Approaches and strategy development towards more sustainable ultra-high-performance concrete

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UiA University of Agder

Doctoral Dissertations at the University of Agder 410

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Foreword

This thesis was submitted to the University of Agder (UiA) for the degree philosophiae doctor (PhD).

The research presented is the product of a PhD project under the research project *'More Efficient and Environmentally friendly Road Construction'* (MEERC) partly founded by the Research Council of Norway (NFR) and Sørlandets Kompetansefond. The research was conducted at the Department of Engineering Sciences at UiA in Grimstad. The supervisors were Associate Professor Katalin Vertes (UiA, OsloMet) and Professor Rein Terje Thorstensen (UiA).

This thesis consists of an extended introduction (Chapters 1–5) and six appended papers. Four of these papers are published journal papers, one is a published conference paper, and the final paper has been submitted to an international journal and a revised version is currently under review.

January 2023, Arendal

Ingrid Lande

Acknowledgements

The time spent working on this PhD has been enriching, both professionally and personally. Many people have supported and guided me through this PhD project, thereby enabling me to complete it successfully.

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I also thank my colleagues at UiA, particularly the MEERC team, Mehrdad, Solomon, Mequanent, Otto, and Una. I enjoyed sharing offices with them. I thank them for the interesting discussions on life and for sharing their knowledge, frustration, and happiness. It has been a pleasure knowing them.

I am grateful for the support, care, and patience of my family and friends. I thank my parents, sister, and grandparents for their continuous belief in me and their ongoing support.

I also specially thank my wife, Benedicte, for her love, support, and care; for the valuable discussions; for believing in me continuously; for being my colleague at the home office during COVID-19; and for taking care of our son while I worked for long hours.

Finally, I thank my dear son William, who we were blessed with in January 2022. It has been the best time of my life spending time with and getting to know him. He lights up our lives with his smile and joy. Now, I look forward to a period during which we can spend more time together.

Summary

Concrete is the most widely used building and construction material in the world. It is crucial for the wealth and growth of nations at all developmental stages, and there is no existing material that is suitable as a substitute. However, high consumption entails considerable CO_2 emissions and resource demand. Actions are required to establish a more sustainable concrete industry, particularly for reducing CO_2 emissions. Multiple measures have been proposed, some of which have been implemented in the industry. A feasible approach could be to use ultra-high-performance concrete (UHPC).

UHPC is a relatively new fibre-reinforced cementitious material with superior material properties compared with normal concrete. This includes a higher strength and better durability. It is asserted that the smart use of UHPC provides sustainable solutions by reducing the material consumption and prolonging the service life of structures. However, the material properties are achieved by using high content of materials with a high CO_2 footprint, such as micro steel fibres and cement.

The main research objective of this thesis is to investigate how the use of UHPC can contribute to improving the sustainability of the concrete industry by investigating alternative approaches and develop a comprehensive strategy. Some cost aspects have been discussed to indicate whether the strategy is commercially viable.

The research involved six studies: Paper I describes a background study to identify directions for a more sustainable concrete industry. Papers II–V report on how approaches to improve sustainability influence the mechanical properties of UHPC. These studies include both literature reviews and experimental activities. Paper VI concludes the research by developing a comprehensive strategy to use UHPC for a more sustainable concrete industry.

Because most of the CO_2 emissions (about 95%) from UHPC materials originate from the production of cement and micro steel fibres, the more efficient use of these materials is a vital step. Several different approaches have been investigated and determined to be efficient. Some approaches identified from attempts aimed at achieving a more efficient application of cement in normal concrete may be transferred to UHPC. These include partial substitution with both binding and inert materials, combined with better particle packing. The use of steel fibres was observed to have the potential to be more effective by enhancing the pull-out properties using longer or deformed fibres and hybrid fibre combinations. The use of industrial by-products or construction and demolition waste as partial replacements for cement or as aggregates was also observed as being feasible. The local development and production of UHPC builds competence, which is vital for the widespread use of UHPC. The research concludes with the formulation of a comprehensive strategy on how the development and use of UHPC can contribute to improving the sustainability of the concrete industry.

Keywords: Ultra-high-performance concrete; Ultra-high-performance fibre-reinforced concrete; Sustainability; Environmental impact; Sustainable concrete; Steel fibres; Cement replacement; Supplementary cementitious materials; Local production.

Sammendrag

Betong er verdens mest brukte byggemateriale, og er sentral for bærekraftig utvikling og vekst for land på alle utviklingsstadier. Det finnes ingen eksisterende materialer som kan erstatte betong. Betong medfører særlig to miljøutfordringer: CO_2-utslipp og ressursbruk – primært vann og sand. På grunn av det enorme forbruket av betong på verdensbasis er disse miljøutfordringene betydelige. Det er derfor nødvendig med tiltak for å gjøre betongindustrien mer bærekraftig. Det er spesielt viktig å redusere utslipp av CO_2. Flere tiltak finnes, og mange er allerede i bruk. Et tiltak som foreløpig ikke er fullt utnyttet, er å bruke ultrahøyfast fiberarmert betong. Denne betongen er ofte kalt UHPC (ultra-high performance concrete) eller UHPFRC (ultra-high performance fibre-reinforced concrete).

UHPC er en forholdsvis ny type betong med forbedrede materialeegenskaper på noen områder, sammenlignet med normal betong. Dette inkluderer blant annet høy trykkfasthet (> 120 MPa), utnyttbar strekkfasthet (> 5 MPa) og betydelig forbedret bestandighet. Ved å utnytte materialegenskapene som ligger i materialet kan UHPC bidra til bærekraftige løsninger for enkelte bruksområder. Dette gjennom blant annet redusert materialforbruk, forlenget levetid og redusert vedlikeholdsbehov. Imidlertid oppnås de forbedrede materialegenskapene ved å bruke høyt innhold av materialer med høyt CO_2-utslipp, som mikrostålfiber og sement. Det er derfor essensielt å bare bruke UHPC der de forbedrede egenskapene medfører så stor reduksjon i materialforbruket, at de totale miljøkonsekvensene reduseres. Det ville selvfølgelig bidra positivt, dersom miljøkonsekvensene ved produksjon av UHPC kunne reduseres.

