.47–10.38 MPa
[45]	FA, GGBFS, SF	Na_2CO_3, Na_2SiO_3, Water glass solution	Fine silica sand (0.65)	Straight copper-coated steel fibres (d = 200 μm, L = 13 mm, V_f = 2 %)	-	0.18	f_c = 135.8–186.0 MPa f_t = 10.0–11.9 MPa
[42]	GGBFS , SF	KOH, Na_2SiO_3	Natural sand, Waste glass, Waste ceramic (n.r.)	Straight steel fibre: (d = 0.3 μm, L = 13 mm, V_f = 3 %)	-	0.09	f_c = 119.0–137 MPa
[20]	FA , GGBFS , SF	Na_2SiO_3 (0.94)[a], water glass solution (3.18)[a]	Fine silica sand (0.3)	PE fibres (d = 24 μm, L = 18 m, V_f = 2 %)	Borax retarder	0.122, 0.172	f_c = 94.4–180.7 MPa f_t = 10.4–15.9 MPa
[21]	GGBFS, SF , Nano-silica	NaOH, Na_2SiO_3	River sand (1.13–1.24)	PP fibres (d = N/A, L = 20 mm, V_f = 1–3 %)	-	0.18–0.21	f_c = 112–155.4 MPa f_b = 12.3–25.43 MPa f_s = 8.6–17.68 MPa E = 22.0–35.75 GPa
[46]	FA , GGBFS , SF	Na_2SiO_3, NaOH (10 M)[b], (R = 3)[c]	Quartz powder (1.0)	Steel fibres: (d = 180–230 μm, L = 13 mm, V_f = 1–2 %) Macro-basalt: (d = 13–19 μm, L = 6 mm, V_f = 1–2 %) Macro-basalt: (d = 13–19 μm, L = 12 mm, V_f = 1–2 %)	SP	0.25	f_c = 126.28–154.67 MPa f_b = 18.89–24.12 MPa
[30]	GGBFS, Wheat straw ash, SF, FA	Na_2SiO_3 (2 M)[b], NaOH (10 M)[b], (R = 3)[c]	Waste rubber powder, Glass waste, Marble waste, Sand (n.r.)	Double hooked end steel fibres (d = 1.15 mm, L = 50 mm, V_f = 2 %)	-	(n.r.)	f_c = 120.0–179.0 MPa f_b = 7.69–14.47 MPa f_s = 6.31–14.53 MPa E = 22.6–33.2 GPa
[31]	GGBFS, Class C FA, Rice husk ash	Na_2SiO_3, NaOH	Waste nickel slag (n.r.)	Straight steel fibre (d = 0.2 mm, L = 13 mm, V_f = 2 %)	-	(n.r.)	f_c = 104.2–146.3 MPa f_b = 11.5–20.8 MPa
[35]	GGBFS, Metakaolin, SF	Na_2SiO_3 (2.23)[a], NaOH (4, 8, 12 M)[b]	Natural river sand (0.36)	Copper plated steel fibre (d = 0.2 mm, L = 14 mm, V_f = 0–2 %)	-	(n.r.)	f_c = 63.1–136.3 MPa
[47]	FA , GGBFS , SF	Na_2SiO_3 (3)[a], NaOH	Quartz sand (0.08–8.43), Quartz flour (n.r.)	-	-	(n.r.)	f_c = 76.28–159.6 MPa f_b = 3.8–8.9 MPa
[11]	FA , GGBFS , SF	Water glass powder (0.5, 1.0, 1.5, 2.0)[a], NaOH	Mesh quartz sand (0.75)	Copper-coated steel fibre (d = 0.2 mm, L = 13 mm, V_f = 0–3 %)	-	0.32	f_c = 88.0–172.33 MPa f_b = 5.5–24.99 MPa
[48]	Steel slag, GGBFS, SF	K2CO3, Na2SiO3	Quartz sand (1.2)	-	-	0.23	f_c = 98.1–160.3 MPa f_b = 6.99–18.12 MPa
[49]	GGBFS , SF, Nano-silica	(n.r.)	Silica flour (0.25), Silica sand (1.0)	Steel fibre (d = 0.2 mm, L = 19.5 mm, V_f = N/A)	SP	(n.r.)	f_c = 177.4–184.2 MPa f_t = 12.3–14.5 MPa
[50]	GGBFS , SF	Na_2SiO_3 (1.5)[a], NaOH (4 M)[b], (R = 3)[c]	Silica flour (0.2), Silica sand (0.8)	Straight steel fibres (d = 0.2 mm, L = 13 mm, 19.5 mm, V_f = 2 %) Hooked-end steel fibres (d = 0. 2 mm, L = length 13 mm, 25 mm, V_f = 2 %)	SP	(n.r.)	f_t = 8.74–12.28 MPa
[51]	Mineral powder, Recycled	Na_2SiO_3 (1.3)[a], NaOH	River sand (n.r.)	-	-	(n.r.)	f_c = 80.0–130.0 MPa

(*continued on next page*)

Table 1 (*continued*)

Ref.	Precursors	Activator	Aggregate (A/P ratio)	Fibre (d, L, V_f)	Admixture	Extra water-to-precursor ratio by weight	Mechanical performance
	concrete fines						
[52]	FA , GGBFS , SF	Na_2SiO_3 (3.3)[a], NaOH	Quartz sand (0.73), Quartz flour (0.27)	-	$BaCl_2$ retarder	0.04	f_c = 116.0–138.0 MPa f_b = 16.0–19.5 MPa
[53]	FA , GGBFS , SF	Na_2SiO_3 (3)[a], NaOH	Quartz sand (1.0), Medium-aluminium ceramic balls (n.r.)	Smooth and straight steel fibres (d = 0.12 mm, L=10 mm, V_f = 0 %, 0.6 %, 1.2 % and 1.8 %)	SP	0.31	f_c = 105.4–176.8 MPa f_s = 3.4–15.3 MPa f_b = 5.9–18.5 MPa
[54]	FA , GGBFS , SF	Na_2SiO_3 (0.94)[a], water glass solution (3.18)[a]	Sea sand (0.3)	PE fibres (d = 24 μm, L = 18 m, V_f = 2 %)	Borax retarder	0.152	f_c = 84.5–145.1 MPa f_t = 8.1–11.9 MPa
[33]	GGBFS , SF	Na_2SiO_3, NaOH	Silica sand (0.16–0.64), Silica flour (0.04–0.16)	Steel fibre (d=0.2 mm, L=19.5 mm, V_f = 0–2 %) PE fibre (d=0.002 mm, L=18 mm, V_f = 0–2 %)	SP	0.3	f_c = 125.1–159.6 MPa f_t = 5.9–10.6 MPa
[55]	GGBFS , SF	Na_2SiO_3 (0.94)[a], NaOH	River sand (0.9)	-	-	0.29	f_c = 65.8–121.3 MPa
[38]	GGBFS , SF	Na_2SiO_3 (3.3)[a], KOH (16 M)[b]	Natural sand (n.r.), Recycled fine waste ceramic (n.r.)	Straight steel fibre (d = 0.2 mm, L = 13 mm, V_f = 0–2 %)	-	(n.r.)	f_c = 91.88–145.0 MPa f_b = 4.72–10.62 MPa f_t = 5.9–14.01 MPa E = 26.8–31.1 GPa
[43]	FA , GGBFS , SF	Na_2SiO_3 (2.25)[a], NaOH (14 M)[b]	Quartz sand (1.0), Crumb rubber (0–50 % by volume)	Straight steel fibres (d = 0.2 mm, L = 13 mm, V_f = 0–2 %) Recycled steel fibres (d=0.3 mm, L = 9.92 mm, V_f = 0–2 %)	$BaCl_2$ retarder	0.13	f_c = 51.3–152.2 MPa
[56]	FA , GGBFS , SF	Na_2SiO_3, water glass solution	Silica sand (0.65)	Straight steel fibre (d = 0.2 mm, L = 13 mm, V_f = 0–2 %)	Borax retarder	0.105	f_c = 163.0–222.0 MPa f_t = 10.3–18.0 MPa
[57]	GGBFS , SF	Na_2SiO_3 (1.5)[a], KOH, (R = 3)[c]	Natural sand (1.33–1.35), Recycled waste glass (7.5 %, 15 %, 22.5 % by volume)	Straight steel fibre (d = 0.2 mm, L = 13 mm, V_f = 0–3 %)	-	(n.r.)	f_c = 60.0–165.0 MPa
[58]	GGBFS , SF	K2CO3, Na2SiO3	Quartz sand (n.r.), Quartz powder (n.r.)	-	-	(n.r.)	f_c = 110.0–129.0 MPa
[40]	SF, GGBFS	Na_2SiO_3 (2)[a], NaOH (6, 10, 14 M)[b], (R = 1.5, 2.5, 3.5)[c]	Quartz sand (0.72–0.74)	PP fibres (d = 0.033 mm, L = 8 mm, V_f = 0.25 %) Steel fibre (d = 0.12 mm, L = 15 mm, V_f = 1 %, 1.25 %, 1.5 %, 1.75 %, 2 %, 2.25 %)	-	(n.r.)	f_c = 101.0–175.0 MPa f_b = 7.6–13.7 MPa f_s = 6.1–8.6 MPa E = 44.0–49.0 GPa
[41]	GGBFS , SF	Na_2SiO_3 (2.5)[a], KOH (16 M)[b]	Crushed glass, Ceramic, Crumb rubber (n.r.)	Steel fibres (d = 0.12 mm, L = 13 mm, V_f = 3 %)	-	(n.r.)	f_c = 80.0–160.0 MPa f_b = 5.7–13.1 MPa f_s = 6.1–13.8 MPa
[37]	GGBFS , SF	K2CO3 (3 M)[b], Na2SiO3 (2.5 M)[b],	Quartz sand (1.0), Quartz powder (n.r.)	Steel fibres (d = 0.12 mm, L = 13 mm, V_f = 1 %)	-	0.2	f_c = 42.0–175.0 MPa
[59]	GGBFS, SF	Na_2SiO_3 (2.07)[a], NaOH (16 M)[b], (R = 3)[c]	Quartz sand (0.75)	Steel fibres (d = 0.2 mm, L = 13 mm, V_f = 0.75 %, 1 %, 1.25 %, 1.5 %, 1.75 %, 2 %) PP fibre (d = 0.035 mm, L = 6 mm, V_f = 0.25 %)	-	(n.r.)	f_c = 112.65–150.61 MPa f_t = 5.17–7.73 MPa E = 42.21–47.64 GPa

