Cleaner Materials 8 (2023) 100183

Contents lists available at ScienceDirect

Cleaner Materials

journal homepage: www.journals.elsevier.com/cleaner-materials

Comprehensive sustainability strategy for the emerging ultra-high-performance concrete (UHPC) industry

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ARTICLE INFO

Keywords:
Ultra-high performance concrete (UHPC)
Ultra-high performance fibre reinforced concrete (UHPFRC)
Environmental impact
CO_2 emissions
Sustainability
Sustainable concrete

ABSTRACT

The concrete industry is facing significant challenges in substantially reducing CO_2 emissions, recycling waste materials and limiting the use of resources. Using ultra-high-performance concrete (UHPC) is one of the many possible solutions to reduce the environmental impact of the concrete industry. Numerous approaches have been applied to meet the challenges of making and utilising UHPC more environmentally friendly; however, an overall approach is lacking. This study aims to fill this gap by constructing a strategy for more sustainable use of UHPC. The strategy is developed by first evaluating measures known from the conventional concrete industry concerning transferability to the UHPC industry. Subsequently, the approach is enriched with measures targeting the special composition and properties of UHPC. The strategy suggested in the conclusion consists of the following tools: *efficient use of cement*, *efficient use of steel fibres*, *circularity: utilise by-products, local production,* and *efficient use of UHPC in structures*.

Introduction

Background

The world is increasingly facing warmer and wilder climates, potentially threatening civilisations through impacts like droughts, flooding disasters, and massive migration waves. A majority of scientists believe that the reasons for climate change are anthropogenic, i.e., high emissions of greenhouse gases, such as CO_2, from industrialised and high-consumption societies. The building materials sector has been identified as the third largest industrial sector worldwide after CO_2 emissions (UNSTAT, 2010).

An exceptionally unanimous reaction from political leaders worldwide is combating emissions, vitally expressed in the United Nations' Sustainability Development Goals (explicitly in UN-SDG no. 13) and in numerous related initiatives. The vast activities of the construction industry leave environmental footprints in addition to CO_2 emissions. More than 20 years ago, Professor Kumar Mehta published the paper “Reducing the Environmental Impact of Concrete” (Mehta, 2001), where several pathways were suggested for conserving natural resources for all three primary constituents of concrete: aggregate, water, and cement. Reducing CO_2 emissions and other environmental footprints from the construction industry would contribute to achieving several additional goals incorporated in the UN-SDGs, like “Clean water” (no 6), “Industry, innovation, and infrastructure” (no 9), “Sustainable cities and communities” (no 11) and “Responsible consumption and production” (no 12).

Concrete is the most widely used construction material in the world. Concrete structures have numerous sustainable advantages, such as resource efficiency (including the potential for incorporating industrial by-products for binders, fillers, and aggregates), local production, and durability (Hooton and Bickley, 2014), with their embodied CO_2 and energy consumption lower than steel (Coffetti et al., 2022). However, massive greenhouse gas emissions and the demand for resources are associated with the concrete industry (Miller et al., 2016; Habert, 2020). Since the 1990s, the concrete industry has been widely accepted as responsible for 5–7% of global anthropogenic CO_2 emissions, mostly attributed to the production of Portland cement, which is the primary binder in construction concrete. In 2012, the concrete industry was also claimed to be responsible for consuming 5.4 gigatonnes (Gt) of limestone, 17.5 Gt of aggregates, and 2 Gt of water in concrete mixes (Miller et al., 2016; Habert, 2020). According to a recent report by Scrivener et al. (Scrivener et al., 2018), which includes parts of the United Nations Environment Program “Sustainable Building and Climate Initiative” (UNEP-SBCI), cement usage has been growing exponentially since 2000, outperforming the growth of all other building materials and the world population (Fig. 1). Thus, reducing environmental footprints from

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https://doi.org/10.1016/j.clema.2023.100183
Received 9 October 2022; Received in revised form 26 February 2023; Accepted 12 March 2023
Available online 18 March 2023

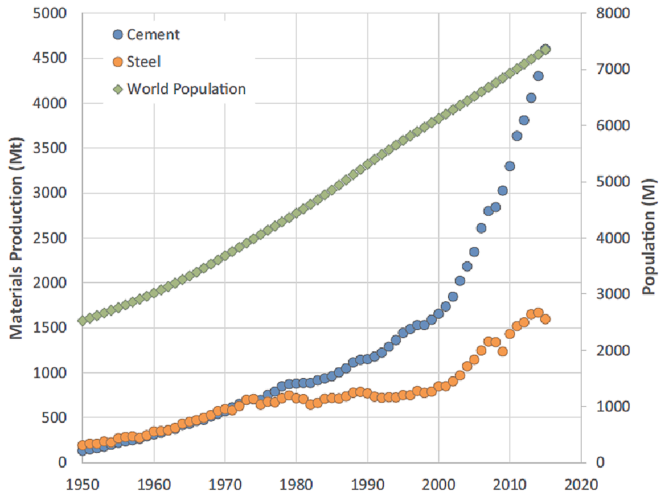

Fig. 1. Comparison of cement and crude steel production growth towards world population, according to Scrivener et al. (Scrivener et al., 2018). Reprinted with permission from Elsevier (Reprinted from Cement and Concrete Research, 2018).

concrete seems imperative for making the construction industry contribute toward reduced CO_2 emissions and natural resources consumption. This goal requires innovations in material production, structural design, and maintenance procedures.

Conclusions from research literature suggest "more efficient use of materials through innovative design, utilisation of advanced and automated production, prefabrication and investigation into smart use of high-performance concrete (HPC) or ultra-high performance concrete (UHPC)" to reduce concrete consumption (Larsen et al., 2019). However, a possible sustainable approach to utilise UHPC has not been sufficiently investigated.

Research gap

HPC/UHPC refers to developing and using concrete types with properties superior to conventional concrete. Some specially designed UHPC types have been given various names in different research communities, but the term ultra-high performance (fibre-reinforced) concrete/cementitious composites, or simply UHPC, is increasingly being used. The development of this nomenclature is illustrated in Fig. 2.

A reconciled definition of precisely which properties define UHPC has not yet been decided. However, an often-used definition made by some authority researchers within the field suggests properties of compressive strength higher than 120 MPa, sustained post-cracking tensile strength of a minimum of 5 MPa, and a discontinuous pore system entailing increased durability (Graybeal et al., 2020). Superior compressive strength is traditionally achieved through the composition of a dense particle skeleton and a high content of binders, tensile strength through the inclusion of high content of microfibres made from high-quality steel, and the discontinuous pore system through all three factors.

Several studies have asserted that using UHPC might be a potentially sustainable opportunity in the construction industry (Amran et al., 2022; Coffetti et al., 2022; Larsen et al., 2019; Racky, 2004). However, the high content of cement (700–1400 kg/m^3) (Shi et al., 2015; Russell and Graybeal, 2013; Habert et al., 2013) and high-strength steel fibres (2–9 vol%) (Graybeal et al., 2020; Russell and Graybeal, 2013; Habert et al., 2013) indicates that the CO_2 emission per volume unit of UHPC is higher than that of conventional concrete (Habert et al., 2013; Sameer et al., 2019).

Wang et al. (Wang et al., 2021) showed various single approaches to reduce the CO_2 emissions of UHPC materials, such as using different industrial by-products to replace cement, micro-silica, or quartz sand in UHPC. The application of common supplementary cementitious materials (SCMs), such as fly ash and blast furnace slag, has been investigated by several researchers (Aghdasi and Ostertag, 2018; Ahmed et al., 2021; Alsalman et al., 2020; Randl et al., 2014; Yu et al., 2017). Others applied other local industrial by-products or construction and demolition (C&D) waste to reduce the cement content, such as red mud (Hou, 2021), basalt

