USE OF WASTE AND ALTERNATIVE MATERIALS FOR THE PRODUCTION OF SUSTAINABLE ULTRA-HIGH-PERFORMANCE CONCRETE

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1. INTRODUCTION

Ultra-high-performance concrete (UHPC) is a special type of concrete that offers ultra-high mechanical strength, high toughness and highly improved durability (Akhnoukh & Buckhalter, 2021; Niu et al., 2025). In Pierre Richard & Cheyrezy (1995), reactive powder concrete (RCP) was developed, marking an important milestone in the development of UPHC (Niu et al., 2025).

UHPC is an advanced cementitious composite, typically consisting of Portland cement, fine aggregate, steel fibers, silica fume (SF) and high-range water-reducing admixtures (HRWR) (Li et al., 2020; Richard & Cheyrezy, 1994; Richard & Cheyrezy, 1995). UHPC formulations utilize an optimized combination of fine aggregate and silica fume and a low water-to-cement ratio along with superplasticizers to achieve exceptional strength (Bajaber & Hakeem, 2021). According to ASTM C1856/C1856M (2017), UPHC is a cementitious composite having at least 120

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MPa compressive strength, in addition to meeting specific durability, toughness and ductility requirements (Li et al., 2020a). When compared to conventional concrete, UHPC has greatly improved mechanical properties, making it suitable for prefabricated elements since it enables designers to reduce dead loads and element dimensions (Odler & Rößler, 1985; Rößler & Odler, 1985), superior durability, making it suitable for the use of infrastructure elements exposed to harsh environments, and self-healing capacity, due to high amount of unhydrated cement particles (Li et al., 2020a). Since UHPC has exceptional impact strength they are preferred in military structures and in other strategic structures where special protection against earthquakes are required, as well as for the reinforcement of reinforced concrete structures. They are also used to produce prefabricated elements (Özalp, 2006). Bridges, high-rise buildings, structural elements where cross-sectional dimensions are required to be reduced, nuclear installations (Bahmani & Mostofinejad, 2022; Noshiravani & Brühwiler, 2013), airports and stadiums (Fehling, are examples of most common applications of UHPC.

Whilst UPHC offers these advantages, it has major disadvantages such as high costs and environmental impacts owing to its high cement and fine quartz sand contents (Ferdosian & Camões, 2017; Guo et al., 2023; Wang et al., 2012; Yazici et al., 2008). Production of ordinary Portland cement (OPC) is thought to be the source of 8% of the total anthropogenic CO_2 emissions, contributing to greenhouse gas emissions significantly (Altuntas et al., 2025; Andrew, 2018). Thus, researchers have been seeking ways to promote sustainability in UHPC production by means of finding supplementary cementitious materials to replace OPC, and alternative, more sustainable sources of aggregates to replace quartz sand (Guo et al., 2023). In this regard, waste valorization is also of utmost importance. In addition to the use of construction and demolition waste,

especially recycling concrete waste, to promote sustainability in concrete production (Song, Peng, & Zhao, 2025), waste generated through the processes of different industries can also be integrated into mixture designs to preserve natural sources, reduce CO_2 emissions and contribute to the waste management policies. In this chapter, it is aimed to provide an insight into the use of alternative and waste materials for the production of more sustainable UHPC by reviewing the relevant literature and drawing conclusions. It is also expected that the results presented here will be beneficial for the decision makers for the development of new standards, instructing the practitioners to use alternative materials to produce UHPC, thus contributing to the literature by filling the gap caused by the lack of standards concerning the use of such materials for UHPC production.

2. COMPONENTS OF TYPICAL UHPC

A typical UHPC mixture design consists of high dosages of cement, silica fume, fine aggregate, superplasticizers and steel fibers. Water-to-cement ratio is kept as low as possible, such as 0.14-0.24 range (Shi et al., 2024). This low ratio ensures reduced porosity and high strength that is at least three times higher than that of conventional concrete (Aylas-Paredes et al., 2025; Odler & Rößler, 1985; Rößler & Odler, 1985; Shi et al., 2015). Coarse aggregates are typically excluded from UHPC. Dense microstructure of UHPC stems from the optimized use of cement particles with fine fillers and supplementary cementitious materials (Aylas-Paredes et al., 2025; Chan & Chu, 2004; Pierre Richard & Cheyrezy, 1995), to improve particle packing density. In addition, use of steel fibers increases toughness significantly by means of energy absorption, crack size and propagation control (Amran et al., 2022; Aylas-Paredes et al., 2025; Zollo,

1997). Table 1 summarizes typical components and dosages of UHPC.