Målet med doktorgradsarbeidet var å undersøke forskjellige tilnærminger for å redusere miljøkonsekvensene ved produksjon av UHPC, og utvikle en strategi for hvordan UHPC kan brukes på mer bærekraftig måte.

Forskningen som presenteres i denne avhandlingen består av seks studier: Artikkel I (Paper I) er en bakgrunnsstudie for å identifisere retninger for en mer bærekraftig betongindustri. I Artikkel II–V (Papers II–V) presenteres studier om påvirkningen av potensielle CO_2-reduserende tiltak på de mekaniske egenskapene til UHPC. Disse undersøkelsene inkluderte analyse av resultater innhentet både ved litteraturstudier og eksperimentelle studier. I Artikkel VI (Paper VI) samles forskningsarbeidet ved å utvikle en helhetlig strategi for å utnytte UHPC mot en mer bærekraftig betongindustri.

På bakgrunn av at det meste (omtrent 95 %) av klimagassutslippene fra UHPC-materialer stammer fra produksjon av sement og mikrofiber av høyfast stål, anses mer effektiv bruk av disse materialene som et viktig skritt mot mer bærekraftig UHPC. Ulike tiltak er undersøkt og funnet effektive. Noen tiltak som brukes for normal betong, var også egnete for UHPC. Dette inkluderer delvis erstatning av sement med ulike tilsetningsmaterialer og forbedret partikkelpakking. Bruken av stålfiber i UHPC kan også forbedres gjennom blant annet hybride kombinasjoner av ulike stålfiber, eller ved forbedring av uttrekksegenskapene (lengre eller deformerte stålfibere). Bruk av industrielle biprodukter eller bygge- og rivningsavfall som tilslag eller som en delvis erstatning for sementinnholdet i UHPC ble også vurdert som mulige tiltak. Kompetansebyggingen som oppnås gjennom lokal utvikling og produksjon av UHPC kan være avgjørende for utbredt bruk av UHPC. Siste del av doktorgradsarbeidet var utforming av en helhetlig strategi for hvordan utvikling og bruk av UHPC kan bidra til å redusere miljøutfordringene til betongbransjen (Paper VI).

Nøkkelord: Ultrahøyfast betong (UHPC); Ultrahøyfast fiberarmert betong (UHPFRC); Bærekraft; Miljøpåvirkning; Bærekraftig betong; Stålfiber; Sementerstatningsmaterialer (SCM); Lokal produksjon

List of publications

Main papers

The thesis includes the following appended papers:

1. **Paper I**

   Larsen, I. L., Terjesen, O., Thorstensen, R. T., & Kanstad, T. (2019). Use of Concrete for Road Infrastructure: A SWOT Analysis Related to the three Catchwords Sustainability, Industrialisation and Digitalisation. *Nordic Concrete Research* 60(1) 31–50. https://doi.org/10.2478/ncr-2019-0007

2. **Paper II**

   Larsen, I. L., Thorstensen, R. T., & Vertes, K. (2018). Lowering environmental impact from ultra-high-performance concrete, utilising industrial by-products. *Proceedings of the 12th Fib International PhD Symposium in Civil Engineering*, 93–100.

3. **Paper III**

   Lande, I., & Thorstensen, R. (2021). Towards Efficient Use of Cement in Ultra High Performance Concrete. *Nordic Concrete Research*, 65(2) 81–105. https://doi.org/10.2478/ncr-2021-0017.

4. **Paper IV**

   Larsen, I. L., & Thorstensen, R. T. (2020). The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review. *Construction and Building Materials*, 256(30), 119459. https://doi.org/10.1016/j.conbuildmat.2020.119459.

5. **Paper V**

   Lande, I., & Thorstensen, R. T. (2021). Locally Produced UHPC: The Influence of Type and Content of Steel Fibres. *Nordic Concrete Research* 64(1) 31–52. https://doi.org/10.2478/ncr-2021-0003

6. **Paper VI**
   Lande, I., & Thorstensen, R. Comprehensive sustainability strategy for the emerging ultra-high-performance concrete (UHPC) industry. *Revised version is submitted to an international journal (December 2022).*

Supporting papers

The following papers are not included in this thesis, however, they have been a valuable part of my research.

7. Larsen, I. L., Thorstensen, R. T., Vertes, K., & Heimdal, A. (2020). Strength and deformation behaviour of fibre reinforced UHPC; an experimental investigation using Digital Image Correlation (DIC). *Proceedings of HiPerMat 2020 5th International Symposium on Ultra-High Performance Concrete and High Performance Construction Materials.* ISBN: 978-3-7376-0828-2. Kassel University Press GmbH. Session A8: Fibre Reinforced Concrete II. 139-140.

8. Larsen, I. L., Thorstensen, R. T., & Vertes, K. (2019). Efficient use of fibres in UHPC - A structured scoping review. *Proceedings for the 2018 Fib Congress: Better, Smarter, Stronger*, 458-469.

9. Vertes, K., Larsen, I. L., & Thorstensen, R. T. (2019). Numerical modelling of fiber-reinforced ultra-high-performance concrete. *Proceedings for the 2018 Fib Congress: Better, Smarter, Stronger*, 577-586.

10. Larsen, I. L., Aasbakken, I. G., O'Born, R., Vertes, K., & Thorstensen, R. T. (2017). Determining the environmental benefits of ultra high performance concrete as a bridge construction material. In *IOP Conference Series: Materials Science and Engineering*, 245(5). doi:10.1088/1757-899X/245/5/052096

11. Thorstensen, R. T., Heimdal, A., Larsen, I. L., & Hansen, H. A. (2016). LCC and Carbon Footprint of Bridge made from locally produced UHPC, compared to Standard Concrete. *Proceedings of HiPerMat 2016 4th International Symposium on Ultra-High Performance Concrete and High*

Performance Construction Materials. ISBN: 9783737600941. Kassel University Press GmbH. chapters 197-198.