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Table 1 (*continued*)

Ref.	Precursors	Activator	Aggregate (A/P ratio)	Fibre (d, L, V_f)	Admixture	Extra water-to-precursor ratio by weight	Mechanical performance
[60]	FA , GGBFS , SF	Waterglass solution (2.61)[a], KOH (12, 14, 16 M)[b]	Natural sand (0.718–0.753)	-	-	0.211–0.221	$f_c = 18.0–134.0$ MPa
[39]	GGBFS , SF	Na_2SiO_3 (2.07)[a], NaOH (8, 12, 16 M)[b], (R = 1, 2, 3)[c]	Quartz sand (0.82–0.83)	-	-	0.146–0.175	$f_c = 105.13–130.11$ MPa $f_t = 5.06–6.14$ MPa E = 41.78–45.20 GPa
[61]	SF, GGBFS, FA	Na_2SiO_3 (1.6)[a], NaOH	Silica sand (1.0)	Straight steel fibre (d = 0.12 mm, L = 15 mm, V_f = 0–3 %)	-	0.1	$f_c = 102.0–156.0$ MPa $f_b = 11.5–22.5$ MPa $f_s = 8.0–17.0$ MPa E = 23.0–33.0 GPa
[62]	SF, GGBFS, FA	Na_2SiO_3, NaOH	Silica sand (1.12)	PP fibres (d = 0.032 mm, L = 50 mm, V_f = 0 %, 0.75 %, 1.75 %, and 2.75 %)	-	0.34	$f_c = 115.0–180.0$ MPa $f_s = 12.0–23.0$ MPa E = 30.0–45.0 GPa
[63]	FA, GGBFS , SF	Na_2SiO_3, NaOH	Quartz sand (1.11)	Steel bar (d = 8–14 mm, L = 6–15 mm, V_f = 2 %, 2.5 %)	-	(n.r.)	$f_c = 32.52–154.45$ MPa
[34]	GGBFS, FA, SF	Waterglass solution (0.85, 1.03, 1.32, 1.83)[a], NaOH	Quartz flour (0.1), Quartz sand (0.69–0.94)	Straight and smooth steel fibres (d = 0.12 mm, 0.2 mm, L = 6 mm, 10 mm, 13 mm, 15 mm, V_f = 0 %–2 %)	SP	0.315	$f_c = 72.0–214.5$ MPa $f_b = 3.4–42.3$ MPa
[64]	GGBFS, FA, SF	Na_2SiO_3 (2)[a], NaOH	Sand (1.18)	Long straight steel fibres (d = 0.12 mm, L = 15 mm, V_f =1 %, 2 %, 2.5 %) Short straight steel fibres (d = 0.12 mm, L = 10 mm, V_f = 2 %) Straight basalt fibres (d = 0.08 mm, L = 15 mm, V_f = 1 %)	SP	0.3	$f_c = 94.0–141.0$ MPa $f_b = 9.6–23.4$ MPa
[65]	GGBFS, SF	3 composite solutions: -K2CO3 + Na2SiO3 -NaCO3 + Na2SiO3 -KOH + Na2SiO3	Quartz powder, Quartz sand (1.0)	PET fibres (d = 36 μm, L = 12 mm, V_f = 0.1 % by mass)	-	0.2, 0.25	$f_c = 74.0–170.0$ MPa
[66]	GGBFS, SF	Na_2SiO_3 (2.5)[a], NaOH (12 M)[b], (R = 1.5)[c]	Quartz powder (0.24–1.3), Natural sand (0.72–2.0)	Hooked-end steel fibres (d = 0.15 mm, L = 10 mm, V_f = 0–2 %)	SP	(n.r.)	$f_c = 55.0–149.0$ MPa
[67]	GGBFS, FA, SF	NaOH, waterglass solution (1.5)[a]	River sand (1.0)	Straight steel fibres (d = 0.12 mm, 0.2 mm, L = 6 mm, 8 mm, 13 mm, V_f = 0 %–3 %) Hook-end steel fibres (d = 0.12 mm, L = 13 mm, V_f =0–3 %) Corrugated steel fibres (d = 0.2 mm, L = 13 mm, V_f =0–3 %)	-	0.107	$f_c = 100.6–170.3$ MPa $f_b = 4.6–34.0$ MPa
[68]	FA , GGBFS , SF	Na_2SiO_3 (1.5)[a], NaOH	Natural quartz sand (1.0)	Straight steel fibres (d = 0.12 mm, L = 13 mm, V_f = 0–3 %)	-	0.1	$f_c = 101.4–154.9$ MPa $f_b = 12.1–23.1$ MPa $f_s = 7.3–16.4$ MPa E = 25.8–31.5 GPa
[69]	GGBFS, MK, SF	Na_2SiO_3 (3.3)[a], K_2SiO_3 (2.5)[a], NaOH (5 M)[b] , KOH (10 M)[b]	Quartz sand (0.5), Quartz powder (0.07–0.08)	-	-	0.175–0.4	$f_c = 141.6–178.6$ MPa

(*continued on next page*)

Table 1 (*continued*)

Ref.	Precursors	Activator	Aggregate (A/P ratio)	Fibre (d, L, V_f)	Admixture	Extra water-to-precursor ratio by weight	Mechanical performance
[70]	GGBFS, FA, SF	NaOH or KOH, K2CO3 or Na2SiO3	Local sand (n.r.), Quartz sand (1.4)	Steel fibres (d = 0.16 mm, L = 6 mm, 13 mm, V_f = 1–2 %)	-	(n.r.)	f_c = 59.0–175.0 MPa
[71]	GGBFS, SF	Na_2SiO_3 (1.2)[a], NaOH	Quartz sand (1.34)	Brass-coated steel fibres (d = 0.16 mm, L = 13 mm, V_f = 1.5 %)	SP	0.054	f_c = 147.5–215.9 MPa f_b = 25.0–41.5 MPa f_s = 15.6–19.5 MPa E = 46.0–84.1 GPa
[36]	GGBFS, SF	Na_2SiO_3 (3.38)[a], NaOH	Quartz sand (0.72)	Brass-coated steel fibres (d = 0.16 mm, L = 6 mm, 13 mm, V_f = 0 %, 0.5 %, 1.5 %, or 2 %)	-	0.054	f_c = 132.0–229.0 MPa f_b = 12.0–48.4 MPa

Note: "n.r." means not reported in the study. FA = fly ash (All fly ashes used in the literature are Class F, unless the one used in [31]), GGBFS = ground granulated blast furnace slag, SF = silica fume, MK = metakaolin, SP = superplasticiser, PVA = polyvinyl alcohol, PE = polyethylene, PP = polypropylene, PET = Polyethylene terephthalate; A/P ratio = aggregate-to-precursor ratio, L = length of fibre, d = diameter of fibre, V_f = volume fraction of fibres, f_c = compressive strength, f_b = flexural strength, f_t = tensile strength, f_s = splitting tensile strength, E = elastic modulus.

[a] Modulus of alkali silicate solution.

[b] Molarity of alkali hydroxide solution.

[c] Alkali silicate-to-alkali hydroxide weight ratio (R)

Table 2

Inventory of energy consumption and carbon emissions of concrete ingredients.

Ingredients (kg/m^3)		UHPGC		UHPC	Embodied energy (MJ/kg)	Carbon emission (kg/kg)	Cost (USD/t)
		Mix 1 [56]	Mix 2 [59]	[72]			
PC		-	-	863	4.8 [6]	0.83 [6]	95 [43]
GGBFS		889.24	850.23	-	0.33 [73]	2.65×10^{-2} [12]	77 [43]
Fly ash		222.31	-	-	0.1 [74]	4×10^{-3} [74]	70 [43]
Silica fume		93.37	283.4	216	0.1 [74]	1.4×10^{-2} [74]	168 [43]
Sand		722.91	846.65	923	0.175 [13]	2.6×10^{-2} [13]	56 [43]
Steel fibres		157	157	156	20.59 [38]	1.49 [38]	1259 [43]
NaOH		-	99.19 (Solid: 44.04)	-	9.5 [75]	0.75 [75]	1516[a]
Na_2SiO_3	M_s[*] = 0.9	105.62 (Solid: 102.73)	-	-	1.057 [76]	0.57 [76]	1944[a]
	M_s[*] = 2.0	-	297.58 (Solid: 165.16)		5.371 [76]	0.289 [76]	2115[a]
	M_s[*] = 3.2	156.89 (Solid: 57.11)	-	-	10.953 [76]	1.066 [76]	2310[a]
Water		107.67	-	194.22	-	-	-
Superplasticizer		52.30	-	92.79	36.76 [13]	1.48 [13]	1293 [43]

Note:

[*] Ms is the modulus of Na2SiO3, which is the ratio of SiO2 to Na2O.