Alternative and waste materials can be used for the production of UHPC either as a replacement to binders or aggregates. The followings sections will provide information on the use of alternative materials for binders and for aggregates, respectively, also highlighting their effects on the fresh, hardened and durability properties of UHPC as well as environmental performance. Also, the use of some new generation sustainable binders to produce UHPC will be briefly discussed.

3. REPLACEMENT OF CEMENT

Main CO_2 emission contributor of Portland cement production is the energy consumed to calcine and grind the clinker. Hence, although Portland cement has great performance, its environmental impact is high (Atasever & Erdoğan, 2024; Hasanbeigi, Price et al., 2010). One of the most straightforward approaches employed in order to reduce the environmental impacts of cement and concrete industry is using pozzolanic materials to partially replace cement. In this way, it is aimed to reduce the amount of clinker to be used, thus decreasing the greenhouse gas emissions arising from the calcination and grinding processes of the clinker. Most common pozzolans include fly ash (FA), silica fume and ground granulated blast furnace slag (GGBFS). (Hu et al., 2024; Lothenbach et al., 2011). However, the availability of these common pozzolans has become limited in the last years, causing the need to find other alternative materials (Hu et al., 2024; Lothenbach et al., 2011). The idea of contributing to waste valorization strategies while doing so is appealing. For this, the applicability of using other industries' waste for the production of UHPC has emerged as an intriguing idea. Thus, it is important to draw conclusions from existing

studies where these common pozzolans and recently explored other alternative and waste materials are used separately or together to produce UHPC. One such alternative mineral additive is limestone, being locally available in most regions. First reported as reactive by Soroka & Setter (1977) through nucleation effect and cement hydration acceleration properties, its effects on fresh and hardened properties were studied by many researchers (Jiang et al., 2024). Li et al. (2020b) utilized a combination of silica fume and limestone and the resulting UHPC reached 153 MPa compressive strength at the end of 28 days of curing, whilst enabling a significant 47% reduction in CO_2 emissions. It is reported that the degree of secondary pozzolanic hydration caused by silica fume is more intensive than alite/belite hydration, enabling the late-age strength development. Benefits of limestone powder were presented as two major contributions: Firstly, limestone powder reduced inter-particles fraction, caused an electrostatic repulsion between particles due to hydroxyl groups' localization Ca^{2+} surfaces, lowered the absorption and consumption of polycarboxylate ether particles of the superplasticizer, consequently ensuring the optimization of water content and superplasticizer dosage. Secondly, an optimum amount of limestone powder used led to a densified microstructure, most likely by filling effect, improved strength and reasonable total free shrinkage.

Another abundant material that may show pozzolanic behavior is clay. Clay, especially the ones containing a certain amount of kaolin, can be used as mineral additives when they are calcined. Calcined kaolinite clay is called as "metakaolin". Metakaolin is a dehydroxylated aluminate-silicate (Aiswarya et al., 2013). When kaolinite clays are calcined at temperatures ranging in 600°C-900°C (Geu, Zhuge, Ma, & Pham, 2025; W. Li et al., 2022; Skibsted & Snellings, 2019), they gain an amorphous, reactive structure. Metakaolin is also very fine, making it a

competitive pozzolan candidate. In fact, it has good synergy with limestone, and a newly proposed binder called as Limestone Calcined Clay Cement (LC^3), whose use to produce UHPC will be discussed, enables a higher clinker replacement ratio up to 50%. In one study utilizing this synergistic effect, Dong, Liu, & Hu (2023) reported that an overall 60% replacement of clinker with a calcined clay/limestone ratio of 2:1, 28-days compressive strength was higher than that of the reference sample.