The following papers belong to the fields of Science, Technology, Engineering, and Mathematics (STEM) education:

12. Heimdal, A., & Lande, I. (2022). Various forms of executing peer reviews in civil engineering education. In *DS 117: Proceedings of the 24th International Conference on Engineering and Product Design Education (E&PDE 2022)*, London South Bank University in London, UK. 8th-9th September 2022. doi: 10.35199/EPDE.2022.113

13. Heimdal, A., Larsen, I. L., & Thorstensen, R. T. (2019). The use of industrial networks to strengthen civil and structural engineering education; A survey-based investigation. In *DS 95: Proceedings of the 21st International Conference on Engineering and Product Design Education (E&PDE 2019)*, University of Strathclyde, Glasgow. 12th-13th September 2019. doi:10.35199/epde2019.93

14. Larsen, I., Heimdal, A., & Norheim, T. (2018). Industrial driven student research; a case study on the potential for industrialising construction of bridges. In *DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018),* Dyson School of Engineering, Imperial College, London. 6th-7th September 2018, 187-192.

15. Thorstensen, R., Larsen, I., & Svennevig, P. (2018). Pursuing diversity in engineering education; a case study on RD&I-cooperation within civil engineering. In *DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018),* Dyson School of Engineering, Imperial College, London. 6th-7th September 2018, 181-186.

16. Thorstensen, R., Larsen, I., & Svennevig, P. (2018). Societal responsibility in engineering education; a case study on RD&I-cooperation within civil engineering. In *DS 93: Proceedings of the 20th International Conference*

on Engineering and Product Design Education (E&PDE 2018), Dyson School of Engineering, Imperial College, London. 6th-7th September 2018, 338-343.

Presentations

A. Larsen, I. L. (2019). The impossible country – made possible with concrete (original title: Det umulige landet – som blir mulig med betong (in Norwegian). *Lørdagsuniversitet Arendal, Arendal, Norway*.

B. Larsen, I. L., & Thorstensen, R. T. (2019). Experiences with UHPC from the University of Agder (original title: Erfaringer med UHPC fra Universitet i Agder). *Betongindustridagene 2019, Seminar: Ultra High Performance Concrete*, Gardermoen, Norway.

C. Larsen, I. L. (2018). Lowering environmental impact from ultra high performance concrete, utilising industrial by-products. Poster presented at *the 12th Fib International PhD Symposium in Civil Engineering*, Prague, Czech Republic.

D. Larsen, I. L. (2018). Efficient use of fibres in UHPC, presented at the *Fib Congress: Better, Smarter, Stronger*, Melbourne, Australia.

E. Larsen, I. L., Heimdal, A., & Norheim, T. (2017). Translation of the title: Standardization of bridge structures (original title: Standardisering avbrokonstruksjoner). At *Bane NOR internal seminar*.

F. Larsen, I. L., Heimdal, A., & Norheim, T. (2017). Findings from the investigation of standardization of bridge structures for national highways (original title: Funn fra undersøkelse om standardisering av brokonstruksjoner for nasjonale hovedveier). Industry panel under the auspices of collaboration between UiA and Nye Veier AS.

G. Heimdal, A. & Lande, I. (2022). Various forms of executing peer reviews in civil engineering education. Presented at *the 24th International Conference on Engineering and Product Design Education (E&PDE 2022)*, London, UK.

H. Thorstensen, R., Larsen, I., & Svennevig, P. (2018). Pursuing diversity in engineering education; a case study on RD&I-cooperation within civil engineering, presented at the *20th International Conference on Engineering and Product Design Education (E&PDE 2018)*, London, UK.

Contents

1 Introduction

1.1 Context

The building and construction industry is generally considered to be responsible for approximately 40% of anthropogenic greenhouse gas (GHG) emissions worldwide [1]. Concrete is the most commonly used material in the world, with 10 billion cubic metres produced annually [2]. According to estimates, global GHG emissions from the concrete industry range from 7–9% [2-6]. These emissions are mainly CO_2, which are primarily generated from the production of cement. Anthropogenic GHG emissions have contributed to observable global climate change [7]. Immediate action is required to reduce emissions and minimise negative impacts [8]. A likely area of conflict is that involving the short and long term actions necessary to reduce the GHG footprint [9], because these actions could be internally contradictory. Actions to limit global warming have been initiated through the United Nations' Sustainability Development Goals (explicitly in UN-SDG no. 13 and implicitly in several others), the Paris Agreement, and numerous other initiatives.

Concrete is essential for the prosperity and growth of countries at all developmental stages. Concrete is necessary for the construction of buildings and critical infrastructure in developing countries, and for maintenance and building upgrades in developed countries [2, 4, 10]. In the United Nations Environment Program Sustainable Building and Climate Initiative (UNEP-SBCI), Scrivener et al. [11] analysed the consumption rates of cement and steel relative to the increase in the world population (Fig. 1). Even without considering the material properties that make concrete essential, it is evident from a volume perspective (Fig. 1) that concrete cannot be replaced by another construction material [2, 11].