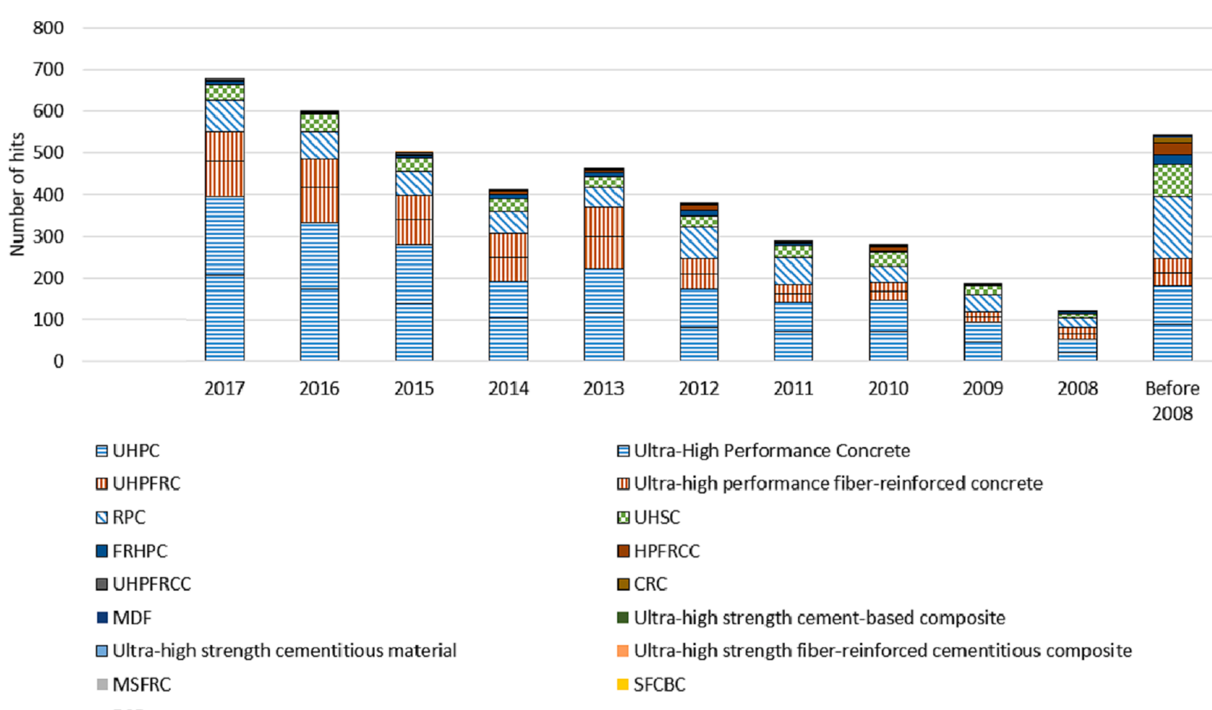

Fig. 2. Development in publication rates on papers regarding UHPC (including alternative notations), according to Larsen et al. (Larsen et al., 2018a).

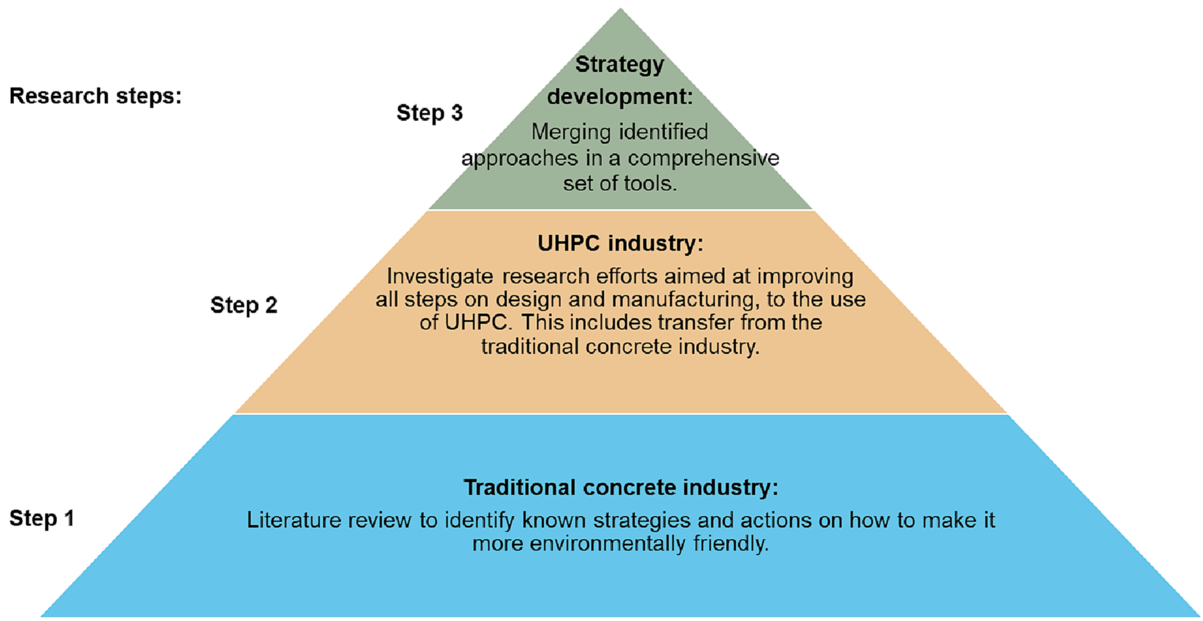

Fig. 3. Stepwise descriptions of the procedure followed to identify strategies to improve the sustainability of UHPC.

powder (Li, et al., 2021), lead-zinc tailings (Wang, 2018), waste from clay bricks and cement solids (Zhu et al., 2016), concrete demolition waste (Wang, 2019) and glass powder (Soliman and Tagnit-Hamou, 2016). Methods replacing costly micro-silica have also been investigated (Soliman and Tagnit-Hamou, 2017a). Other sustainable approaches found in research include applying fibre types other than micro straight steel fibres (Hajiesmaeili, 2019; Yoo et al., 2017a; Le Hoang and Fehling, 2017; Wu et al., 2016); hybrid configurations of different fibre types (Meng and Khayat, 2018; Yoo et al., 2017b; Wu et al., 2017; Lande and Thorstensen, 2021b), or attempts to control and improve the distribution and orientation of the fibres (Yu et al., 2017; Song, 2018; Song et al., 2018). Alternative approaches have focused on applying aggregates other than the typical quartz sand used in UHPC (Zhao et al., 2014; Soliman and Tagnit-Hamou, 2017b; Yang, 2020; Larsen et al., 2018b).

Some studies have focused on the structural level through life cycle assessments (LCA) of UHPC solutions compared to traditional methods (Habert et al., 2013; Sameer et al., 2019; Hajiesmaeili et al., 2019; Bertola et al., 2021b).

Most of the presented research initiatives seem to focus on exploiting locally available waste materials or by-products, which is an attractive initiative in line with the efforts towards a circular economy. However, comprehensive strategies on how the emerging UHPC industry might make efforts towards more sustainable utilisation of UHPC are lacking. This study intends to contribute to the development of a strategy for a sustainable UHPC industry based on a theory-informed approach.

Methods

The efforts towards the above-mentioned intention presented in this paper have been approached by reviewing the existing research literature, including an investigation into a more sustainable conventional concrete, followed by a focus on the contribution of UHPC. The stepwise procedure is illustrated in Fig. 3.

Informed by the findings, a discussion is conducted to merge all contributing actions that have been found fruitful into one comprehensive strategy. The conclusion is a suggested strategy comprising different tools that might be applied to reduce CO_2 emissions and other negative environmental impacts of the emerging UHPC industry.

Results and discussion

The intention behind this paper is to suggest a comprehensive strategy for the sustainable development of the UHPC industry. The first step is to define the boundaries for evaluating the environmental impact of measures (e.g. as in LCAs), considering different time horizons. LCA analysis is developed as a tool for calculating environmental impacts. However, as LCA is a system analysis, the system's boundaries must be defined. If the boundaries are set too narrow, the risk is that the best solution might be found as one that optimizes on a sub-level, while in reality, this solution is less good in a broader view.

The discussion below is initiated with considerations of the relevance of different limitations for the time horizon as system borders for the environmental evaluation (*Section Time considerations*). Subsequently, the discussion on how to reduce the climate impact is approached by first analysing Mehta's strategy developed for the conventional concrete industry, focusing on how these tools have been applied in the industry and how they are still relevant for further development and applications (*Section An existing strategy to expand*). The scope is broadened (*Section Research approaches for a more sustainable concrete industry)* by evaluating how recent research initiatives are contributing to sustainability regarding the different time considerations (*Section Time considerations*). Subsequently, to approach UHPC, the transferability of measures from the conventional concrete industry is discussed (*Sections UHPC composition, material properties, and environmental impact* and *Constructing a strategy for the sustainable use of UHPC*), enrichened with additional measures with special relevance for UHPC. To inform this discussion, special attention is given to the composition, material properties and environmental impacts of this relatively new class of materials. Finally, a comprehensive strategy is developed (*Section Constructing a strategy for the sustainable use of UHPC*).

Time considerations

A possible conflict of interest may arise regarding environmental footprint when considering different time horizons. The impacts of a measure are often evaluated considering the lifetime expectancy, whether it is regarding cost (life cycle cost (LCC)) or environmental footprint (LCA). Infrastructure, such as bridges and tunnels, are often designed to have a service life of 100 years. Consequently, LCC and LCA estimations are often made considering this life span, leaving 100 years to "pay off" the sunk investment, whether capital or carbon. However, rapid climate change minimises the consequences that might call for solutions within shorter time horizons. For this reason, Jahren and Sui (Jahren and Sui, 2013) suggested three alternative foci for sustainability evaluations/actions. In this study, we considered the following foci:

- *Focus 2030*: according to the Paris Agreement and the UN-SDG.
- *Focus 2050*: net zero emissions by 2050 to limit global warming to 1.5 °C (Masson-Delmotte, et al., 2021).
- *Focus lifetime* (e.g., 100 years for infrastructure): as "normal procedure" for LCC and LCA.