Another waste material that is thought to replace cement clinker in UHPC production instead of typical pozzolanic materials is waste marble powder. In recent years, increased demand for marble has led to increased amount of marble waste that is generated during the cutting and polishing of marble. Depending on the type of marble and the production methods, amount of generated waste changes between 30%-50% of the total processed marble by volume (Rana et al., 2016; Rashad et al., 2025). When these wastes are not disposed of appropriately, they might pollute water and rivers (Piccini et al, 2019), soil (Danish et al., 2023; Rashad et al., 2025), air, and when these are not managed properly, they might lead to fully occupied landfill sites and the depletion of natural marble resources (Abbas & Muntean, 2025). Marble powder is fine and has a similar composition to that of limestone, thus it can be used as a mineral additive in cement and concrete production when its oxides could play roles in hydration reactions, or where it could be used as a filler only. There are studies in literature where marble powder is incorporated into UHPC mixture designs (Hardjasaputra et al., 2017; Metwally et al., 2025), confirming the applicability of waste marble powder use to produce cost effective and sustainable UHPC. In a comprehensive review, Metwally et al. (2025a) discussed the usability of fly ash, silica fume, ground granulated blast furnace slag, marble waste powder, basalt waste powder, glass waste powder and granite waste powder as

aggregate or cementitious material replacement to develop metakaolin-based ultra-high-performance geopolymer concrete (UHPGC). Results reported in the literature showed that these waste materials could help develop a cost-effective and more environmentally friendly UHPGC. Bahmani & Mostofinejad (2022) studied the use of slag, limestone, metakaolin, nano-silica, rice husk ash, zeolite, lithium slag, glass powder, cathode ray tube glass sand and incinerator bottom ash comparatively. Produced UHPC samples were studied through characterization methods such as scanning electron microscopy (SEM), x-ray diffraction (XRD), mercury intrusion porosimeter (MIP), thermogravimetric analysis (TGA) and energy dissipative x-ray spectroscopy (EDS). Results revealed that the use of marble powder up to a certain optimum level reduced porosity and improved strength and durability, the use of rice husk ash instead of silica fume reduced CH content and increased porosity, use of slag could reduce porosity, cathode ray tube glass sand increased C_2S/C_3S peak intensity but decreased C-S-H and weakened the bond between cement paste and fine aggregate. In an attempt to produce cementless UHPC, Peng et al. (2025) used calcium carbide residue (CCR) as an activator, incorporating SF and GGBFS. CCR is a byproduct of polyvinyl chloride production (Gong et al., 2022; Peng et al., 2025). Accumulation of this waste poses threats to the environment. The fact that CCR contains high amount of $Ca(OH)_2$ (Peng et al., 2025; Pourabbas Bilondi, Toufigh, & Toufigh, 2018) has paved the way for the investigation of the use of CCR as an activator. In this regard, produced specimens were characterized using XRD, SEM, TGA and MIP methods. Three different curing regimes were adopted, namely standard curing, high temperature curing and combined curing. XRD analyses revealed that calcite and portlandite were observed, coming from CCR, in samples cured under standard curing conditions. In addition, hydration of GGBFS provided additional portlandite. Adoption of high temperature curing promoted pozzolanic

reactions. Consequently, use of CCR, GGBFS and SF was found to be beneficial for cost-effective and sustainable UHPC production.

4. REPLACEMENT OF AGGREGATE

Since UHPC production requires a significantly higher amount of ultra-fine aggregate usage when compared to conventional concrete, related costs and CO_2 emissions are also elevated. In addition, natural river sand resources are being depleted. All these have led researchers to seek alternative aggregate sources (Bajaber & Hakeem, 2021; Hamada et al., 2023; zhang et al., 2025). Recycled aggregates that are typically obtained through crushing construction and demolition waste are important candidates, bearing in mind that they typically have poor mechanical properties and therefore must be improved. Guo et al. (2023) concluded that using 15% LC^3 and 20% recycled aggregate could help producing sustainable UHPC with comparable mechanical properties, highlighting that the combined use of LC^3 and recycled aggregates improved interfacial transition zones (ITZs). Yu, Feng, Leng, Wu, & Li (2025) reported that recycled fine aggregates improved by carbonation are suitable for producing sustainable UHPC with acceptable mechanical properties. Similarly, Ma et al. (2025) observed that using recycled fine aggregate with hybrid steel and polyethylene fibers led to improved mechanical performance and environmental performance.