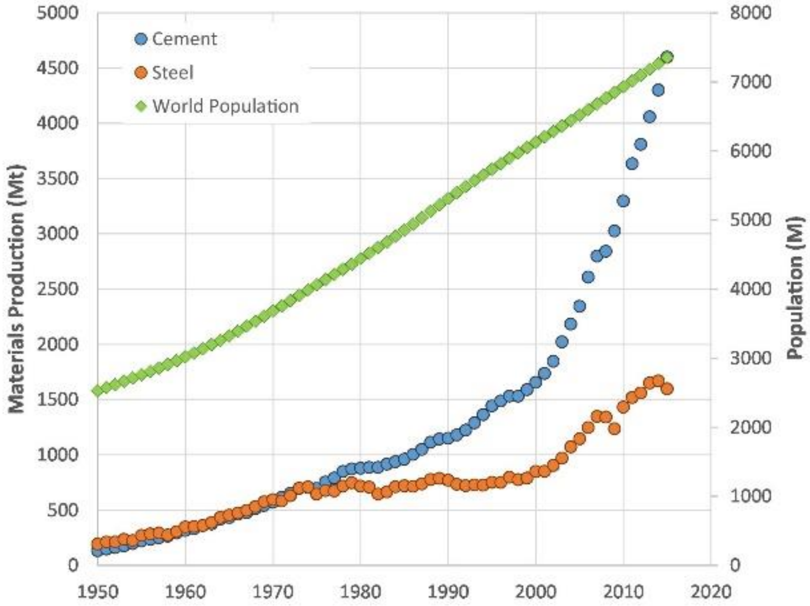


Fig. 1 Increase in world population compared with cement and steel production 1950–2015 [11].
Reprinted with permission from Elsevier [12].

Sustainability is normally defined as the overlap between economic, social, and environmental aspects. Although concrete affects all parts of the sustainability term, most technical research focuses only on the environmental aspects, specifically on measures to reduce CO_2 emissions [2, 4, 10, 11, 13]. Several research approaches have been adopted by the industry, such as the use of supplementary cementitious materials (SCMs) to reduce the consumption of Portland clinker in cement. However, additional approaches have emerged from new research directed towards even more efficient applications. One approach that has not been investigated sufficiently is the potential contribution of the use of ultra-high-performance (fibre-reinforced) concrete (UHPC). It is frequently asserted that UHPC can substitute for normal concrete in certain applications, thereby reducing the environmental footprint while maintaining commercial competitiveness.

1.2 Motivation—identifying a research deficiency

In 2009, Mehta proposed a fundamental strategy for reducing CO_2 emissions from the conventional concrete industry [13]. This strategy consists of three tools: 1) using less concrete for new structures, 2) consuming less cement in concrete mixtures, and 3) consuming less clinker to produce cement. Although acknowledged for many years and partly adopted by the industry, these tools remain highly relevant and are regularly presented in contemporary publications

[2, 5, 11]. Approaches other than those of Mehta have also been identified and discussed, such as more efficient cement production [2, 5, 11], applications within the circular economy [5], facilitation of carbon uptake [2, 5], use of new cement types [2, 4, 5, 11], and carbon capture, use, and storage (CCS/CCU) [2, 4, 5, 11].

An emerging approach is to use UHPC, which is a relatively new fibre-reinforced cementitious material with improved material properties compared with normal concrete [14]. UHPC is also referred to as ultra-high-performance fibre-reinforced concrete (UHPFRC) [14, 15], however for the purposes of this thesis it is referred to as UHPC. This material is generally described by three main property requirements: compressive strength above 120 MPa (previously 150 MPa), sustained post-cracking tensile strength above 5 MPa, and improved durability through a discontinuous pore structure [16]. The composition of UHPC differs from that of normal concrete [17]. The differences include a high binder content, the absence of coarse aggregates, a low water-to-cement (w/c) ratio, and a large volume of micro steel fibres (generally > 2 vol%) (see Fig. 2).

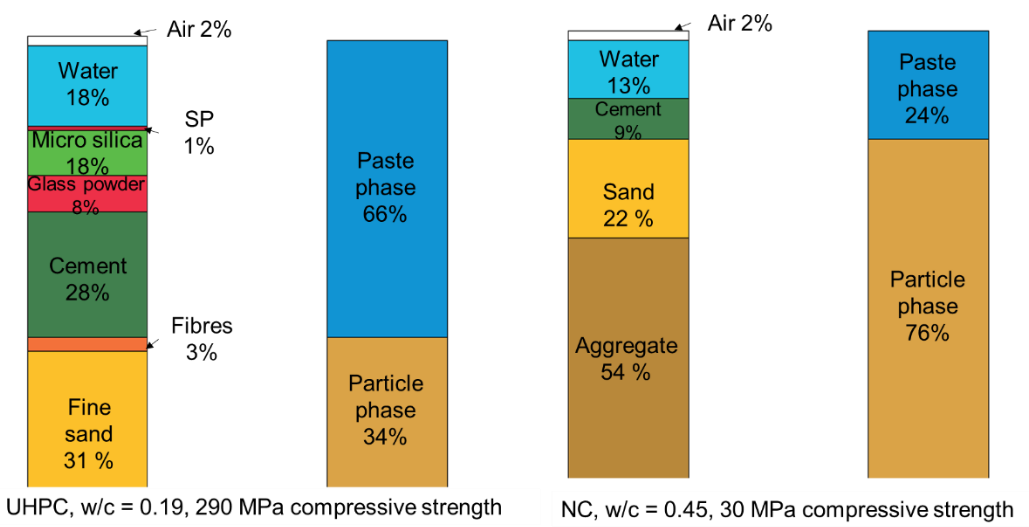


Fig. 2 Example of mix proportions by volume of UHPC compared with normal concrete (NC), redrawn according to [17].

The bridge sector has taken a global pilot position in the use of UHPC for both new structures and rehabilitation of deteriorated structures [14, 16, 18-20].

The use of the material strength and high durability of UHPC may reduce the emissions from material consumption and extend the service life by a factor of at least two [21]. A considerable improvement in service life is considered by

Mehta [13] to be the best long-term solution for the sustainability of the concrete industry.

There may be opportunities to further improve the sustainability of UHPC, in addition to reducing the requirement for concrete for new structures through the smart use of existing UHPC materials. There have been frequent alternative attempts to achieve this recently. Cement and micro steel fibres contribute to approximately 95% of the total CO_2-equivalents (CO_2-eq.) from UHPC materials [22], as illustrated in Fig. 3.