There is no "right answer" to which of these foci should be preferred. For example, consider using UHPC for the renovation of a bridge. Owing to the high cement and steel fibre content, the environmental impact per

Table 1
Overview of approaches for a more sustainable concrete industry and the effect on various foci.

Approaches/tools	**Effect of various actions versus focus** [1]			**Ref.**
	2030	**2050**	**Lifetime**	
*Consume less concrete for new structures (*Mehta's *Tool no.1):*				(Mehta 2009)
Design efficiency: innovative structures and designs to reduce the use of concrete	➡	➡	➡	(Jahren and Sui 2013; Mehta 2009; Miller et al. 2021; Habert et al. 2020; Scrivener et al. 2018)
Reuse elements/structures		➡↺↻	➡↺↻	(Jahren and Sui 2013; Mehta 2009; Miller et al. 2021; Habert et al. 2020)
Prefabrication	➡	➡↺↻	➡↺↻	(Miller et al. 2021; Habert et al. 2020)
Building flexibility		➡↺↻	➡↺↻	(Jahren and Sui 2013)
Apply durable concrete materials for longer service life with limited maintenance		➡	➡	(Jahren and Sui 2013; Mehta 2009; Scrivener et al. 2018)
Repair existing structures with HPC/UHPC	➡	➡	➡	(Habert et al. 2020; Bertola et al. 2021; Hajiesmaeili et al. 2019; Habert et al. 2013)
*Consume less cement for making concrete (*Mehta's *Tool no.2):*				(Mehta 2009)
Apply 56- or 90-day compressive strength (especially relevant for alternative binders)	➡	➡	➡	(Mehta 2009)
Utilise superplasticisers instead of water (and cement) to adjust workability or reduce the water content	➡	➡	➡	(Mehta 2009; Scrivener et al. 2018; Coffetti et al. 2022)

(continued on next page)

Table 1 (*continued*)

Utilise other chemical admixtures	➡	➡	➡	(Scrivener et al. 2018; Coffetti et al. 2022)
Utilise fillers (inert materials) in combination with admixtures	➡	➡	➡	(Scrivener et al. 2018; Habert et al. 2020)
Optimize particle size and grading to limit the need for cement paste	➡	➡	➡	(Habert et al. 2020; Mehta 2009; Scrivener et al. 2018)
*Consume less clinker for making cement (*Mehta's *Tool no.3):*				(Mehta 2009)
SCMs added in concrete mix or blended cements	➡↻	➡↻	➡↻	(Jahren and Sui 2013; Mehta 2009; Monteiro et al. 2017; Miller et al. 2021; Habert et al. 2020; Scrivener et al. 2018; Coffetti et al. 2022)
Utilise locally available by-products from other industries to substitute cement	➡↻	➡↻	➡↻	(Scrivener et al. 2018)
Cement manufacturing:				
Efficiency of clinker production, e.g., use of alternative fuels, dry technologies	➡↻	➡↻	➡↻	(Jahren and Sui 2013; Miller et al. 2021; Habert et al. 2020; Coffetti et al. 2022; Scrivener et al. 2018)
Use of alternative cements (non-Portland clinkers) (e.g., geo-polymers)		➡	➡	(Monteiro et al. 2017; Miller et al. 2021; Habert et al. 2020; Scrivener et al. 2018; Coffetti et al. 2022)
CCS/CCU		➡	➡	(Scrivener et al. 2018; Monteiro et al. 2017; Miller et al. 2021; Habert et al. 2020;

(continued on next page)

Table 1 (*continued*)

				Coffetti et al. 2022)
Recycling:				
Recycle components	➡↺↻	➡↺↻	➡↺↻	(Jahren and Sui 2013; Mehta 2009; Miller et al. 2021; Habert et al. 2020)
Recycle concrete aggregates	➡↺↻	➡↺↻	➡↺↻	(Monteiro et al. 2017; Miller et al. 2021; Scrivener et al. 2018; Coffetti et al. 2022)
Recycle other materials (e.g., excavation materials, C&D waste) as aggregate in concrete	➡↺↻	➡↺↻	➡↺↻	(Miller et al. 2021; Habert et al. 2020)
Facilitate CO_2 uptake at the end-of-life	➡↺↻	➡↺↻	➡↺↻	(Miller et al. 2021; Habert et al. 2020)
Recycling of materials as a binder in concrete	➡↺↻	➡↺↻	➡↺↻	(Miller et al. 2021; Habert et al. 2020; Scrivener et al. 2018)

Legend:

➡ *Contributes to reducing CO_2 emissions.*

↺↻ *Contributes to circularity through recycling, reuse, etc.*

SCMs: Supplementary cementitious materials. CCS/CCU: Carbon capture and storage/carbon capture and use. C&D waste: Construction and demolition waste.

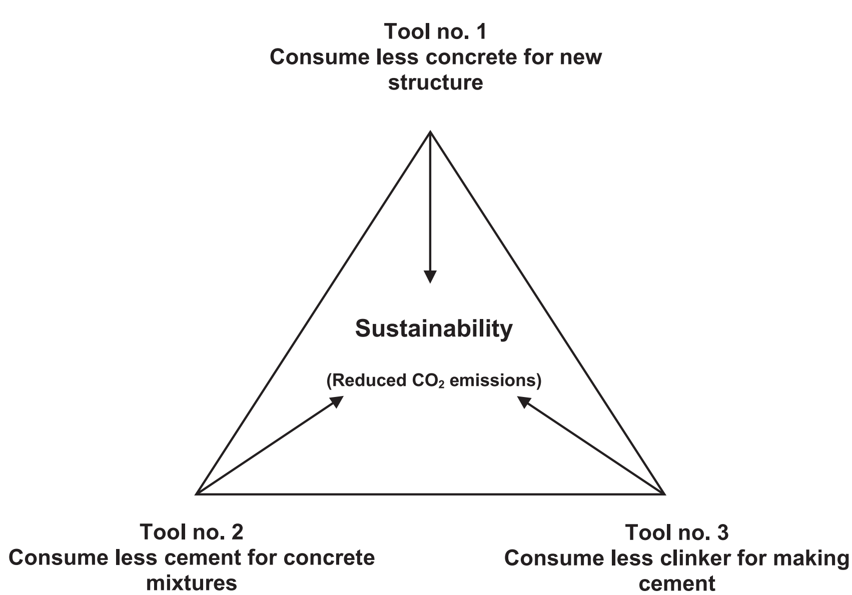

Fig 4. Mehta's strategy for a more sustainable concrete industry in terms of reduced CO_2 emissions. Redrawn according to Mehta (Mehta, 2009).

unit volume of UHPC is higher than that of conventional concrete. In a shorter-time horizon (*Focus 2030*), using conventional rehabilitation methods might be favourable unless UHPC opens for methods where less material is consumed. Hence, a reduction in material consumption should be efforted when applying UHPC. However, from the lifetime perspective (*Focus lifetime*) of the bridge, using UHPC might be favourable as the service life is extended, limiting the need for future maintenance and repair. The following discussions will consider each of the three foci to include the influence of the time span in the evaluations (ref. Table 1).

An existing strategy to expand

Mehta (Mehta, 2009) suggested a strategy consisting of three "tools" to achieve considerable reductions in CO_2 emissions of the concrete industry (Fig. 4). The tools are as follows: 1) *Consume less concrete for new structures*, 2) *Consume less cement in concrete mixtures*, and 3) *Consume less clinker in cement*.

Mehta's first tool, *Consume less concrete for new structures* (Mehta, 2009), has been suggested by other researchers, such as Scrivener et al. (Scrivener et al., 2018), Miller et al. (Miller et al., 2021) and Habert et al. (Habert, 2020). Reducing CO_2 within this tool can be achieved by innovative designs to limit concrete consumption (Habert, 2020; Scrivener et al., 2018; Mehta, 2009) using concrete with high durability that extends the time before a structure needs to be demolished and rebuilt (Habert, 2020; Scrivener et al., 2018; Mehta, 2009) and using reusable prefabricated elements (Mehta, 2009). One example involves using high-strength concrete for new bridge designs to reduce concrete volume and environmental impact (Habert et al., 2012). The other is using UHPC for bridge rehabilitation (example in (Habert et al., 2013; Hajiesmaeili et al., 2019). Reducing the consumption of concrete would benefit the environmental impact in all three time foci. Scrivener et al. (Scrivener et al., 2018) highlighted that measures within the structural design can contribute to a significant reduction in CO_2 emissions, but requires considerable investments in research, development, and education for engineers to discover opportunities within this field.