[a] Prices are from a major supplier in the UK.

consumption, followed by Na_2SiO_3. In Mix 2 where no superplasticiser is used, Na_2SiO_3 and NaOH constitute the second and third largest energy contributors, with GGBFS following. In contrast, for UHPC production, PC, superplasticizer, and steel fibres exhibit comparable energy demands and represent the three largest contributors, whereas the energy required for manufacturing sand, silica fume, and fly ash remains relatively low in both UHPGC and UHPC.

Regarding carbon emissions, the distribution differs significantly between UHPGC and UHPC. In UHPC, PC production contributes the highest emissions (716 kg), accounting for approximately one-third of the total carbon footprint, surpassing the entire CO_2 emissions associated with UHPGC production as shown in Fig. 4. Steel fibres constitute the second-largest source of CO_2 emissions, generating approximately one-third of those attributed to PC, while superplasticizers and sand rank third and fourth, respectively. Conversely, in UHPGC, steel fibres and Na_2SiO_3 are the two largest sources of CO_2 emissions, followed by NaOH or superplasticizer, depending on the mix composition. The carbon footprints of GGBFS and sand are relatively similar, while other materials contribute only minor emissions. Overall, steel fibres and alkali activators are the primary contributors to the carbon footprint of UHPGC production.

It is noteworthy that the compressive strengths of UHPGC Mix 1 and Mix 2 are 199.0 MPa and 150.6 MPa, respectively, while the compressive strength of UHPC mixture is 142.2 MPa. Their corresponding unit embodied energy per compressive strength are 31.86,

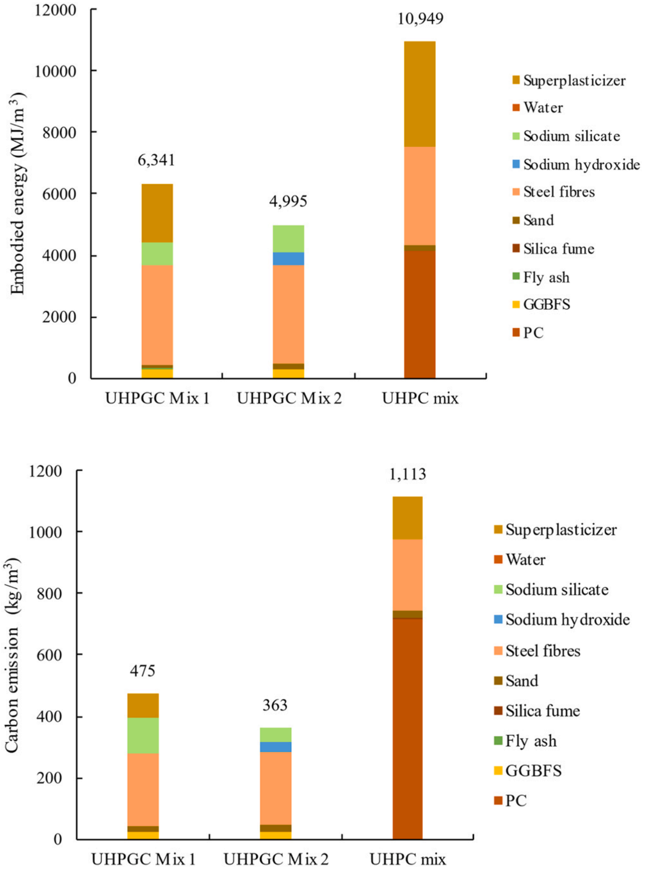

Fig. 4. Sustainability indicators of different concrete composites.

33.17 and 50.38 MJ/m^3/MPa, respectively, and their unit carbon emission per compressive strength are 2.39, 2.41 and 5.97 kg/m^3/MPa, respectively. It is evident that the energy consumption for producing UHPGCs is lower than that of UHPC with the same steel fibre content, and the carbon footprint of UHPGC mixtures is nearly half, or even less, than that of UHPC. Clearly, the environmental impact of UHPGC is significantly lower than that of UHPC.

The significant energy demands associated with steel fibre production highlight the need for future research to explore more sustainable fibre options, such as recycled steel fibres or synthetic recycled fibres, for use in UHPGC or UHPC production. Additionally, investigating alternative activators that are less energy-intensive and more readily available is recommended to further mitigate the environmental impact of UHPGC.

3.3. Mechanical properties

The mechanical properties of UHPC and UHPGC were compared in terms of compressive strength, flexural strength, tensile strength, and elastic modulus, based on available data from existing literature. Notably, when multiple curing durations are reported in the literature, the 28-day mechanical properties are prioritized for comparison in this section. If the 28-day properties are unavailable, the 7-day or 56-day strength is used, depending on the available data. The UHPC mixture used for the mechanical strength comparison in Fig. 5 is based on the mixture detailed in Table 2, which serves as the reference for comparison with the UHPGC mixtures. As can be seen in Fig. 5(a), UHPGC achieved a maximum compressive strength of 222 MPa and an average of 160 MPa, which is approximately 18 MPa higher than that of UHPC (142.2 MPa). However, as shown in Fig. 5(b), the flexural strength of UHPC (39.7 MPa) significantly exceeds the average flexural strength of UHPGC (16.7 MPa), although a peak flexural strength of 42.3 MPa was reported by Xu et al. [34] for UHPGC. In terms of tensile strength and elastic modulus (Fig. 5(c) and (d)), the average values for UHPGC are 9.8 MPa and 40.4 GPa, respectively, with peak values reaching 15.9 MPa and 49 GPa. However, tensile strength and elastic modulus data for UHPC, as reported by Arunothayan et al., are not available. These comparative analyses demonstrate that UHPGC offers mechanical performance similar to that of UHPC, highlighting its potential as a viable alternative to UHPC in applications. The key parameters influencing both the fresh and hardened performances of UHPGC will be discussed in the following section.

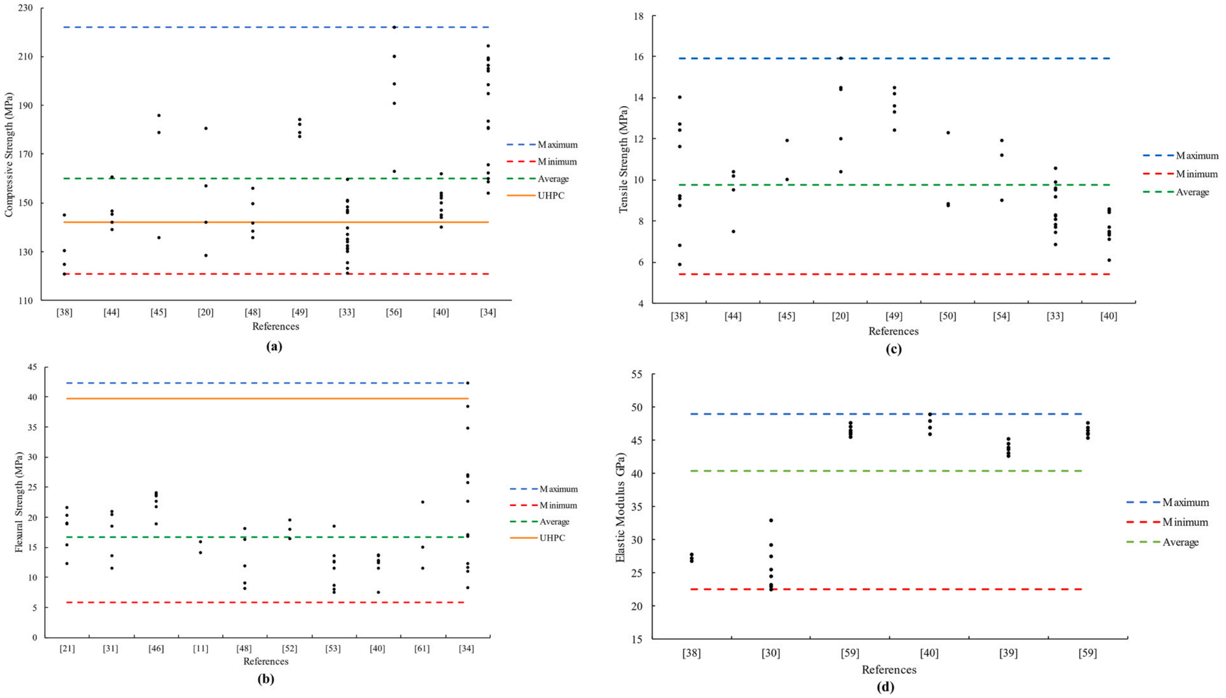

Fig. 5. Hardened properties of UHPGC collected from literature in comparison to a typical UHPC: (a) compressive strength, (b) flexural strength, (c) tensile strength, and (d) elastic modulus.