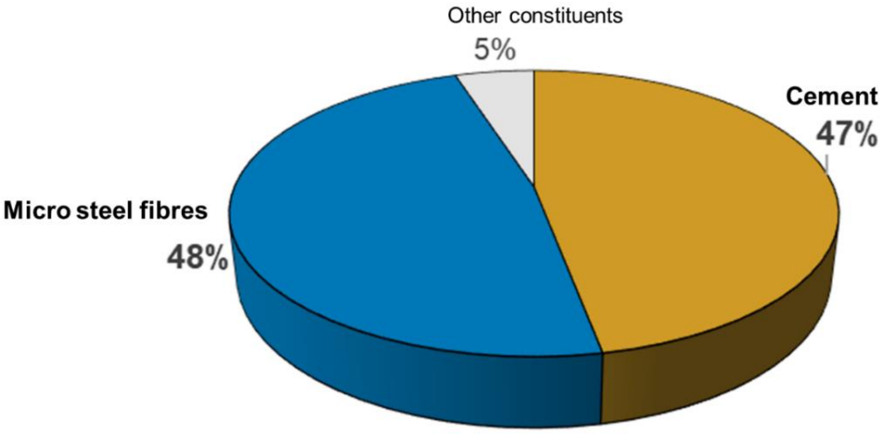


Fig. 3 Contributions to the Global Warming Potential (GWP), CO_2-eq. of UHPC per cubic metre. The percentages are based on the paper by Stengel & Schießl [22].

Several different approaches have been proposed to achieve more sustainable UHPC. Some studies have investigated the use of several different industrial by-products to reduce cement consumption [21, 23-27]. Another measure for this purpose is the use of particle packing models [23, 25, 28, 29]. A third approach is to use industrial by-products, including construction and demolition waste (C & D waste), to replace the high-quality aggregates normally used in UHPC [30-32]. Focus has also been placed on the influence of different types of steel fibres in UHPC to achieve more efficient use [33-36]. Other researchers have investigated the local development of UHPC as an alternative to commercially available types [37-41]. This can potentially limit the CO_2 emissions related to the transport of large volumes of pre-bagged UHPC materials from a limited number of suppliers to construction sites worldwide.

Numerous individual initiatives, in addition to those aforementioned, are emerging. However, these studies are mostly focused on narrow approaches, such as the use of a specific source of material. Furthermore, an accompanying improvement in the environmental footprint of UHPC has often been reported. There does not appear to be a comprehensive strategy with regard to how UHPC can be produced and used more sustainably, such as that developed by Mehta [13] for normal concrete. Such a strategy should be developed based on accumulated knowledge from ongoing and published efforts regarding how individual measures synergise.

1.3 Research objectives

The main research objective of this thesis is to develop a comprehensive strategy for how the UHPC industry can contribute to improving the sustainability of the concrete industry, by investigating alternative approaches. Cost aspects were considered to indicate whether the strategy is commercially viable.

UHPC was designed to satisfy certain specific mechanical criteria. These properties should not be compromised by measures aimed at increasing the sustainability of UHPC. It is well known that the two constituents, Portland clinker cement and microfibres made from high-strength steel, are the sources of approximately 95% of CO_2-eq. Thus, the challenge is to identify means of manipulating these two constituents. The efforts presented in this thesis were undertaken to investigate how potential CO_2-reducing measures influence the mechanical properties of UHPC and, in some instances, how it relates to cost efficiency.

The methods applied to achieve this research objective included a combination of literature reviews and experiments conducted by the author. The experiments were conducted in a stepwise manner to accumulate knowledge. These efforts were concluded by the development of a comprehensive strategy consisting of a set of tools. This strategy can inform the development and use of UHPC to improve the sustainability of the concrete industry. This is suggested as a guideline for a more sustainable concrete industry. The main research objective was approached through the following research objectives (ROs):

RO1: Identify directions for a sustainable concrete industry.

Addressed in Paper I.

RO2: Investigate the potential for reducing the consumption of cement in UHPC.

Addressed in Papers II and III.

RO3: Investigate the potential for efficient use of steel fibres in UHPC.
Addressed in Papers IV and V.
RO4: Demonstrate the potential for locally produced UHPC mixes using by-products and surplus materials.
Addressed in Papers II, III, and V.
RO5: Develop an overall strategy for more sustainable UHPC.
Addressed in Paper VI.

1.4 Contributions of the thesis

This thesis summarises and elaborates on how the six appended papers contributed to addressing the research objectives. The contributions of this thesis are extracted from each of the appended papers and are summarised as follows:

1.4.1 Paper I

Summary: This paper presents an investigation of the sustainable use of concrete for road infrastructure in a novel industrialised context. The study uses a SWOT analysis related to the frequently used terms *sustainability*, *industrialisation,* and *digitalisation*. Directions for the more sustainable use of concrete are identified and discussed. The main opportunities and threats are summarised in the conclusion.

Contributions: Identification of a set of approaches for the sustainable use of concrete.

This paper has been published as: Larsen, I. L., Terjesen, O., Thorstensen, R. T., & Kanstad, T. (2019). Use of Concrete for Road Infrastructure: A SWOT Analysis Related to the three Catchwords Sustainability, Industrialisation and Digitalisation. *Nordic Concrete Research* 60(1) 31–50. https://doi.org/10.2478/ncr-2019-0007.

1.4.2 Paper II

Summary: An experimental study was conducted to investigate the potential of using cement in UHPC more efficiently. This is achieved through the partial substitution of the cement with a locally available inert filler. The inert filler is filter-harvested granite powder obtained from gravel production. As an additional means to reduce the cost and environmental footprint, the aggregate comprised an unused fraction from the production of machine gravel. The experimental results show the potential to replace up to approximately 40% of cement with an inert filler with little reduction in the compressive strength.

Contributions: Demonstrating the potential for reducing the active cement component with inert material in locally developed UHPC while maintaining the compressive strength.

This paper has been published as: Larsen, I. L., Thorstensen, R. T., & Vertes, K. (2018). Lowering environmental impact from ultra high performance concrete, utilising industrial by-products. *Proceedings of the 12th Fib International PhD Symposium in Civil Engineering*, 93–100.