Tool 2, Consume less cement for making concrete mixes, is a well-established industrial approach (Scrivener et al., 2018) that includes measures like utilising chemical admixtures to adjust the consistency of fresh concrete instead of applying more water or even reducing the water content (Scrivener et al., 2018; Mehta, 2009). Another measure could involve optimising particle packing to reduce cement consumption. A third measure is to apply an inert filler to substitute part of the cement while also reducing the water content by dispersant admixtures (Habert, 2020; Scrivener et al., 2018). Reduction of the cement (Portland clinker) content in concrete mixes would benefit all the three time foci of the LCA, with the most considerable effect already in a short time horizon (*Focus 2030*) (Jahren and Sui, 2013). John et al. (John et al., 2018) showed that by applying inert filler to substitute cement while focusing on dense particle packing, a cement reduction of up to 70% was achieved without affecting the mechanical strength. This measure could considerably reduce the CO_2 emissions of the concrete mixes and has a large potential to reduce the emission. The measures originally presented by Mehta have until recently been repeated and elaborated upon by others, for example, Scrivener et al. (Scrivener et al., 2018) and Habert et al. (Habert, 2020).

In *Tool 3, Consume less clinker in cement,* using a high content of one or more supplementary cementitious materials (SCMs) is proposed, which includes the application of SCMs, such as fly ash, blast-furnace slag, silica fume, and natural pozzolans (Coffetti et al., 2022; Scrivener et al., 2018; Mehta, 2009), as well as limestone powder (Habert, 2020; Scrivener et al., 2018). These may be added during concrete mixing or manufactured by the cement producer in blended cement. Consuming less clinker in cement would benefit all three time foci. Clinker substitution with low-CO_2 SCMs has a considerable effect already at *Focus 2030* and is mentioned as one of the most promising approaches within the next 20–30 years (Scrivener et al., 2018). Many of SCMs also contribute to increased durability of concrete structures (Mehta, 2009), resulting in effects also in the lifetime perspective of a structure. Adding SCMs is a well-established measure in the concrete industry (Scrivener et al., 2018; Favier et al., 2018). Currently, the majority of cements sold in Europe are blended types (Favier et al., 2018). The most sold cement in Europe is Portland composite cement (CEM II-A), where up to 20% of Portland clinker is substituted with limestone (Favier et al., 2018). Fly ash and blast furnace slag are the widely used SCMs (Habert, 2020). Owing to decreased availability in the future, it is vital to find other materials to substitute cement (Habert, 2020; Scrivener et al., 2018). Adding various types of SCMs in UHPC mixes to substitute cement has also been reported by several researchers (Aghdasi and Ostertag, 2018; Alsalman et al., 2020; Randl et al., 2014; Yu et al., 2015).

According to Mehta (Mehta, 2009), a reduction of 50% in cement clinker consumption may be possible when these three tools are combined. Active research (Coffetti et al., 2022; Habert, 2020; Scrivener et al., 2018; Miller et al., 2021; Favier et al., 2018; Monteiro et al., 2017; International Energy Agency (IEA), 2018) is still ongoing, for example, on developing new SCMs and cement substitution with inert fillers, demonstrating that Mehta's strategy has the potential for CO_2 reductions exceeding expectations. The three tools of Mehta's strategy have also been applied by Marsh et al. (Marsh et al., 2022), suggested as part of a circular economy strategy for concrete within the category of *Reduction of material*.

The validity of Mehta's strategy is probably undisputed, yet it still seems relevant nearly 15 years after it was presented. Thus, further efforts are suggested in this paper to continue and expand on Mehta's strategy by extending it to UHPC.

Research approaches for a more sustainable concrete industry

The section intends to analyse the suggested and applied measures from the traditional concrete industry and, if possible, transfer and extend suitable measures towards UHPC. Issues on the sustainable development of ordinary concrete have been discussed for decades, with multiple approaches presented in the literature (e.g., those presented in *Section An existing strategy to expand*). Another example is the paper "Reducing the Environmental Impact of Concrete" (Mehta, 2001); which focuses on consuming and conserving natural resources. Currently, the primary focus of sustainability seems to be CO_2 emissions. However, the conservation approach of natural resources comprises the relatively new term "circular economy" or "circularity", indicating that this approach becoming increasingly relevant.

Table 1 summarises the comprehensive results from international research on approaches for making the concrete industry more sustainable. All results are presented with categorisation on how they contribute to each of the three "time foci" (*Section Time considerations*), similar to Jahren and Sui (Jahren and Sui, 2013). The measures are categorised as whether they primarily contribute to reducing CO_2 emissions or conserving natural resources through reuse or recycling, using the notation *circularity*.

Based on the findings in Table 1, UHPC can be an alternative approach for a more sustainable concrete industry, considering different time perspectives:

- Reduced material consumption resulting from the use of UHPC might positively influence a short-time perspective (*Focus 2030*) if the total emissions are lower for conventional concrete structures.
- Applying UHPC as a durable construction material, which provides a longer service life, might positively influence the long-term perspective (*Focus 2050* and *Focus Lifetime perspective*).
- Repairing existing structures with UHPC could potentially have an effect in a short time perspective (*Focus 2030*), as well as in the two other perspectives.

Table 2
Typical compositions of commercially available UHPC powder mixes from dominant producers (Russell and Graybeal, 2013; Camacho et al., 2012; Azmee and Shafiq, 2018; Akhnoukh and Buckhalter, 2021).

	Ductal	Cemtec	DURA	BSI	CRC	Cor-tuf mix
Materials	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
Cement	712–746	1050	911	1114	930	790
Micro-silica	231–242	268–275	225	169		308
Fine sand	1020–1066	514–730	911	1072	1325	765
Ground quartz	211-224	N/A	N/A	N/A	N/A	N/A
Silica flour	N/A	N/A	N/A	N/A	N/A	216
Superplasticiser	9–30.7	35–44	38	40–44	N/A	14
Water	109–142	180–190	200	212	149	166
Steel fibres	156–161	470–858	173	221–234	150–300	247

- Using UHPC in prefabricated elements, which can be easily disassembled and reused, might contribute positively if the unique properties of UHPC can be utilised to reduce the material consumption to a level where the total CO_2 emission is reduced. A positive effect can potentially be achieved in all time perspectives.

UHPC composition, material properties, and environmental impact

UHPC material composition and production

The composition of UHPC differs from that of conventional concrete in several ways, contributing to an increase in CO_2 emissions per unit volume of the material. Some typical characteristics of UHPC are the absence of coarse aggregates (UHPC often has a maximum particle size of less than 1 mm) (Bertola et al., 2021a), low *water-to-cement* ratio (*w/c*-ratio) of approximately 0.14–0.3 (Shi et al., 2015; Graybeal, 2013), extensive use of superplasticisers (Shi et al., 2015; Russell and Graybeal, 2013), high binder content, and micro-steel fibres (Graybeal et al., 2020; Shi et al., 2015; Russell and Graybeal, 2013; Bertola et al., 2021a) primarily in the range of 2–6 vol% (Graybeal et al., 2020; Russell and Graybeal, 2013). The binder content is often composed of 700–1000 kg/m^3 Portland cement (Shi et al., 2015; Russell and Graybeal, 2013; Abokifa and Moustafa, 2021) and micro-silica content of approximately 25% of the mass of cement (Shi et al., 2015; Russell and Graybeal, 2013; Graybeal, 2013; Naaman and Wille, 2012). A cement content of up to 1400 kg per m^3 (Habert et al., 2013) and micro-silica content of up to 50% were found (Abokifa and Moustafa, 2021). Occasionally, additional cementitious binders, such as fly ash, blast furnace slag, or limestone powder (Shi et al., 2015; Graybeal, 2013; Abokifa and Moustafa, 2021); are used. Solid materials are densely packed, often through particle packing models, such as the modified Andreasen and Andersen model (Lande and Thorstensen, 2021b; Yu et al., 2015; Lande and Thorstensen, 2021a; Yu et al., 2014). Quartz sand in fractions with particle sizes ranging from 0.1 to 600 μm is often used for aggregates and as fillers to help densify the particle skeleton (Shi et al., 2015).

Few commercial producers of UHPC dominate the global market. The typical compositions of these products have been reported previously (Russell and Graybeal, 2013; Camacho et al., 2012; Azmee and Shafiq, 2018; Akhnoukh and Buckhalter, 2021). A summary is presented in Table 2.

In conclusion, Fig. 5 shows a typical composition of UHPC, representative of commercially available UHPC and UHPC reported in the literature.