3.4. Key parameters affecting the performance of UHPGC

The main parameters that affect the fresh properties of UHPGC are precursor, activator and fibre. The basic structures of geopolymer consist of silica tetrahedra (SiO_4) and aluminium oxide tetrahedra (AlO_4) linked by common oxygen atoms [77]. Therefore, the silica (Si) to aluminium (Al) ratio in the precursor plays an important role in the properties of geopolymer concrete. Additionally, calcium content in the precursor, typically introduced through GGBFS, also significantly affects fresh properties by accelerating reaction kinetics. In a study by Xu et al. [34], increasing the Si/Al ratio from 2.5 to 4.5 by adjusting the proportions of GGBFS and fly ash led to a reduction in flowability from 240 mm to 205 mm. Similarly, as the GGBFS ratio increased from 0.193 to 0.933, flowability decreased from 340 mm to 265 mm, representing a 22.1 % decline. Furthermore, the calcium content in the precursor notably affects the setting time. Gao et al. [78] found that a GGBFS/fly ash ratio of 70/30 resulted in an initial setting time of 27 minutes, which increased to 76 minutes for a 30/70 ratio. The final setting time also extended from 71 to 128 minutes. In addition to the precursor composition, the content and concentration of alkaline activators also play a crucial role in the geopolymerisation reaction, significantly influencing the fresh characteristics of UHPGC. A higher concentration of alkaline activators enhances the chemical reaction between the activator and the precursor materials, leading to a faster setting time and improved strength development. However, it may also result in a more viscous mixture, potentially affecting the ease of mixing and handling [79,80]. Waqas et al. [81] designed twenty trial mixes with varying alkaline activator solution dosages (35 % and 40 %), Na_2SiO_3 to NaOH ratios (2.0, 2.5, and 3.0), and NaOH concentrations (10 M, 12 M, and 14 M) to study the effect of these parameters on the fresh and mechanical properties of fly ash and GGBFS-based geopolymer concrete. Their study concluded that the workability of the mixes decreased with reduced activator solution dosage, and increased Na_2SiO_3 to NaOH ratio and NaOH concentration. While increasing the Na_2SiO_3 to NaOH ratio prolonged both the initial and final setting times of the concrete [79]. Notably, the concentration of NaOH has the greatest effect on the workability and setting time, while the Na_2SiO_3 content has a greater effect on the later strength characteristics [80]. Apart from the influence of precursor and activator on fresh properties, most of the study results showed that the flowability of fresh mixes decreased with increasing fibre content and fibre length [11,21,61]. Aisheh et al.[40] investigated the fresh properties of UHPGC reinforced with PP fibres, steel fibres, and their combination. They found that flowability exhibited an almost linear decline as the fibre volume fraction increased from 0 % to 2.25 %, regardless of fibre type. Similarly, Xu et al. [28] observed that the flowability of G-UHPC incorporating steel fibres of different lengths (6 mm, 12 mm, and 13 mm) with a diameter of 0.12 mm decreased nearly linearly with fibre length. This reduction was attributed to the greater surface area and interlocking effect of longer fibres, which increased internal friction and hindered the movement of the fresh mix.

The main parameters affecting the mechanical properties of UHPGC include the binder composition, activator type and dosage, reinforcement strategies and curing regime. The binder composition significantly affects the strength development of UHPGC by influencing the geopolymerisation process, gel formation, and microstructure. High-calcium binders, such as GGBFS, enhance strength development by facilitating C-S-H or C-A-S-H gel formation, leading to a denser microstructure with reduced porosity [20,82]. Lao et al. [20] further demonstrated this effect by showing that when the GGBFS content increased from 20 % to 80 % at a water-to-binder ratio of 0.22, the compressive strength significantly improved from 103.9 MPa to 180.7 MPa. However, they also observed that with increasing GGBFS content, the tensile strength and ductility of the developed geopolymer composite initially declined before subsequently improving. Conversely, low-calcium precursors, such as fly ash and metakaolin, improve long-term durability but have a slower effect on early strength compared to high-calcium binders [82,83]. In a study on fly ash-based UHPGC, Lao et al. [84] achieved a compressive strength of 122.7 MPa, a tensile strain capacity of 8.0 %, and a tensile strength of 12.9 MPa by using 6 % alkalinity. This mix reduced energy consumption by 50.0–74.6 % and lowered the cost per MPa by 40.1–53.6 % compared to the control mix with cement. Besides, the type and dosage of alkaline activators have a significant impact on the strength development of UHPGC as well. It has been generally found that sodium-based activators result in higher UHPGC mechanical and microstructural properties than lime-based or potassium-based activators [85]. However, exceptions exist. For example, Ambily et al. [70] used a combination of sodium silicate with sodium hydroxide and potassium silicate with potassium hydroxide to activate GGBFS and silica fume. With the addition of 1 % fibres measuring 6 mm in length, the potassium-based mixture achieved a 28-day compressive strength of 130 MPa, whereas the sodium-based mixture reached only 75 MPa. Additionally, increasing the fibre content to 2 % with 13 mm fibres in the potassium-activated mix further boosted the compressive strength to 175 MPa. Furthermore, the dosage of the alkaline activator also significantly influences the strength development of UHPGC. In Aisheh et al. [40] study, increasing the Na_2SiO_3/NaOH ratio from 1.5 to 3.5 and the NaOH concentration from 6 M to 14 M to activate GGBFS and silica fume resulted in a maximum compressive strength of 115 MPa at 28 days. When 2 % steel fibres were added, the 28-day compressive strength increased to 150 MPa, while the flexural strength reached 13.3 MPa. This significant improvement was attributed to the combined effect of an optimal activator dosage and fibre reinforcement, which enhanced both compressive strength and ductility. In addition to the activator, the type, geometry, size, and dosage of fibres also play a critical role in the overall performance of UHPGC. Of all the fibres, steel fibres are the most extensively studied fibres for UHPGC due to their outstanding mechanical properties and their effectiveness in bridging micro-cracks, which enhances flexural and compressive strengths and improves load-carrying capacity. Numerous studies on UHPGC have demonstrated that the mechanical strengths improve as steel fibre content and length increase [34,57,64,67,86]. For instance, Xu et al. [34] examined the effects of steel fibre size and dosage on the hardened properties of UHPGC made with GGBFS and fly ash activated by NaOH and waterglass, finding that increasing the fibre length-to-diameter ratio (aspect ratio) and fibre dosage improved flexural and compressive strengths. The highest flexural strength (42.3 MPa) was observed at a 3 % fibre dosage with an aspect ratio of 125, while compressive strength increased significantly from 0 % to 2 % fibre dosage, reaching a maximum of 214.5 MPa at 3 %. Liu et al. [67] systematically investigated the impact of steel fibre geometry, size and dosage on the mechanical performance of newly developed UHPGC, which was produced using GGBFS, fly ash, and silica fume, activated by NaOH and waterglass. They used four straight steel fibres with varying volume fractions (0 %, 1 %, 2 %, and 3 %) and aspect ratios (6/0.12, 8/0.12, 13/0.12, and 13/0.20), as well as two types of deformed steel fibres (hooked-end and corrugated). The findings revealed that increasing fibre volume and decreasing fibre diameter enhanced the mechanical strengths of UHPGC, with flexural behaviour improving as fibre volume and length increased. At 3 % fibre content, the highest flexural strength (33.3 MPa) and compressive strength (170.4 MPa) were achieved with straight fibres (aspect ratio 13/0.12), compared to the unreinforced mix (101.9 MPa). Deformed fibres had inferior strengthening and toughening efficiency, while straight fibres, particularly those longer and smaller in diameter, offer better performance. Furthermore, curing conditions significantly influence the reaction kinetics of the geopolymer binder and, consequently the rate of strength development and overall porosity [11]. Extensive investigations have demonstrated that heat curing is essential for accelerating polymerisation and achieving the desired mechanical properties of geopolymer concrete within a relatively short timeframe [41,48,60]. Among various heat curing methods, oven and autoclave curing are the most frequently employed techniques to enhance the strength gain rate of UHPGC [30,41]. For instance, Tahwia et al. [41] investigated the fresh and hardened properties of waste materials-based UHPGC under four curing regimes: ambient, water, autoclaved, and oven curing. In their study, oven curing was performed at 80 °C for 24 hours, while autoclave curing was conducted at 90 ± 5 °C for 48 hours. Their findings revealed that compressive strength increased by 6.35 % and 10.42 % under oven and autoclave curing, respectively, compared to ambient temperature curing. These results align with the findings of Althoey et al. [30], further confirming the effectiveness of elevated temperature curing in enhancing the mechanical performance of UHPGC.

Due to the limited research on the durability of UHPGC, the main parameters affecting its durability can be summarised as precursors, activators and fibres based on the available studies. Dense particle packing and the use of highly reactive aluminosilicate materials will create a dense microstructure that will enhance the durability of UHPGC. Moreover, a higher alkali concentration can significantly mitigate chloride penetration by enhancing the geopolymerisation reaction and thus reduces the porosity of the material [35]. Additionally, the incorporation of steel fibres further enhances the durability of UHPGC by decreasing porosity, preventing the formation of cracks and lowering permeability, ultimately improving its resistance to chloride ion penetration [87,88]. Further improvements in durability can be achieved by adding polypropylene fibres or by partially replacing steel fibres with polypropylene fibres, as compared to the use of steel fibres alone [82]. Future studies are recommended to explore additional factors affecting the durability of UHPGC.

3.5. Cost analysis

The cost comparison analysis between UHPGC and UHPC presented in this chapter is based on the mixture proportions and cost information provided in Table 2. The compressive strength of UHPGC Mix 1, Mix 2 and UHPC mixture are 199.0 MPa, 150.61 MPa and 142.2 MPa, respectively, and their corresponding unit cost per compressive strength are 4.89, 7.55 and 3.42 USD/tonne/MPa, respectively. The unit cost per compressive strength of the UHPGC Mix 2 is approximately twice that of the UHPC mix, whereas the unit cost for UHPGC Mix 1 is slightly higher than that of the UHPC mix. The primary cost difference between UHPGC and UHPC arises from the use of activators in UHPGC, with Na_2SiO_3 being a significant contributor to this increase. Na_2SiO_3 has a very high unit price and is used in large quantities, accounting for the largest share (55–58 %) of the total cost of UHPGC production. As shown in Fig. 6, the cost of steel fibre is the second largest contributor to UHPGC costs, following Na_2SiO_3 and NaOH. Although NaOH has a similar unit price to Na_2SiO_3, it is used at about a quarter of the amount of Na_2SiO_3 in UHPGC Mix 2, resulting in a significantly lower overall cost, placing it third in the cost composition. The unit price of superplasticiser is slightly higher than that of steel fibre, but due to the lower dosage, its cost is about one-third of the cost of steel fibre in the production of UHPGC Mix 1. In terms of precursors, silica fume (USD 168/tonne) has the highest unit cost, while GGBFS (USD 77/tonne) and fly ash (USD 70/tonne) have similar unit costs. However, the high dosage of GGBFS in UHPGC mixes makes it account for 6–7 % of the total UHPGC cost, which is approximately three times the cost of fly ash and silica fume in UHPGC Mix 1, and 1.5 times the cost of silica fume in UHPGC Mix 2. Sand has the lowest unit price among all raw materials used in UHPGC production, despite being the second most utilised material in UHPGC mixes, its overall cost remains among the lowest or second lowest in the production process.