1.4.3 Paper III

Summary: This study is an extension of the work presented in Paper II. It comprises analyses of results from both a literature review and an expanded experimental program. A literature review is conducted to identify the typical materials used for cement substitution in international research and to discuss how the reduction in cement through substitution with these materials influences the compressive strength of UHPC. The findings are used to enrich the discussion and benchmark the results of the experimental program. It is found that materials possessing binding properties have been used as substitutes for cement in investigations aimed at maintaining mechanical properties. Only a few studies have investigated substitutions with inert materials. The experimental results show the feasibility of substituting up to approximately 40% of the cement with inert materials with little reduction in the compressive strength and flexural tensile strength.

Contributions: A systematic overview of the accumulated results found in research on the more efficient use of cement in UHPC. Additionally, it demonstrates the potential for substituting up to 40% of the cement content in UHPC with an inert material while maintaining the strength-based properties.

This paper has been published as: Lande, I., & Thorstensen, R. (2021). Towards Efficient Use of Cement in Ultra High Performance Concrete. *Nordic Concrete Research*, 65(2) 81–105. https://doi.org/10.2478/ncr-2021-0017.

1.4.4 Paper IV

Summary: An analysis of the influence of steel fibre reinforcement on the compressive and tensile strengths of UHPC is conducted by analysing experimental data obtained in international research. Relevant data are gathered using a systematic literature search. The fibre content, type (shape and length), and hybrid combinations of different fibres are studied. The accumulated results reveal that the fibre content, fibre type, and hybrid combinations have diverse influences on the tensile strength of UHPC. Using hybrid combinations and fibres with better pull-out properties show the potential to increase the flexural tensile strength in some cases. The effect of steel fibres on the compressive strength varies between investigations, from low to substantial increases. It is also concluded that the influence of steel fibres may be affected by other factors, such as specimen geometry, mix design, and curing conditions.

Contributions: Systemised accumulation and analysis of international research regarding the impact of using different steel fibres on the compressive and tensile strengths of UHPC. This demonstrates the opportunities for more efficient use of steel fibres in UHPC.

This paper has been published as: Larsen, I. L., & Thorstensen, R. T. (2020). The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review. *Construction and Building Materials*, 256(30), 119459. https://doi.org/10.1016/j.conbuildmat.2020.119459.

1.4.5 Paper V

Summary: This paper presents an accumulated analysis of the influence of steel fibres from a series of experiments executed on local UHPC mixes. Steel fibre content, type, and hybrid combinations are investigated on material strength and deformation behaviour. Digital image correlation (DIC) is used to study crack propagation. Different local UHPC mixes are developed using recommendations provided in the literature, in addition to the modified Andreasen and Andersen particle packing model. Variations in the steel fibre content, type, and hybrid combinations are found to have little influence on the compressive strength. For flexural tensile strength, hybrid combinations of fibres perform comparably to the use of micro fibres. The use of only hooked-end fibres seems to be unfavourable. The efficiency of the steel fibres is found to differ between the mixes.

Contributions: The potential for increasing the efficiency of fibre use by varying the content, type, and hybrid combination of steel fibres in locally produced UHPC compositions is demonstrated. In addition, the potential for developing UHPC materials while exploiting different locally available aggregates is demonstrated.

This paper has been published as: Lande, I., & Thorstensen, R. T. (2021). Locally Produced UHPC: The Influence of Type and Content of Steel Fibres. *Nordic Concrete Research*, 64(1) 31–52. https://doi.org/10.2478/ncr-2021-0003.

1.4.6 Paper VI

Summary: An overall strategy for how the UHPC industry can contribute to improving the sustainability of the concrete industry is developed and presented. The strategy is developed after reviewing existing research on normal concrete and UHPC, while benefitting from the knowledge accumulated in Papers I–V. The result is a five-tool strategy for a more sustainable UHPC industry.

Contributions: A sustainable strategy for UHPC consisting 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* is proposed. This strategy is intended to direct and support future efforts in the research environment and improve the sustainability of the concrete industry using UHPC.

This paper is under review: Lande, I., & Thorstensen, R. Comprehensive sustainability strategy for the emerging ultra-high-performance concrete (UHPC) industry. *Revised version is submitted to an international journal (December 2022).*

1.5 Interrelations between the papers

Fig. 4 demonstrates how the six papers are interrelated to satisfy the main objective of this thesis.

Paper I is a background paper that establishes directions for more sustainable concrete road infrastructure, among others. It can be concluded that efficient use of materials through the smart use of UHPC is an opportunity.

Papers II–V reveal efforts to investigate different approaches to make UHPC more sustainable. Papers II and III consider how a reduction in cement content influences the strength-based properties. The results and discussions are informed both from international research identified through a systematic literature review, and from experiments on locally developed UHPC conducted by the author.

Papers IV and V focus on the efficient use of steel fibres. Paper IV describes the state-of-the-art in international research on how steel fibres influence the key strength properties of UHPC. The objective was to determine how steel fibres can be used efficiently in UHPC. Based on the knowledge acquired through the work presented in Paper IV, further experimental investigations were conducted by the author on how different fibre types and combinations influence the mechanical properties of locally produced UHPCs. Paper V presents and discusses the experimental results of the observations presented in Paper IV.

The study concludes with the development of an overall strategy for making UHPC more sustainable. This is presented in Paper VI.

Fig. 4 Interrelationship of papers in conjunction with the research objectives (RO).

1.6 Thesis structure

The thesis comprises five chapters:

- Chapter 1 (this chapter) introduces the general background and the research objectives. It also presents the papers, their interrelationships, and the structure of this thesis.
- In Chapter 2, overviews of the research approach and problem description are presented for each research objective.
- In Chapter 3, the main observations of the appended papers are discussed.
- The main conclusions are drawn (Chapter 4), and further directions for the research topic are recommended (Chapter 5).
- The papers are appended at the end of the thesis.