Steel fibres are usually included in UHPC, which is essential to avoid the brittle behaviour occurring in tension and compression (Larsen and Thorstensen, 2020). The steel fibres used in UHPC are usually micro-steel fibres with high tensile strength (Shi et al., 2015; Larsen and Thorstensen, 2020; Haber et al., 2018). The data for steel fibres typically used in commercially available UHPC products are listed in Table 3.

An implication of the small size of the fibres typically used in UHPC compared to those traditionally used in concrete (Fig. 6) is that the number of fibres to be distributed in the material mix is multiplied when the vol.-% is kept constant.

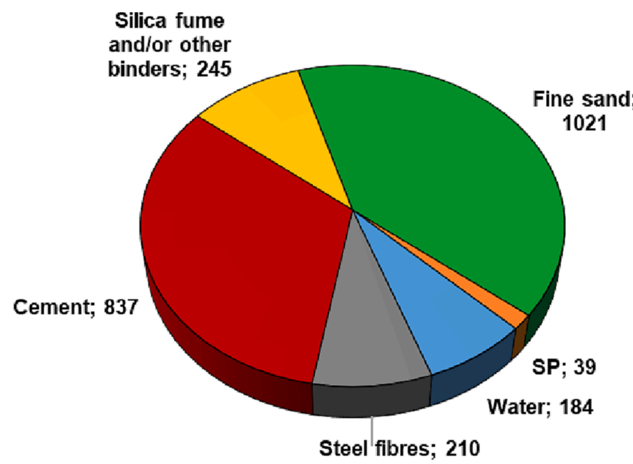

Fig. 5. Typical composition of UHPC presented in (Lande and Thorstensen, 2021a) (based on data in (Lande and Thorstensen, 2021c), each material stated in kg/m^3.

Table 3
Typical data for steel fibres in commercially available UHPCs (Haber et al., 2018).

Supplier origin	Steel fibre content [vol. %]	Steel fibre type	l_f [mm]	d_f [mm]	Fibre tensile strength [MPa]
US [1]	3	HE	30	0.55	1100
Europe	2	HY (SS and SS)	20 and 13	0.3	2100
Europe	4.5	SS	13	0.3	2400
US [2]	2	SS	13	0.2	3750
Canada and US [2]	2	SS	13	0.2	3750
Europe	3.25	SS	13	0.2	3750

HE: Hooked-end fibres. SS: Straight steel fibres. HY: Hybrid combination.
[1] Laboratory developed. [2] Subsidiary of a multinational corporation.

The extent of this difference was modelled using ANSYS (Fig. 7). This high number of microfibres contributes to the high tensile strength of UHPC, which often exhibits strain-hardening properties. However, the fibre content can be challenging for the workability of UHPC in the fresh state. The primary measure to overcome this problem is using high dosages of superplasticising additives (SP).

UHPC can be produced using conventional equipment (Russell and Graybeal, 2013; Spiesz and Hunger, 2017). However, mixing time is usually longer (Russell and Graybeal, 2013; Spiesz and Hunger, 2017). Curing at high temperatures is widely accepted to accelerate and improve the strength development of UHPC without compromising the final quality; which is commonly known to be the result of traditional concrete being cured. This unique strength development is often explained by its high pozzolanic content (Shi et al., 2015). Steam curing

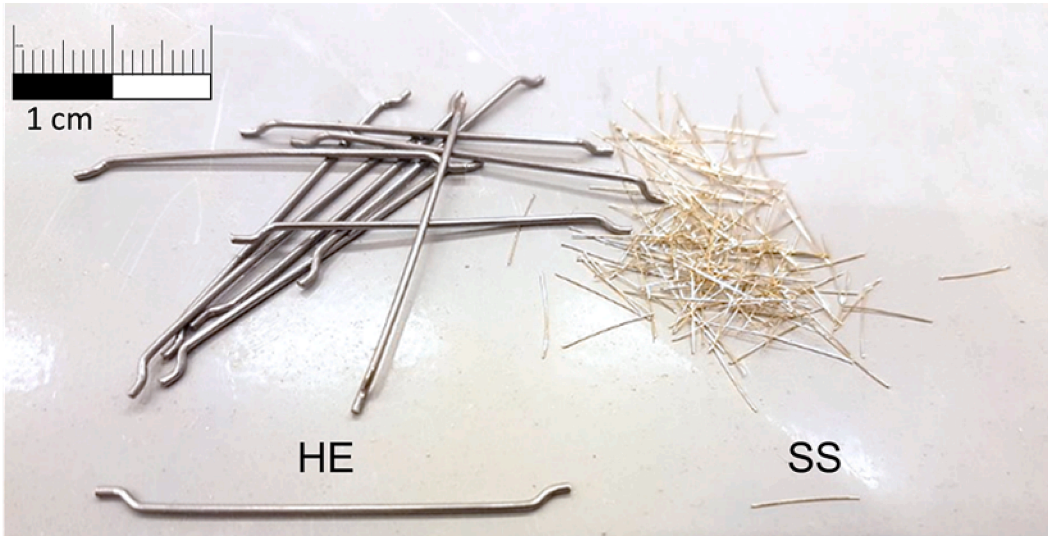

Fig. 6. Steel fibres typically used in UHPC (SS) compared to fibres typically used in traditional concrete (HE) (Lande and Thorstensen, 2021b).

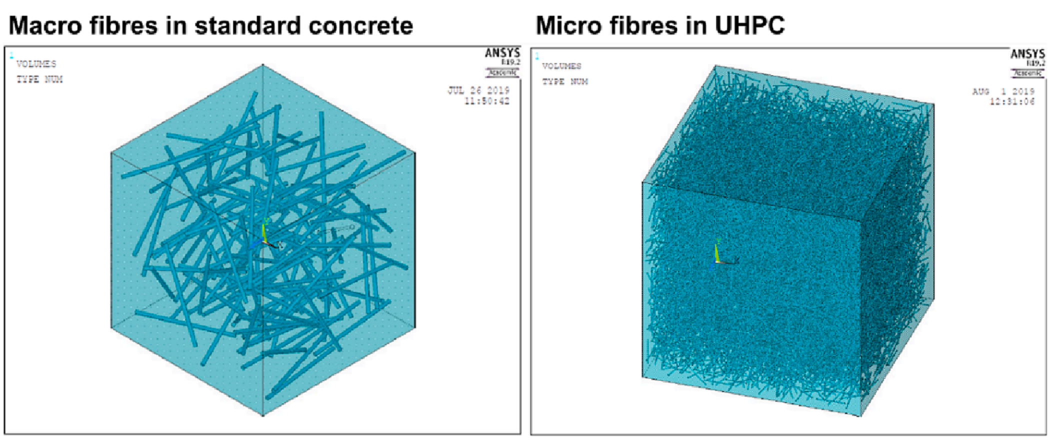

Fig. 7. Typical distribution of fibres in a 10 cm cube in standard concrete (left) vs UHPC (right) (own simulations).

at 90 °C for 48 h has been found to accelerate strength development and improve the final compressive and tensile cracking strength, E-modulus, and durability (Russell and Graybeal, 2013; Graybeal, 2006). However, applying steam curing at building sites is not feasible or economically efficient in most practical cases. Thus, curing at elevated temperatures might be used for prefabricated elements, but ambient-temperature curing is usually applied for production at construction sites. The UHPC properties are also achievable when curing at ambient temperatures (Spiesz and Hunger, 2017; Wille et al., 2011).

Material properties

The combination of a dense mix of fine particles and a strong cementitious matrix, as well as the application of high content of high-strength steel fibres, results in high compressive strength, low permeability (high durability), and high tensile strength with post-cracking ductility (Haber et al., 2018). Properties vary based on the UHPC mix design (i.e.; constituents, proportions, and packing of dry materials), production method, and applied curing method. Additionally, the production process (i.e., mixing and placing) affects the dispersion and orientation of the steel fibres, which in turn affects the mechanical behaviour (Russell and Graybeal, 2013).

The compressive strength of UHPC varies from around the strength limit for UHPC materials (120 MPa) (Wu et al., 2016; Yu et al., 2015; Yu et al., 2014; Graybeal, 2006; Alsalman et al., 2017) to above 180 MPa (Yoo et al., 2017a; Le Hoang and Fehling, 2017; Yoo et al., 2017b; Graybeal, 2006) without using synthetic aggregate and pressure curing. The flexural strength of UHPC depends on the applied fibre type and content (Yoo et al., 2017a; Le Hoang and Fehling, 2017; Yoo et al., 2017b; Larsen and Thorstensen, 2020; Gesoglu et al., 2016). UHPC products can have flexural strengths above 40 MPa (Yoo et al., 2017b; Graybeal, 2006) and uniaxial tensile strength from around 6 up to 13 MPa (Russell and Graybeal, 2013; Haber et al., 2018).