In the production of UHPC mixes, steel fibre accounts for the highest cost, representing 40 % of the total material cost. Despite being the least used material in the mix design, superplasticiser is the second most expensive due to its high unit cost. PC is the second most consumed material in UHPC production; however, it ranks as the third most costly material due to its lower unit price compared to steel fibre and superplasticiser. Sand is the most used but has the lowest unit price, making it the second lowest overall cost. Silica fume is the most expensive material in terms of unit price, but it is not used in large quantities, making it the lowest overall price. Notably, the cost values for UHPC presented in this section are estimated for the purpose of comparison with UHPGC. For typical cost values of UHPC mixture, please refer to the work done by Mugahed et al. [7].

4. Limestone calcined clay cement

An emerging method for producing low-clinker UHPC in recent years is the use of LC^3 as an alternative to PC. LC^3 is a new type of cement that consists of clinker (50 %), calcined clay (30 %), limestone (15 %) and gypsum (5 %) [89]; whereas, traditional Portland cement consists of 95–98 % clinker and 2–5 % gypsum. By November 2024, research on the use of LC^3 as an alternative to PC in the

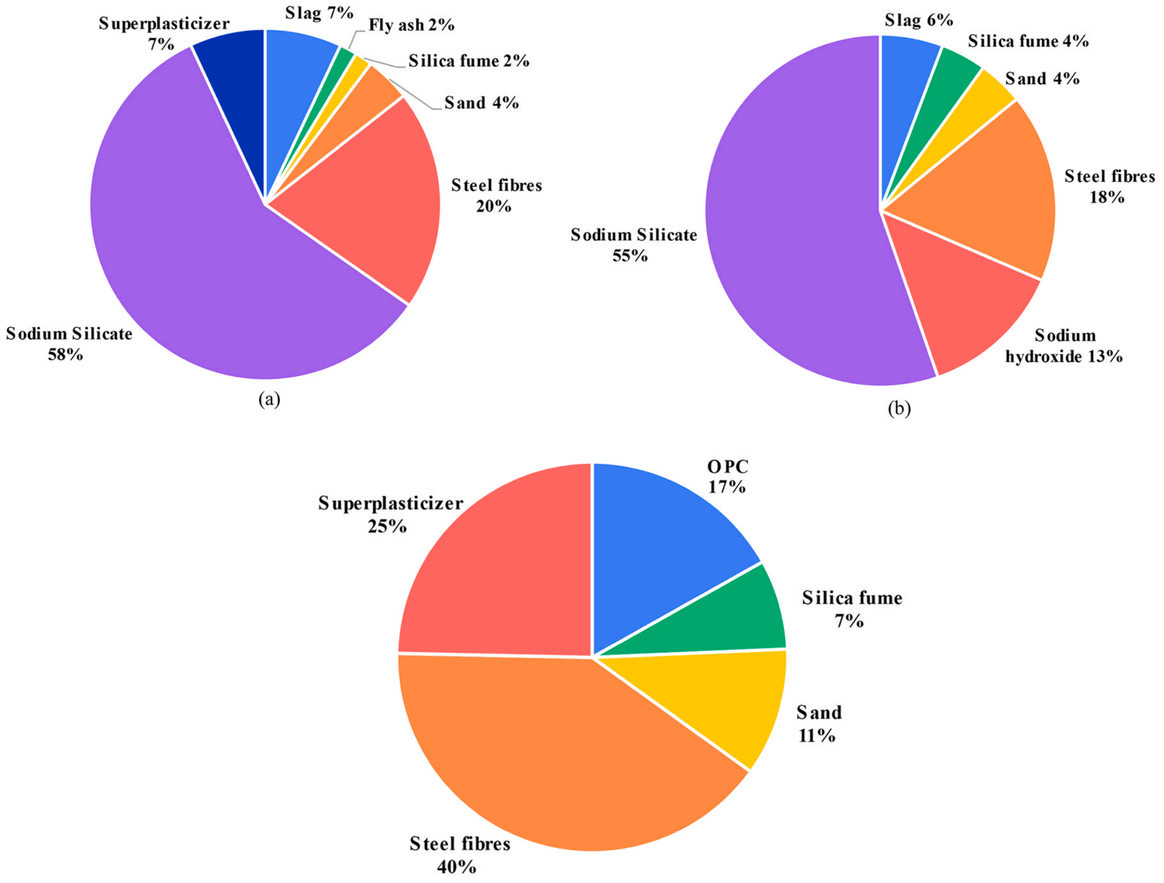

Fig. 6. Cost composition of (a) UHPGC Mix 1, (b) UHPGC Mix 2, and (c) UHPC.

manufacture of UHPC is very limited, with only ten publications. In 2021, the relevant article was published for the first time, followed by two articles in 2022, and seven in the next two years. Of these articles, they are all research articles. Two countries have conducted research in this field, namely China and South Korea, with nine and one articles published, respectively. According to published articles, LC^3-UHPC is characterised by low carbon emission, cost efficiency and high compressive strength [15,16], making it a promising eco-friendly construction product. Guo et al. [15] explored the mechanical properties and microstructural features of UHPC with various amounts of LC^3 (15 % and 30 %) and recycled fine aggregate (30 %, 60 %, and 100 %). The findings indicated that the compressive strength of the mix containing 15 % LC^3 and 30 % recycled aggregate (around 131 MPa) was similar to that of the mix containing 100 % cement and 30 % recycled aggregate (around 126 MPa). The tensile strength of the mix with 30 % LC^3 (8.54–10.92 MPa) was also comparable to the control mix with 100 % cement (9.48–12.64 MPa). The result indicated that LC^3 incorporation resulted in the formation of additional hydration products, which improved pore structure and reduced porosity. Besides, when compared to the control mix (100 % cement with quartz sand), the mix containing 15 % LC^3 and 30 % recycled aggregate achieved a reduction of 120 kg of carbon dioxide and 580 MJ of energy per cubic meter, highlighting the significant environmental benefits of incorporating LC^3 and recycled fine aggregates in UHPC. It is worth noting that LC^3 is now officially included in the BS EN 197–5:2021 standard [90] for the preparation of mortars and concretes. However, the half proportion of clinker in the composition could be further replaced by sustainable materials and make LC^3-based UHPC more environmentally friendly. Furthermore, the durability of UHPC incorporating LC^3 remains an area that requires further investigation to fully understand its long-term performance and resilience under various environmental conditions.

5. Recycled fibres

To reduce environmental impact, some research has employed recycled fibres as an alternative to steel or synthetic fibres. Using recycled fibres plays a significant role in reducing environmental impacts, minimising waste streams and landfill disposal and lowering the overall cost of concrete [91]. Studies have shown that a variety of fibres recovered from different waste streams are suitable for producing reinforced concrete, but only a few studies have focused on the incorporation of recycled fibres in UHPC. The search keywords used to retrieve publications on UHPC incorporating recycled fibres included “ultra-high-performance fibre-reinforced concrete”, “ultra-high-performance concrete”, “fibre reinforced ultra-high-performance concrete” and “recycled fibre” or “waste fibre”.

Fig. 7 shows the publication timeline on UHPC containing fibres up to November 2024, with a total of 34 articles, of which 94 % are research articles, while dissertations and review articles each account for 3 %. As depicted in Fig. 8, according to the national affiliation of the researchers, a total of 19 countries have investigated the recycled fibre-reinforced UHPC. China headed the list with ten publications, followed by Saudi Arabia with five. Meanwhile, the United Kingdom, Poland and the United States of America each contributed four publications. Other countries such as Iran and Iraq have contributed one to three articles each.

Among the limited articles on the use of recycled fibres as an alternative to industrial fibres in the production of UHPC, Isa et al. [23,92] developed a cost-effective and eco-efficient UHPC incorporating recycled tyre steel cords (RTSC) and recycled tyre steel fibres (RTSF). Their findings indicated that RTSC exhibited properties comparable to manufactured steel fibres, particularly in terms of compressive, flexural and shear strengths, with fibre length significantly influencing performance. Specifically, 12 mm and 15 mm RTSC lengths demonstrated superior strengths and post-cracking stiffness. However, at the same fibre content, the RTSF exhibited a 40 % lower flexural strength and 64 –74 % lower shear strength than corresponding mixtures containing RTSC. Notably, a hybrid combination of RTSC and RTSF achieved strengths comparable to mixes containing only RTSC or manufactured fibres. In addition to its mechanical performance, RTSF offers significant cost and environmental benefits over RTSC and manufactured fibres, being 48–80 % more cost-efficient and 69–135 % more environmentally efficient, depending on fibre dosage. This demonstrates the potential of RTSF as a sustainable and economical alternative in UHPC production. Similarly, in a study by Zhong et al. [93], the replacement of industrial steel fibres with recycled tyre steel fibres (up to 1.0 %) in UHPC, resulted in an increase in compressive, flexural and tensile strengths by 2–12 % compared to UHPC containing 2 % manufactured steel fibres. This substitution also significantly reduced the material cost, embodied carbon, and embodied energy of mono-fibre reinforced UHPC by approximately 9–57 %, highlighting the

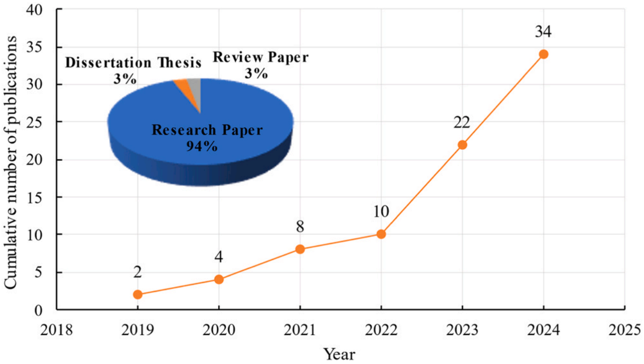

Fig. 7. Trends of publications on recycled fibres till November 2024.