2 Research approach

2.1 Overview

Fig. 5 shows a flowchart of the research approaches applied in this study. The research approach and problem description for each research objective (RO1–RO5) are described in the following sections. The applied research methods are described in detail in each appended paper.

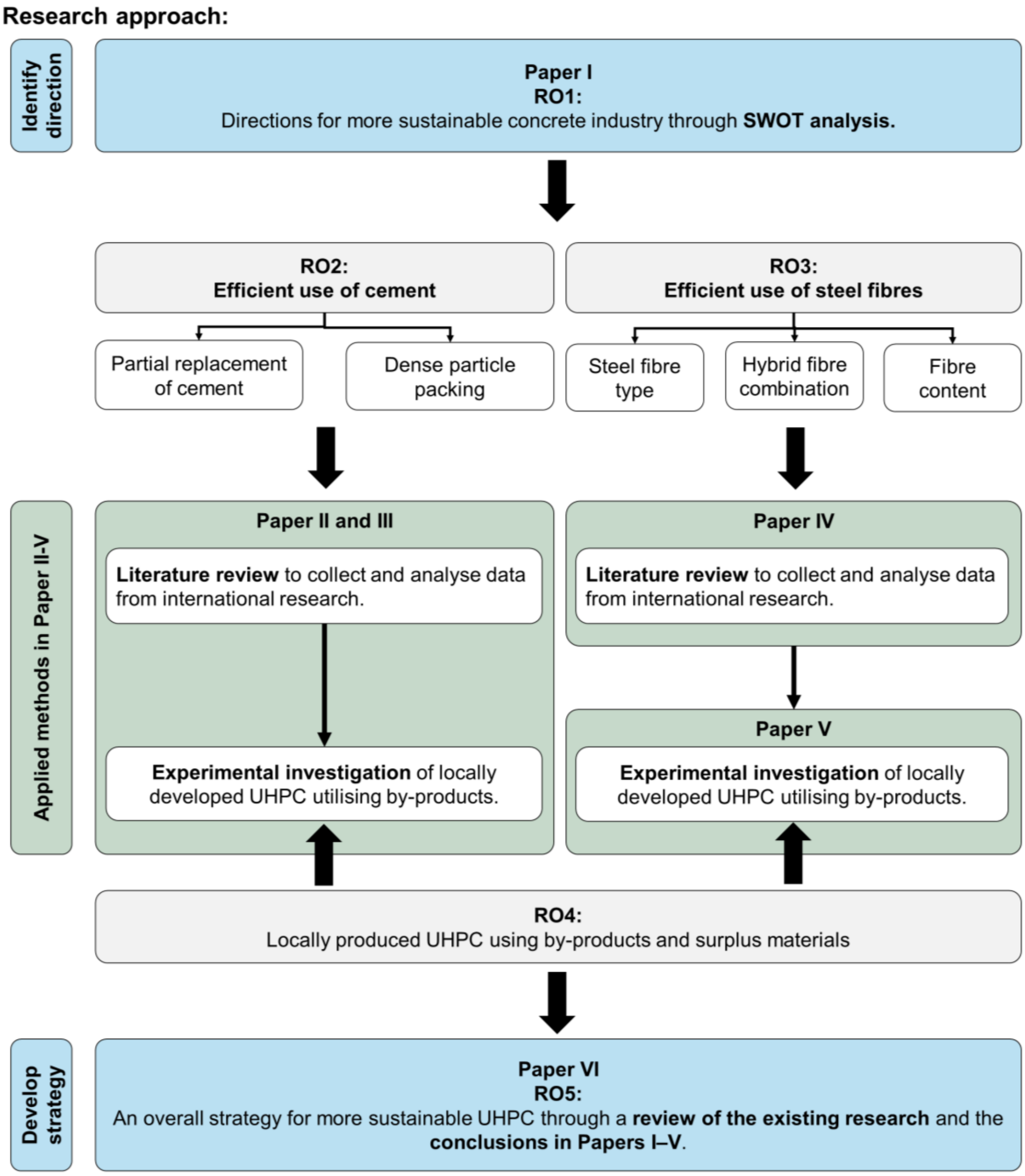


Fig. 5 Overall research approach.

2.2 Directions for a more sustainable concrete industry (RO1)

2.2.1 Problem description

This thesis is a result of the research project *'More Efficient and Environmentally friendly Road Construction'*. The project is commonly owned by the University of Agder and the national building client organisation Nye Veier. The Norwegian government established Nye Veier to increase innovation for constructing national highways in an economic and environmentally friendly way. This research work was initiated in collaboration with another PhD candidate to identify the research pathways. The first task was to investigate the potential within the often-used terms in both research and industrial development: *Sustainability*, *Industrialisation*, and *Digitalisation*.

2.2.2 Research approach

Research objective 1 (RO1): Identify directions for a sustainable concrete industry was investigated in the study reported in Paper I. The investigation was conducted as a SWOT analysis of the use of concrete for road infrastructure. This illustration in Fig. 6 shows the methodology.

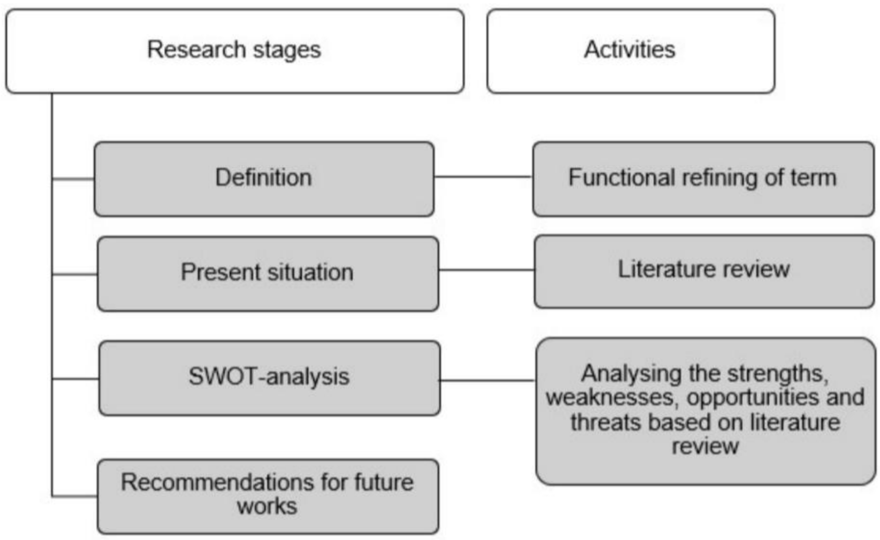


Fig. 6 Research methodology applied in the study reported in Paper I.