The increased durability properties include considerably better resistance against chloride ingression and carbonation and improved frost resistance (freeze-thaw) compared to conventional concrete (Russell and Graybeal, 2013). The higher resistance against these mechanisms is predicted to provide structures with at least twice the service life of conventional concrete structures (Randl et al., 2014).

Environmental impacts of UHPC materials

Calculations on how the different constituents contribute to the CO_2 emissions of UHPC have been reported previously (Habert et al., 2013; Sameer et al., 2019; Stengel and Schießl, 2014). Fig. 8 shows a comparison of the CO_2 emissions of various UHPC mixes, calculated based on the sum of the CO_2 emissions of each constituent material based on the numbers found in the literature (Habert et al., 2013; Shi et al., 2019). Table 4 shows the embodied CO_2 emissions applied in the calculations. Locally available by-products were assumed to have no environmental impact. The same method for calculating CO_2 emissions was also applied in Fig. 9.

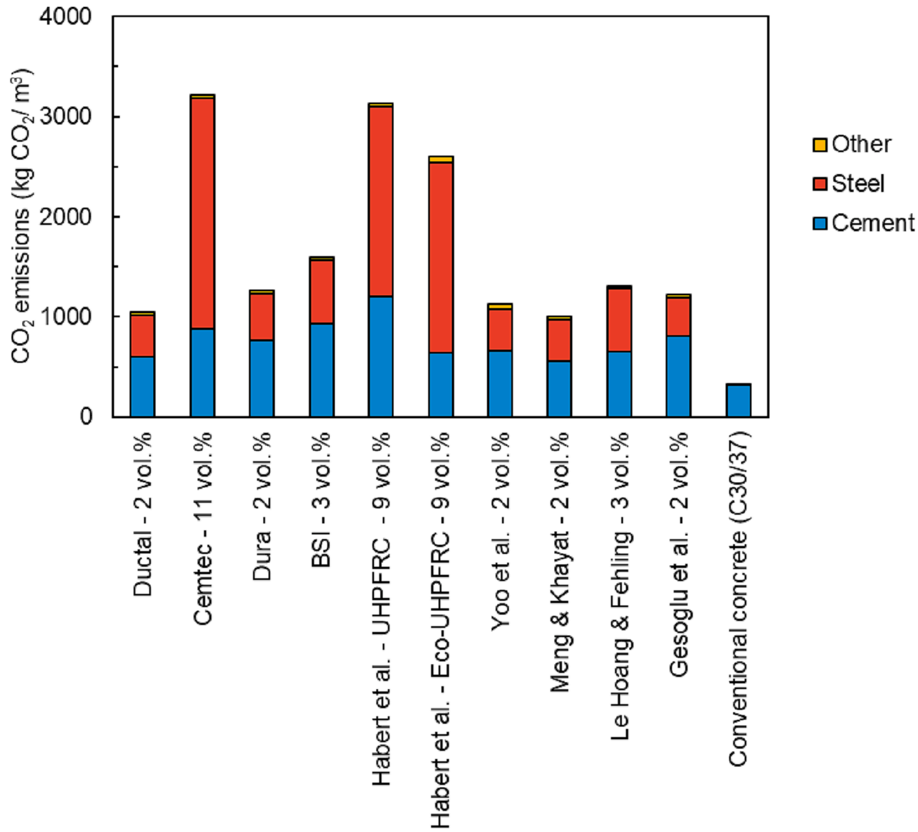

Fig. 8. Comparison of CO_2 emissions of UHPC material per cubic meter from different references, including proprietary recipes (Russell and Graybeal, 2013; Camacho et al., 2012; Azmee and Shafiq, 2018; Akhnoukh and Buckhalter, 2021) and recipes found in research (Habert et al., 2013; Yoo et al., 2017a; Le Hoang and Fehling, 2017; Meng and Khayat, 2018; Yoo et al., 2017b; Gesoglu et al., 2016). Data for conventional concrete was found in (Habert et al., 2013).

Table 4
Embodied CO_2 emissions of constituents in UHPC.

Constituents	Embodied CO_2 [kg CO_2 per kg material]	Reference
Cement	8.4×10^{-1}	(Habert et al., 2013)
Micro-silica	3.1×10^{-4}	(Habert et al., 2013)
Limestone filler	2.6×10^{-2}	(Habert et al., 2013)
Blast furnace slag	1.9×10^{-2}	(Shi et al., 2019)
Fly ash	9.0×10^{-3}	(Shi et al., 2019)
Sand	2.4×10^{-3}	(Habert et al., 2013)
Quartz sand	1.0×10^{-2}	(Shi et al., 2019)
Superplasticiser	7.5×10^{-1}	(Habert et al., 2013)
Water	1.5×10^{-4}	(Habert et al., 2013)
Micro-steel fibres	2.68	(Habert et al., 2013)

Fig. 8 shows that the CO_2 emissions varied between the UHPC mixes. The variations were primarily due to the differences in the applied cement or steel fibre contents. Other constituents have a low impact, and the potential for reducing the environmental footprint of UHPC while maintaining its properties is further discussed in *Sections Efficient use of cement* and *Efficient use of steel fibres*.

Over 95% of the CO_2 emissions from a typical UHPC are approximately 50% due to the production of cement and 50% due to the micro-steel fibres (Fig. 8 and (Habert et al., 2013; Stengel and Schießl, 2014), with the production of 1 kg of micro-steel fibres typically emitting around 2.7 kg of CO_2 equivalents (Habert et al., 2013; Stengel and Schießl, 2014), while the production of steel fibres for conventional concrete emits between 0.77 and 1.5 (Chiaia et al., 2014; Mapei, 2017). The primary contributor to the cost of UHPC is micro-steel fibres, followed by reactive powders (e.g., micro-silica) and cement (examples presented in (Graybeal, 2013; Stengel and Schießl, 2014).

Curing at elevated temperatures increases CO_2 emissions. Shi et al. (Shi et al., 2019) found that the influence of steam curing was 125.7 kg of CO_2 emissions per m^3 of UHPC.

Constructing a strategy for the sustainable use of UHPC

According to *Section An existing strategy to expand* and Table 1, one strategy to reduce the environmental footprint of the concrete industry is to reduce the consumption of concrete in new structures. Owing to the unique material properties of UHPC, the material consumption of some applications can be reduced by using UHPC. In addition, the durability properties of UHPC far exceed those of conventional concrete, resulting in increased service life. These two approaches align with Mehta's *Tool no. 1* for conventional concrete.

A further reduction in the CO_2 emissions of UHPC can also be approached by extending the logic of Mehta (Mehta, 2009) by finding measures to reduce the content of the most emitting constituents for the UHPC material. For conventional concrete types, the most emitting material is cement, whereas, for UHPC, the primary contributors are cement and micro-steel fibres.

Based on these considerations, a strategy for sustainably using UHPC was constructed based on five tools, as presented in the following section.

Efficient use of cement

Considering the high content of cement in UHPC and with almost 50% of the CO_2 emissions from UHPC stemming from the cement (Fig. 8), Mehta's strategy "to achieve considerable reductions in the CO_2 emissions of the concrete industry" (Mehta, 2009) (Fig. 4) is still relevant. Two of Mehta's tools focused on cement. Several research papers reviewed in the present study align with Mehta's strategy to reduce