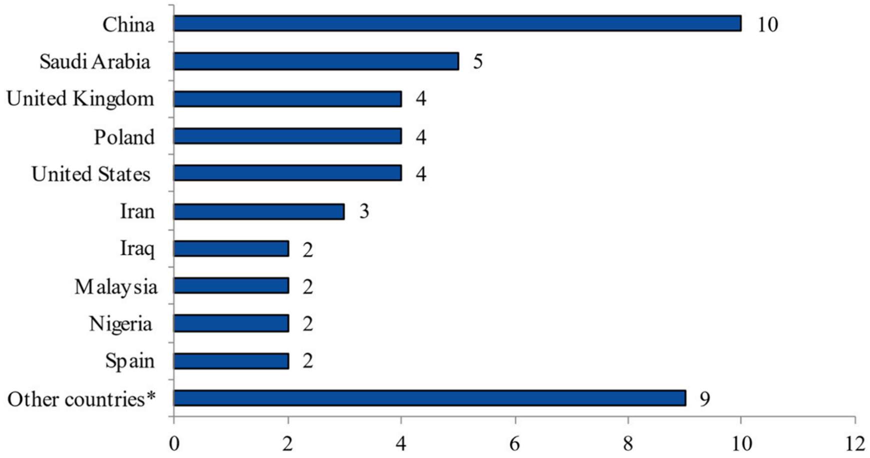

Fig. 8. Publications on recycled fibres till November 2024 (based on the national affiliation of the researcher). *Other countries include Canada, Croatia, Ecuador, France, Malta, Pakistan, South Korea, Türkiye, United Arab Emirates (each country contributing one article).

potential environmental and economic benefits of using recycled tyre steel fibres. However, the mechanical properties deteriorated when the replacement rate exceeded 1 %. In another related study, Yang et al. [94] also recommended the use of recycled steel fibres. Their experiments demonstrated that both corrugated recycled steel fibres with rubber (RSFR) and without rubber (RSF), each 40 mm in length, enhanced splitting tensile strength, fracture energy, and high-temperature anti-spalling behaviour of UHPC. Nevertheless, RSFR reduced compressive strength by 5.3 MPa compared to plain UHPC, likely due to weak bonding and increased air voids, while RSF improved compressive strength by 4.3 %. In addition to the use of recycled steel fibres, Overhage et al. [95] explored the potential of recycled carbon fibres (rCF) in UHPC. The rCF in UHPC demonstrate enhanced mechanical performance, especially tensile strength. The addition of resized rCF increased the tensile strength by at least 14.9 % compared to UHPC reinforced with virgin carbon fibres (vCF). Furthermore, the compressive strength of UHPC with 1 % resized rCF was 32 % higher than that of plain UHPC, while the compressive strength of UHPC with 0.5 % resized rCF was slightly lower by 8.2 %. The use of rCF also showed promising results in combination with steel fibres, increasing the tensile strength by up to 66.1 % compared to plain mortar. Although the study did not directly compare cost and environmental impacts, the potential for recycled fibres to offer a more sustainable and cost-effective alternative is evident. Overall, the use of recycled fibres in UHPC not only enhances mechanical properties but also offers significant environmental and cost benefits. Future research should focus on evaluating the long-term durability and high-temperature performance of recycled fibres in UHPC. Additionally, exploring novel recycled fibre types and optimizing hybrid fibre systems could further improve mechanical properties and sustainability.

6. Recycled fine aggregates

The search keywords used to retrieve publications on UHPC incorporating recycled fine aggregates included “ultra-high-performance fibre-reinforced concrete”, “ultra-high-performance concrete”, “fibre reinforced ultra-high-performance concrete”, “UHPC”, “UHPFRC”, “FR-UHPC” and “recycled aggregate”, “recycled sand” or “recycled materials” or “waste aggregate”. After the second round of excluding irrelevant articles, a total of 80 articles were selected as the basis for data analysis. As shown in Fig. 9, the very first article was published in 2014, with no research progress observed in this area between 2014 and 2016. Publications remained limited

Fig. 9. Trends of publications on recycled fine aggregates till November 2024.

from 2017 to 2019, but from 2019 onwards, there was a remarkable increase in the number of published articles, with a total of 56 articles released. Of these articles, research articles accounted for 95 %, making it the predominant article type, followed by review articles at 4 %, and conference articles at 1 %. As illustrated in Fig. 10, according to the national affiliation of the researchers, China is a front runner with 54 published articles. Saudi Arabia, South Korea, Australia and Egypt each contributed between five and six articles, while other countries such as Italy and Malta contributed one to four articles.

The impact of using recycled fine aggregate as a substitute for natural sand on UHPC properties varies depending on the treatment and processing methods employed. Some studies suggest that additional measures are required to mitigate the negative impact of recycled fine aggregate on mechanical properties, as it increases the permeable pore volume and reduces strength [96]. For example, Huang et al. [97] improved the performance of recycled fine aggregate through carbonation treatment and investigated its effect on replacing quartz sand in UHPC, with replacement ratios ranging from 0 % to 30 % by mass of total sand. The results showed that increasing the carbonated recycled fine aggregate content from 0 % to 30 % reduced autogenous shrinkage by 45 %, owing to enhanced surface performance that increased restraint on mixture shrinkage. In contrast, using 20 % uncarbonated recycled fine aggregate led to 12 % and 10 % reductions in 28-day compressive and flexural strengths, respectively. However, when 20 % carbonated recycled fine aggregate was used, the 28-day compressive and flexural strengths were similar to those of UHPC without recycled fine aggregate. Moreover, the addition of 20 % carbonated recycled fine aggregate not only reduced the global warming potential by 5 % but also decreased UHPC cost by over 15 %, highlighting its potential for sustainable and cost-effective UHPC production. In another study by Jean et al. [98], the chloride permeability coefficient and frost resistance of a mix containing 100 % carbonation-treated recycled fine aggregate showed a 50 % decrease and a 27.6 % increase, respectively, compared to a mix with 100 % untreated recycled fine aggregate. Beyond pretreatment, other strategies such as incorporating nanomaterials have been explored to improve the performance of UHPC containing recycled fine aggregates. Feng et al. [25] found that the addition of recycled sand had a significant negative impact on compressive strength compared to mixes made with only natural sand. Replacing 25 % of the natural sand with recycled sand resulted in a 12 % reduction in compressive strength, reducing it from 151.89 MPa to 133.37 MPa. A more significant reduction was observed when 50 % of the natural sand was replaced, leading to a 32 % decrease in compressive strength, which dropped to 103.22 MPa. However, this deficiency could be mitigated by adding 1 % of nanomaterials (e.g., nano silicates) to the UHPC containing 25 % recycled sand, which resulted in a 14 % increase in compressive strength, raising it to 152.09 MPa, effectively restoring the strength and even exceeding that of the reference mix made with only natural sand. Yu and Wu [99] proposed another method to improve the mechanical properties of UHPC using recycled fine aggregates by incorporating graphene oxide. The inclusion of graphene oxide enhanced the mechanical properties, volumetric stability and durability of UHPC containing 100 % fine recycled aggregates, making them comparable or even superior to those of UHPC containing natural river sand. Notably, Zhou et al. [24] demonstrated that UHPC made with exclusively recycled fine aggregate sourced from construction and demolition waste exhibited higher compressive strength compared to the mixture using natural quartz sand, without any pretreatment or additional materials. In this case, the compressive strength, uniaxial tensile strength and strain capacity of the mixture containing 0–1 mm recycled fine aggregate were 141.32 MPa, 10.44 MPa and 0.56 %, respectively. These values were 11 %, 18 % and 23 % higher than the values registered for the mixture using quartz sand, respectively. Additionally, Xu et al. [100] developed UHPC by incorporating artificial geopolymer aggregates (GPA) (ranging from <0.3 mm to 2.36 mm), resulting in ultra-high compressive strengths (147.4–165.6 MPa) for all GPA-based mixes. Notably, GPA sizes between 0.30 and 0.60 mm led to the highest tensile strain capacity (8.2 %), tensile strength (15.2 MPa), and strain energy density (858.5 kJ/m^3). Those result indicates that it is feasible to produce UHPC using 100 % recycled fine aggregate with standard mixing and curing techniques, without the need for pre-treatment or additional additives to enhance its performance. Future research on recycled fine aggregate in UHPC should focus on optimizing mixture designs, studying long-term performance, investigating particle size effects, and exploring its potential for large-scale

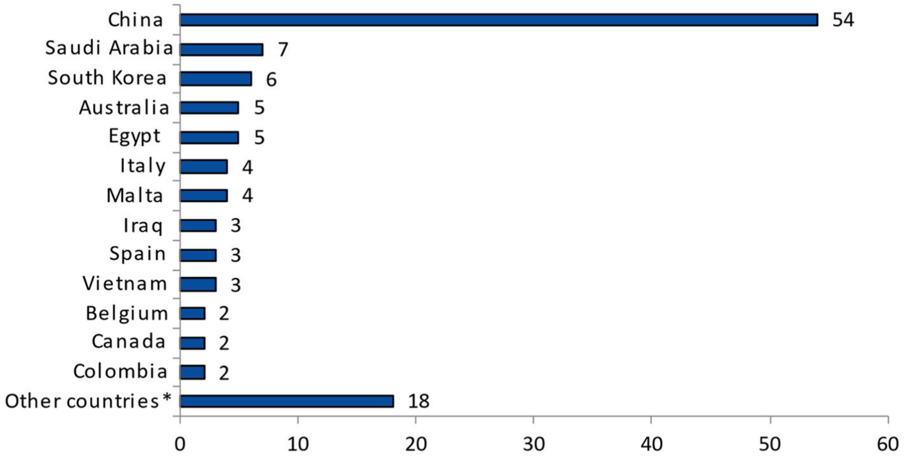

Fig. 10. Publications on recycled fine aggregates till November 2024 (based on the national affiliation of researchers). * Other countries include Bangladesh, United Kingdom, France, India, Iran, Japan, Kuwait, Netherlands, Norway, Oman, Pakistan, Palestine, Poland, Singapore, Thailand, United Arab Emirates, United States (each country contributing one article).

applications and regeneration of fully recycled concrete.