5. USE OF SUSTAINABLE BINDERS

The development of clinker-based, magnesium-based and alkali-activated sustainable binders has become the focus of research on construction materials, due to the aforementioned

environmental issues related to the production of Portland cement. The use of these as binders to produce UHPC has gained attention due to increased CO_2 emissions related to the high cement content of UHPC (Li et al., 2021; Peng et al., 2025; Yang & Peng, 2015). Among these binders, LC^3 stands out with its capability of reducing clinker by 50% by utilizing the synergy between calcined kaolinite clay and limestone. Dong et al. (2023) observed that when cement was replaced by LC^3 at a replacement level of 60% and when calcined clay/limestone ratio was 2:1, 28d compressive strength was higher than that of the reference sample. Guo et al. (2023) combined LC^3 with recycled fine aggregate to produce more sustainable UHPC with acceptable mechanical properties and the outcomes were promising as 30% LC^3 combined with 30% recycled fine aggregate allowed for reduced CO_2 emissions whilst maintaining acceptable mechanical performance. Pozzolanic reaction and nucleation effect of calcined clay accelerated the hydration. All LC^3 participated in the hydration reactions. MIP results revealed improvements in pore size distribution after LC^3 addition. Also, 30% LC^3 incorporation reduced porosity. Huang et al. (2024) produced UHPC with LC^3, seawater and sea sand incorporation and employed different curing regimes. LC^3 incorporated samples showed highest compressive and flexural strengths across all curing ages and regimes. Limestone powder decreased chloride diffusion coefficient by 4.3%, whilst addition of calcined clay further decreased it, as it was reduced by 35%-40.4% when 20% calcined clay was used. This was attributed to the pozzolanic reaction of calcined clay and pore structure refinement caused by carboaluminates. Thus, it was demonstrated that LC^3 incorporation improved mechanical performance and chloride resistance of seawater and sea sand incorporated UHPC. Use of another clinker based sustainable binder, calcium sulfoaluminate (CSA) cement is also the focus point of research conducted on sustainable UHPC. J. Y. Wang, Chen, & Wu (2019) reported that

CSA-UHPC hardened quickly, reaching 62 MPa compressive strength and 4.4 MPa tensile strength at the end of the first four hours. Cui et al. (2022) reported significant improvements in sulfate resistance of UHPC when CSA cement is incorporated. Meng et al. (2024) observed reductions in CO_2 emissions and energy consumption by 25%-40% and 25%-35%, respectively, when CSA cement was incorporated in UHPC (Meng, Gao, Yang, & Fang, 2025). Magnesium-based binders are also utilized in UHPC. Qin et al. (2022) observed lower shrinkage, higher early strength and on par 28d strength when magnesium phosphate cement (MPC) was used in UHPC. These were attributed to denser microstructure, refined pore structure and strengthened matrix-aggregate interface, when MPC was used with ultra-fine fly ash.

6. CONCLUSIONS

UHPC is a superior cementitious material produced by using cement, silica fume, fine aggregate, fibers and superplasticizers, and possesses significantly improved mechanical performance, durability and toughness when compared to conventional concrete. However, high cement and fine aggregate dosages required to formulate a proper UHPC increases greenhouse gas emissions dramatically. To overcome this, numerous studies have been conducted by employing alternative and/or waste materials to replace cement or aggregate in UHPC designs. In addition, new generation sustainable binders such as LC^3, CSA cement or MPC are also incorporated in UHPC designs to replace cement. Studies in which waste materials such as silica fume, fly ash, ground granulated blast furnace slag, marble powder, basalt powder, zeolite, glass powder and recycled aggregate are used together or combined with binders such as LC^3, CSA cement or MPC show promising results in terms of

reducing the costs and greenhouse gas emissions associated with the distinctive mixture designs of UHPC, whilst maintaining acceptable mechanical and durability performances. In addition, the use of waste materials is shown to be valuable as it contributes to waste management strategies and preservation of natural resources.

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