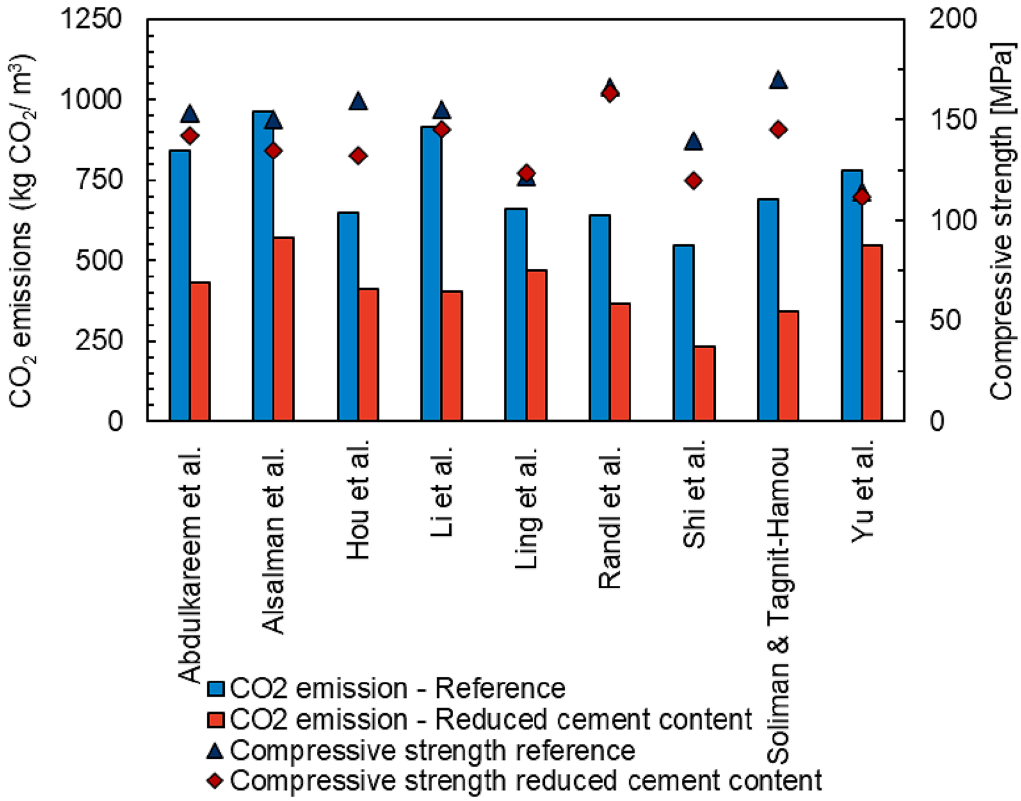

Fig. 9. Comparison of CO_2 emissions of UHPC material without steel fibres per cubic meter from different references. The compressive strength is also given on the secondary axis. The figure shows the reference UHPC recipe compared to a recipe with reduced cement content while limiting the reduction in compressive strength to 15%. The values are found in (Alsalman et al., 2020; Randl et al., 2014; Yu et al., 2017; Hou, 2021; Soliman and Tagnit-Hamou, 2016; Shi et al., 2019; Abdulkareem et al., 2021; Li et al., 2020; Ling et al., 2021) and calculated in accordance with Fig. 8.

cement consumption, identifying alternative binders and densifying the particle skeleton as the primary measures (Habert, 2020; Scrivener et al., 2018).

As UHPC has a high cement content and a low *w/c* ratio (between 0.14 and 0.3) , large portions of the cement will remain unhydrated (Yu et al., 2014; Zhao and Sun, 2014). Unhydrated cement particles have a higher mechanical strength than hydration products and might consequently contribute to building strength by acting as fillers, thus densifying the particle skeleton (Zhao and Sun, 2014). However, using cement as a filler results in unnecessarily high costs and an environmental footprint. Efforts should be made to substitute the share of cement particles that remain unhydrated with materials with lower costs and environmental footprints.

Applying the measures listed in Table 1 to reduce the content of cement clinker by applying different SCMs is also possible for UHPC. These measures are often applied in combination with dense packing of the constituents using the modified Andreasen and Andersen model (Yu et al., 2017; Hou, 2021; Yu et al., 2015; Qian, et al., 2020). Previous research has found that it is possible to reduce the cement content in UHPC without considerably reducing its mechanical strength. Traditional SCMs, such as fly ash, blast-furnace slag, and limestone powder, can be applied (Alsalman et al., 2020; Randl et al., 2014; Yu et al., 2015; Shi et al., 2019; Huang et al., 2017). Additionally, various locally available C&D waste or industrial by-products are appropriate to reduce the cement content in UHPC (Wang, 2018; Wang, 2019; Qian, et al., 2020). This will be further discussed in *Section Circularity: Utilise by-products*. Fig. 9 shows that it is possible to considerably reduce the CO_2 emissions from UHPC materials by substituting part of the cement with other materials having lower CO_2 emissions without considerably reducing the compressive strength.

Achieving a high reduction in the cement content of UHPC can reduce CO_2 emissions considerably in a short time horizon (*Focus 2030*) and promote circularity by using by-products or recycled wastes to substitute cement partly.

Considering the present initiative on developing a strategy for reducing the CO_2 emission from UHPC, it is suggested to compress two of Mehta's tools into one new tool: *Efficient use of cement (Tool A)*.

Efficient use of steel fibres

Considering that approximately 50% of the CO_2 emissions of UHPC at the material level stem from the production of microfibres made from high-strength steel (Fig. 8), it seems reasonable to focus on this issue as a separate tool. As illustrated in Fig. 8, a considerable influence of steel on CO_2 emissions was observed when the steel fibre content was increasing (6–9 vol%). Ongoing research has focused on using lower content of steel fibres through applying fibre combinations (hybrid fibre configurations) of different fibre types (Meng and Khayat, 2018; Yoo et al., 2017b; Wu et al., 2017; Niu et al., 2021; Al-Osta et al., 2021) or applying various fibres with better pullout properties, such as longer or deformed steel fibres (e.g. twisted or hooked-end) (Yoo et al., 2017a; Wu et al., 2016; Gesoglu et al., 2016; Yoo et al., 2016). Several recent papers have attempted to utilise hybrid fibre configurations, combining the microfibres usually applied in UHPC with macro hooked-end fibres (e.g., (Meng and Khayat, 2018; Yoo et al., 2017b; Lande and Thorstensen, 2021b). Using the hybrid fibre configuration could potentially achieve synergetic effects that compensate for the reduced number of macrofibers compared to microfibres (Lande and Thorstensen, 2021b). Other approaches for more efficient use of fibres are the improvement of fibre distribution and orientation by controlling the casting process (Yu et al., 2017; Song, 2018; Song et al., 2018; Huang et al., 2018) and using synthetic fibres or other materials with lower CO_2 emissions (Hajiesmaeili, 2019).

A dedicated tool for the strategy is suggested regarding the fibre content: *Efficient use of steel fibres (Tool B)*. In line with the suggested *Tool A*, applying approaches for efficiently using fibres can reduce CO_2 emissions in a short time horizon (*Focus 2030*).

Circularity: Utilise by-products

Using waste materials from other industries, including C&D waste, has been fruitful in the concrete industry as cement replacement materials and to replace virgin aggregates (Mehta, 2001). This measure can also be applied to UHPC, for example, by using industrial by-products to partly substitute cement in UHPC (*Section Efficient use of cement*). Various by-products can be utilised in UHPC to substitute cement, such as common SCMs (e.g. fly ash and blast furnace slag) (Randl et al., 2014; Yu et al., 2015; Meng et al., 2016), inert rock dust collected from rock crushing (Yang, 2020; Larsen et al., 2018b; Lande and Thorstensen, 2021a), recycled construction and demolition (C & D) waste (Zhu et al., 2016; Wang, 2019; Xu, et al., 2021) and locally available industrial by-products (Hou, 2021; Wang, 2018; Ling et al., 2021).

Applying locally available by-products might be a solution in the future to limit the environmental impacts and costs of the transportation and extraction of virgin materials. In addition, alternatives to the current sources of SCMs, such as fly ash and blast furnace slag, must be considered as their availability is decreasing as industries transition from using energy from coal combustion; in addition, the degree of recycled steel is increasing (Habert, 2020; Scrivener et al., 2018). By-products or surplus materials have been used to replace high-quality quartz sand in UHPC (Lande and Thorstensen, 2021b; Zhao et al., 2014; Soliman and Tagnit-Hamou, 2017b; Yang, 2020; Larsen et al., 2018b; Lande and Thorstensen, 2021a), as the production of quartz sand to obtain the required aggregate size (150–600 μm) can be energy intensive and polluting (Soliman and Tagnit-Hamou, 2017b; Yang, 2020). Utilising by-products in new production is consistent with the idea of conserving natural resources within the circularity framework.

A third tool for the new strategy is suggested: *Circularity: Utilise by-products (Tool C)*. Applying this tool could have an impact already in a short time horizon, possibly contributing to reduced consumption of natural virgin resources and CO_2 emissions. This tool can also be applied to steel fibres, for example, using recycled tires as steel fibres (Isa et al., 2020).

Local production

An element rarely addressed in research is the CO_2 emissions stemming from the transport of UHPC from a small number of producers worldwide (see *Section UHPC material composition and production*), possibly resulting from research being primarily focused on material development. Research on emissions from actual construction projects seems to be minimally considered as a research focus. Nevertheless, UHPC can be successfully produced using local constituents (Lande and Thorstensen, 2021b; Graybeal, 2013; Abokifa and Moustafa, 2021; Wille et al., 2011; Alsalman et al., 2017; Vítek et al., 2013; Fidjestol et al., 2012), and in standard ready-mix facilities for conventional concrete (Spiesz and Hunger, 2017; Vítek et al., 2013) using standard curing methods (Spiesz and Hunger, 2017; Wille et al., 2011). This approach might contribute to reducing emissions from the structural use of UHPC at actual construction sites.

Thus, a fourth tool is suggested for this strategy: *Local production (Tool D)*. Applying this tool may contribute to improving the sustainability of UHPC already in a short-time horizon. Developing regional competence through local production might also contribute to making UHPC a competitive product in the market, which is a prerequisite for making it a sustainable solution for the concrete industry.