7. Recycled materials as substitutes for silica fume, fly ash or GGBFS

The search keywords used in this section included “ultra-high-performance fibre-reinforced concrete”, “ultra-high-performance concrete”, “fibre reinforced ultra-high-performance concrete”, “UHPC”, “UHPFRC”, “FR-UHPC”, “bagasse ash”, “rice husk ash”, “palm oil shell”, “red mud”, “waste clay”, “wheat straw ash”, “steel slag” and “replace/replacing cement”. A total of 110 articles were selected to meet the setting, as can be seen in Fig. 11. Before 2020, there was a steady increase in publications, after which the field experienced a sharp rise in the past four years. Of these publications, 81 % are research articles, 13 % are review articles, and conference articles are the least represented at 6 %. China remains the leading contributor with 48 articles, followed by Saudi Arabia and Egypt in second and third place, contributing 16 and 15 articles respectively, with a gap of 32 articles separating the top contributor from the second place. Palestine, United States and other countries have published between one and eight articles (see Fig. 12).

In most UHPC manufacturing formulations, silica fume, fly ash and GGBFS are the most widely used SCMs as substitutes for cement, but these materials are sourced from limited supplies, and some are expensive. Therefore, in recent years, there has been a growing interest in the use of agricultural and industrial wastes like bagasse ash, rice husk ash, palm oil shell, wheat straw ash, etc. as SCMs to replace cement. This shift aims to produce more affordable and sustainable UHPC. For example, Alyami et al. [27] investigated the mechanical properties of UHPC after replacing cement with rice husk ash, sugarcane leaf ash and olive waste ash at replacement rates of 0–50 % w/w. Their findings indicated that a 20 % w/w replacement of PC with rice husk ash and sugarcane leaf ash resulted in maximum 28-day compressive strengths of 180.8 MPa and 176.4 MPa, respectively. Additionally, they observed splitting strengths of 23.1 MPa and 22.8 MPa, respectively, and flexural strengths of about 32.5 and 32 MPa, respectively. In the case of olive waste ash, a 10 % cement substitution resulted in the highest 28-day compressive, split tensile, and flexural strengths of 164.2 MPa, 21.3 MPa, and 29.6 MPa, respectively. However, higher PC substitutions led to diminished strengths. The authors recommended using a combination of 25 % rice husk ash and 25 % sugarcane leaf ash as a replacement for 50 % PC (w/w) to produce UHPC. This combination resulted in compressive, tensile, and flexural strengths exceeding 155 MPa, 19 MPa, and 27 MPa, respectively. Wu et al. [101] investigated the application of coal gangue powder as a cement substitute in UHPC with substitution rates ranging from 20 % to 60 %. Their findings showed that coal gangue powder improved the compressive strength of UHPC at later ages, while also enhancing its durability and reducing autogenous shrinkage. In addition, calcined coal gangue powder exhibited higher pozzolanic activity compared to untreated coal gangue powder, which helped to densify the microstructure of UHPC in the range of capillary pores. From a sustainability perspective, the recommended mixture is 60 % untreated coal gangue powder as a cement substitute, which reduces CO_2 emissions by 51.2 % to 238.6 kg/m^3 . Furthermore, Yan et al. [102] studied the use of red mud as a cement substitute in UHPC and found that incorporating 20 % red mud improves mechanical properties, increasing 28-day compressive and flexural strength by 12.5 % and 16.7 %, respectively. Red mud reduces drying shrinkage by 20.62 %, and enhances Na_2SO_4 resistance, although higher red mud content reduces resistance. From a sustainability perspective, 20 % red mud lowers CO_2 emissions by 32 % and cost by 7.02 %. However, exceeding 20 % red mud decreases strength and increases embodied CO_2. Thus, UHPC with 20 % red mud offers a balance of improved performance, cost savings, and environmental benefits. In a similar vein, Tayeh et al. [26] found that incorporating 1–3 % of nano-sized agricultural wastes, such as nano sugar cane bagasse ash, nano cotton stalk ash, and nano rice straw ash resulted in a densified matrix and increased the compressive strength of UHPC by 18–21 %. Other studies have similarly investigated the inclusion of sugar cane bagasse ash as a filler in UHPC [103], recycled steel slag powder as an SCM in UHPC [104], and recycled glass waste to produce UHPC [105]. For future work, it is recommended to investigate the effect of agricultural wastes on concrete performance under various severe conditions and conduct cost analyses for the use of nano-wastes under different curing regimes. Additionally, exploring other recycled materials that do not require pretreatment such as calcination, particularly those locally available, can further enhance the sustainability of UHPC while offering cost-effective alternatives.

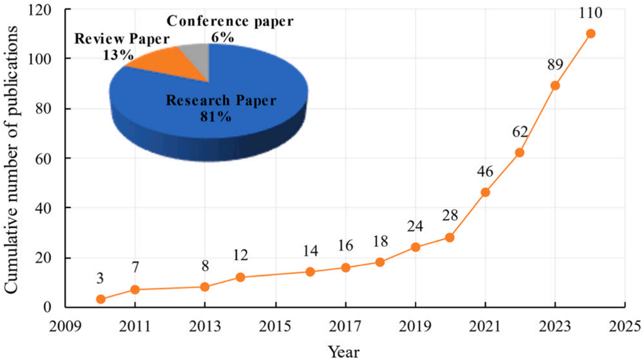

Fig. 11. Trends of publications on recycled materials as substitutes for silica fume, fly ash and GGBFS till November 2024.

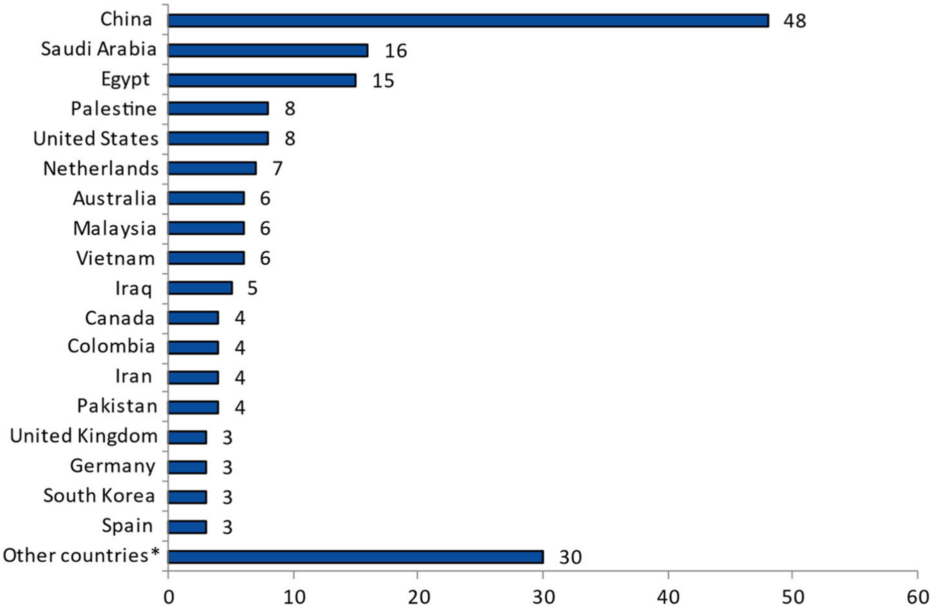

Fig. 12. Publications on recycled materials as substitutes for silica fume, fly ash and GGBFS till November 2024 (based on the national affiliation of the researcher). * Other countries include Algeria, Belgium, India, Indonesia, Singapore, Thailand, Yemen, Brazil, Cyprus, Czech Republic, France, Ireland, Japan, Jordan, Libya, Lithuania, Poland, Portugal, Qatar, Romania, Slovenia, Turkey, United Arab Emirates (each country contributing one to two articles).

8. Natural or recycled coarse aggregates

The search keywords used in this section included “ultra-high-performance fibre-reinforced concrete”, “ultra-high-performance concrete”, “fibre reinforced ultra-high-performance concrete”, “UHPC”, “UHPFRC”, “FR-UHPC”, “coarse aggregate” and “recycled coarse aggregate”. Between 2012 and 2015, a total of five papers were released. This number doubled between 2015 and 2016, with ten papers were published. Since 2017, there has been a steady increase in the number of publications, and this trend leads to a total of 153 papers have been published in the field by November 2024, as depicted in Fig. 13. Of these publications, 91 % are research papers while conference and review papers account for only 6 % and 3 %, respectively. Thirty-one countries have conducted research on the UHPC incorporating either natural or recycled coarse aggregates, with China well ahead of other countries. The Netherlands is in second place with a gap of 105 papers compared to China. United Kingdom, United States and other countries contributed between one to eight papers as shown in Fig. 14.

One of the main barriers to the widespread adoption of UHPC is its high cost. A potential solution to mitigate this issue is to incorporate coarse aggregates, whether natural or recycled, into UHPC mixtures to reduce the reliance on powder materials, thereby lowering the overall cost [28,29]. However, the incorporation of coarse aggregates may adversely affect mechanical performance to some extent. Li et al. [106] designed a UHPC incorporating coarse basalt aggregate with a maximum particle size of 16 mm. The results showed that increasing the basalt size from 3 mm to 16 mm led to a linear decrease in 28-day compressive strength from 144 MPa to 132 MPa and a slight reduction in tensile splitting strength from 9.8 MPa to 8.2 MPa. This strength reduction can be attributed to the lower strength of some aggregates compared to the paste, a weaker interfacial transition zone (ITZ) between the aggregate and paste,

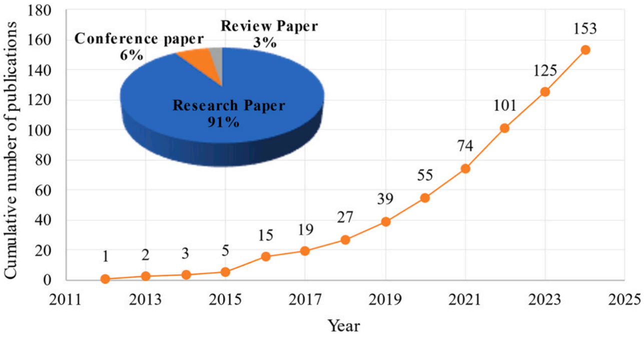

Fig. 13. Trends of publications on coarse aggregates till November 2024.

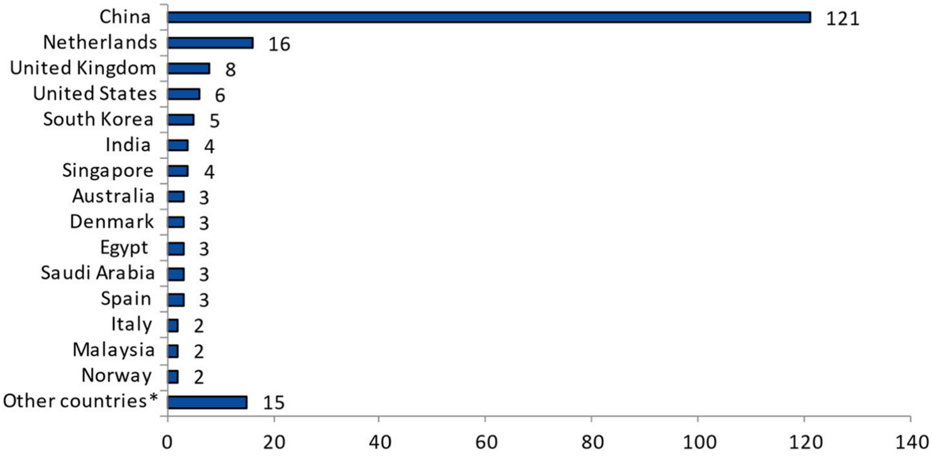

Fig. 14. Publications on UHPC containing coarse aggregates till November 2024 (based on the national affiliation of the researcher). * Other countries include Austria, Belgium, Brazil, Canada, Indonesia, Jordan, Malta, Pakistan, Palestine, Poland, Qatar, South Africa, Vietnam, and Yemen (each country contributing one article).

and stress concentration at aggregate contact points. Additionally, the use of coarser aggregates necessitated a lower powder content, with the authors suggesting that the optimal powder content for UHPC incorporating basalt aggregate is approximately 800 kg/m^3 for a maximum aggregate size of 8 mm and 700 kg/m^3 for a size of 16 mm. Li et al. [29] investigated the elastic modulus and tensile fatigue behaviours of UHPC containing different coarse aggregate contents (10–30 %) with a particle size ranging from 5–10 mm. They found that the elastic modulus of UHPC with coarse aggregate (67 GPa) was significantly higher than that of UHPC without coarse aggregate (40 MPa). However, the fatigue life and fatigue strength of UHPC with coarse aggregate decreased significantly with the increase of coarse aggregate content from 10 % to 30 %. In addition, during the mixing process, the coarse aggregate adsorbed a significant amount of free water, leading to a reduction in hydration products and an increase in the pore volume within the UHPC. This effect further contributed to a reduction in the tensile fatigue strength of UHPC. In order to address the weak ITZ and high water absorption of recycled coarse aggregate in an environmentally friendly manner, Leng et al. [28] developed a sustainable UHPC by treating recycled coarse aggregate with an accelerated carbonation technique, using a particle size range of 2.36–4.75 mm. This carbonation treatment promoted cement hydration on the coarse aggregate surface and reinforced the transition zone between the old mortar and the aggregate. As a result, the carbonation treatment strengthened the recycled coarse aggregate, leading to a 9.1 % increase in compressive strength of the UHPC mixture compared to that using natural aggregate, achieving a compressive strength of 122.66 MPa. Furthermore, the use of carbonated recycled coarse aggregate in UHPC production can reduce environmental parameters (renewable energy input, non-renewable energy input, global warming potential, nitrification potential, and acidification potential) by approximately 5 %, 2 %, 7 %, 3 %, and 16 %, respectively, and decrease the cost by 10 % compared to UHPC with natural fine aggregates.

Currently, studies on the application of coarse or recycled aggregates in UHPC are still relatively limited. Future work should focus on exploring a broader range of coarse aggregate types, sizes, and sources to better understand their impact on the mechanical, durability, sustainability, and cost properties of UHPC. Additionally, the investigation should include optimal mix designs, the effects of various pretreatment technologies on aggregate properties, and the long-term performance of UHPC containing coarse or recycled aggregates under diverse environmental conditions. However, detailed discussions on the microstructure/mesostructure, mechanical properties and durability of recycled coarse aggregates in ordinary concrete have been presented in studies like [107], and these studies can provide valuable references for the future application of recycled coarse aggregates in UHPC.

9. Conclusion and recommendations for future research

Each approach discussed in this article has its pros and cons. Geopolymer and LC^3 are among the most widely studied sustainable alternatives to PC for producing UHPC. However, while LC^3 shows promise, the study of its use in UHPC is still limited. Challenges such as the variability in clay quality and the high-temperature calcination required for LC^3 production must be addressed. Future research is recommended to explore the optimal mix design, curing methods, and long-term performance of LC^3-based UHPC while exploring lower-energy calcination techniques. Additionally, the impact of LC^3 on the durability of UHPC in practical applications requires further investigation.

The environmental analysis indicates that UHPGC has a lower carbon footprint than cement-based UHPC. However, the unit cost per compressive strength of UHPGC remains higher than that of UHPC, primarily due to the price of activators and fibres. To address this issue, future research should explore the use of waste-derived activators and recycled fibres to produce UHPGC to further reduce energy consumption and the unit cost of the material. Additionally, large-scale handling of alkaline solution presents practical challenges, requiring further investigation to optimise production processes and improve the feasibility of UHPGC for widespread application. These efforts will contribute to the development of a more economical and environmentally friendly UHPGC suitable for practical engineering use. Moreover, assessing the long-term performance and durability of UHPGC under various environmental conditions is crucial to ensure its reliability and facilitate its widespread adoption in structural applications.

The incorporation of recycled fibres in UHPC has shown promising mechanical performance, with certain types achieving strengths comparable to manufactured fibres, while also offering significant cost and environmental benefits. However, performance depends on fibre type, dosage, and hybrid combinations, which influence not only mechanical strength but also durability and resistance to extreme conditions. Future research should focus on assessing long-term durability, high-temperature resistance and optimising hybrid fibre systems to enhance mechanical properties and sustainability.

While incorporating recycled fine aggregates offers sustainability benefits, challenges remain in maintaining performance. Pretreatment methods, such as carbonation, improve properties but are energy-intensive and costly, limiting large-scale application. Additives like nanomaterials and graphene oxide also improve strength but increase costs. Future studies should optimise mix designs and pretreatment methods to reduce costs, enhance performance, and support the broader use of recycled fine aggregates in sustainable construction.

In addition, incorporating coarse aggregates into UHPC can further reduce cost and environmental impact, but it may weaken strength due to ITZ issues and water absorption. Optimised mix designs and pretreatment methods can mitigate these effects, improving performance and sustainability. Future research should refine aggregate selection, mix proportions, and durability assessment to maximise the benefits of coarse aggregate incorporation in UHPC.

The replacement of commonly used SCMs (silica fume, fly ash and GGBFS) with agricultural and industrial wastes has shown good mechanical properties and can provide a more economical and sustainable alternative solution. However, the variability in waste composition and transportation-related emissions remains a challenge. Future research could focus on exploring more locally available agricultural and industrial wastes to enhance economic and environmental feasibility.

It would also be desirable to conduct a comprehensive study on the long-term performance and durability of newly developed UHPCs using various approaches discussed in this article. Additionally, research on the impact of different curing methods on the cost, energy consumption, and carbon emissions of UHPGC/UHPC is currently scarce. Further investigations are needed to comprehensively assess how curing methods influence not only the mechanical performance but also the environmental footprint and cost, facilitating the identification of more sustainable production practices for these materials.

CRediT authorship contribution statement

Chougan Mehdi: Writing – review & editing. **Xiao Jianzhuang:** Writing – review & editing, Funding acquisition. **Zhao Xiao (Arling):** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Nematollahi Behzad:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors greatly acknowledge the support provided by the Royal Society International Exchanges 2023 award (IES\R3\233378).

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The authors also greatly acknowledge the "University of Sheffield Institutional Open Access Fund" for covering the article publishing charge for open access publication

Data Availability

Data will be made available on request.

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