Efficient use of UHPC in structures

Finally, a fifth tool should be dedicated to identifying where the use of UHPC might be favourable (in terms of cost and environmental impact) to substitute traditional concrete or other materials. Even though UHPC was developed during the 1980s, an increase in research interest and application was not observed until recently, as illustrated in Fig. 2, possibly because of a lack of financial motivation. This situation might have changed recently, powered by a CO_2 reduction focus. Despite the superior qualities of UHPC, its purpose as a better alternative remains unclear. UHPC should be preferred in cases where it can be a competitive solution and its environmental footprint is lower compared to using conventional materials. Research on different structural applications where the unique material properties of UHPC might be favourable has been initiated, and applications have been demonstrated (Spiesz and Hunger, 2017; Toutlemonde and Resplendino, 2011; Aarup, 2017; Resplendino, 2012; Brühwiler and Denarié, 2013; Brühwiler and Bastien Masse, 2015; Brühwiler, 2016). The increased strength can reduce the material consumption of some structures, and the service life can be considerably extended (Amran et al., 2022; Randl et al., 2014). A promising area of research is the bridge sector. UHPC is especially applicable for rehabilitating deteriorated bridges (Graybeal et al., 2020; Bertola et al., 2021a; Brühwiler and Denarié, 2013; Brühwiler and Bastien Masse, 2015; Brühwiler, 2016). In such cases, UHPC is often applied as an overlay on existing reinforced concrete structures, improving the structural capacity (Zhu et al., 2020; Zhang, 2019) and durability (Bertola et al., 2021a) without increasing the dead load for which the structure was designed. From a life cycle perspective, using UHPC for bridge rehabilitation has been found to have a lower environmental impact than traditional methods (Habert et al., 2013; Hajiesmaeili et al., 2019). UHPC can also be applied to new structures as a primary construction material (Graybeal et al., 2020; Russell and Graybeal, 2013; Bertola et al., 2021a; Haber et al., 2018). The applications within the bridge sector are well documented, for example, by the US Federal Highway Administration in (Russell and Graybeal, 2013; Haber, 2021). In Europe, Switzerland has taken the lead in applying UHPC within the bridge sector, winning projects in commercial terms and documenting projects effectively (Bertola et al., 2021a; Brühwiler and Bastien Masse, 2015; Brühwiler, 2016). However, relatively few research initiatives (Habert et al., 2013; Sameer et al., 2019; Hajiesmaeili et al., 2019; Bertola et al., 2021b; Larsen et al., 2017) have investigated the environmental impact of applying UHPC in structures.

Consequently, a fifth tool in the strategy is suggested: *Efficient use of UHPC in structures (Tool E)*. Reduced material consumption could potentially reduce CO_2 emissions already in a short time horizon, for example, when using UHPC for bridge rehabilitation (Hajiesmaeili et al., 2019). However, a short-time horizon reduction is not always the case, owing to the high cement and steel fibre content resulting in higher CO_2 emissions than traditional methods (Habert et al., 2013; Bertola et al., 2021b; Stengel and Schießl, 2014; Larsen et al., 2017). Utilising the improved durability of UHPC for infrastructure (e.g., bridges and bridge rehabilitation) can provide a longer service life, reduce the need for new structures in the future, and limit the need for extensive repair work and maintenance. In such cases, using UHPC will contribute to reduced CO_2 emissions over a longer time horizon (*Focus 2050* and *Focus lifetime*) (Habert et al., 2013; Bertola et al., 2021a; Larsen et al., 2017).

Five tools towards a wholistic strategy

The five tools suggested in this model might represent a holistic approach to reducing the environmental footprint of the emerging UHPC industry. It is not our intention that any research or industrial initiative should address all five tools simultaneously. However, the suggested model may represent a comprehensive strategy to position the total environmental impact of individual initiatives.

Limitations still exist against the broader use of UHPC and even the possibility of making it an available solution, primarily due to the lack of generally accepted design and production standards and local competence. However, this scenario was not evaluated in this study. Nevertheless, some of the above-suggested tools might contribute, for example, to building local competence and availability through local production (*Tool D*). Omitting the lack of general codes has been proven possible, as several countries have managed to obtain UHPC in the market (e.g., Denmark (Aarup, 2017), France (Resplendino, 2012), and Switzerland (Bertola et al., 2021a) in Europe, in addition to the US and several others (Russell and Graybeal, 2013).

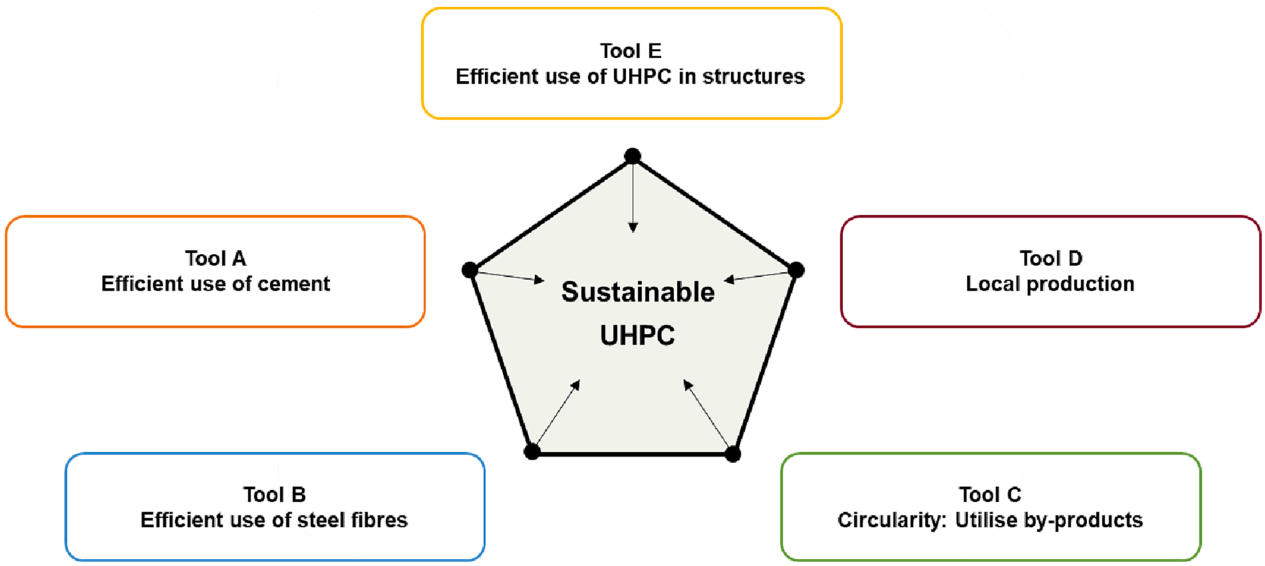

Fig. 10. Strategy for making UHPC more sustainable.

Conclusions

A strategy for making UHPC more sustainable, comprising five tools, is suggested and presented in the text below and in Fig. 10.

- *Efficient use of cement* has been targeted in the traditional concrete industry for decades, mostly through the use of SCMs. Considering the high cement content associated with UHPC, this measure should be given renewed effort. Additionally, given the special composition and properties of UHPC, efforts to densify the particle packing should be focused on.
- *Efficient use of steel fibres* is imperative to UHPC, as fibres are one of the two main contributors to CO_2 emissions from this industry. Measures might include the utilisation of better pullout properties, fibres made of materials with lower emissions, hybrid combinations of fibres with different properties and optimising the orientation and distribution of fibres.
- *Circularity: Utilisation of by-products* is presently a main target for most production industries, and it is also relevant for construction. Locally available industrial by-products and C&D waste might be utilised for substituting both cement and aggregate in UHPC.
- *Local production of UHPC* might contribute by reducing the need for transportation. However, it might also contribute by raising the awareness and competence needed locally to widespread the use of this relatively new class of materials.
- *Efficient use of UHPC in structures* regards identifying for what kinds of structural applications the use of the special properties of UHPC would be beneficial. Bridge rehabilitation has been found as one. Several more are believed to exist but must be documented.

The application of each of these tools has the potential to contribute to reducing the environmental impact. Awareness of the whole range of tools might contribute to better utilisation of several or all five simultaneously, improving the sustainability of the industry. All measures might influence the three-time foci (*Focus 2030*, *Focus 2050*, or *Focus lifetime*) differently. Generally, it might be wise to explain in any research initiative which foci are being considered as part of the suggested solution, as the three foci might be internally conflicting.

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.

Data availability

All data used are harvested from already published papers.

Acknowledgements

The work presented in this paper is part of the ongoing project MEERC (More Efficient and Environmentally friendly Road Construction), partly funded by the Research Council of Norway (NFR) [project number 273700] and Sørlandets Kompetansefond [2016/33].

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