The conclusion is a set of recommendations for future research on the sustainable use of concrete in the construction of road infrastructure.

2.3 Efficient use of cement (RO2)

2.3.1 Problem description

A high content of both cement and micro silica (silica fume) is used in UHPC. The cement content in a typical UHPC is in the range of 700–1000 kg/m^3 [14, 42] and that of micro silica is approximately 25% of the cement (by mass) [14, 17, 41, 42]. In addition to cement and micro silica, other binders commonly used as SCMs can also be used such as fly ash or blast-furnace slag [39, 41, 42]. The total binder phase of UHPC is generally in the ratio 1 : 0.25 : 0.25 for cement : micro silica : other SCMs [41, 43]. The combination of cementitious materials generally yields a total binder content greater than 1000 kg/m^3 [14, 39, 41].

To reduce porosity, the w/c ratio is kept low, generally in the range of 0.14–0.3 [41, 42]. This results in a high content of non-hydrated cementitious particles in the hardened UHPC [44, 45]. The non-hydrated particles function as fillers.

Approximately half of the CO_2 emissions of UHPC materials are caused by cement production. Specifically, 47% of the total CO_2-eq. in a UHPC mixture with 752 kg/m^3 of cement and 242 kg/m^3 of steel fibres [22]. The high binder content also contributes to an increase in unit cost [22, 41]. Because parts of the cement function as fillers, replacement with materials with lower CO_2 emissions contributes to more sustainable UHPC.

Measures applied in normal concrete to reduce the cement content can potentially be applied to UHPC, such as Mehta's [13] *Tool 2 consume less cement in concrete mixtures*, and *Tool 3 consume less clinker for producing cement*. These measures were identified in the study reported in Paper I.

2.3.2 Research approach

Research objective 2 (RO2): Investigate the potential for reducing the consumption of cement in UHPC was investigated in studies reported in Papers II and III. The objective was addressed by gathering and analysing international research (Paper III) and conducting an experimental program (Papers II and III).

Some preliminary results from the experimental program are presented in Paper II, and the complete program is presented in Paper III. This is a carefully selected research strategy in which some of the results are presented at an *fib* (International Federation for Structural Concrete) conference, and this opportunity is used to discuss the approach and results in a competent research community. The feedback received from the conference is used to develop a journal paper on the full dataset (Paper III).

The objective of both studies is to investigate certain key mechanical properties of UHPC while reducing the cement content through substitution.

A structured literature review was performed to identify commonly used types of materials to substitute for cement in UHPC and to determine how a reduction in the cement content influences the compressive strength.

For the experimental part of the investigation, cement was substituted with an inert filler in a locally produced UHPC mix. Granite dust was used as the filler, which was harvested in a filter for the production of gravel. The particle size distribution corresponded to that of the cement, thus maintaining the accumulated particle packing of the UHPC mix. The influences of cement substitution on the compressive and flexural tensile strengths were studied. The testing regime was designed according to the EN standard for cement mortar EN 196-1 (Fig. 7) and the ASTM standard C109/C109M. These testing regimes have been used in several similar studies [23, 28, 46].

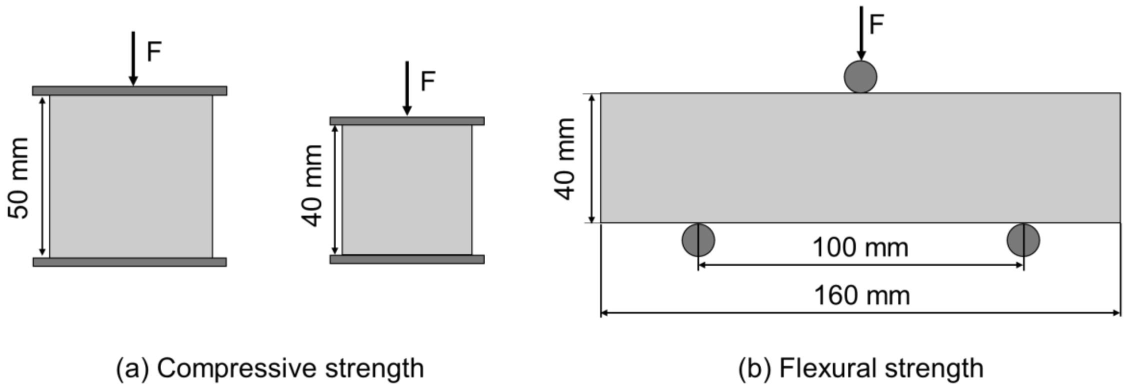


Fig. 7 Experimental test methods applied in Papers II and III (EN 196-1 and ASTM C109/C109M)

The binder and CO_2 intensity indices are calculated according to the procedure described by Damineli et al. [47]. The indices are compared with the results reported in the literature. These two indices measure the amount of binder required and CO_2 emitted, respectively, to attain a compressive strength of 1 MPa. The binder intensity index is used to measure the cost, whereas the CO_2 intensity index is related to the environmental impact (GWP).

2.4 Efficient use of steel fibres (RO3)

2.4.1 Problem description

Discrete fibres are generally a part of UHPCs. High-strength straight micro steel fibres are those most used, such as those with a fibre length of 13 mm and diameter of 0.2 mm [20, 42] (Fig. 8). Commercially available UHPC products generally have fibre contents in the range of 2–6 vol% [14, 16, 20], but values up to 11 vol% have also been seen [14].

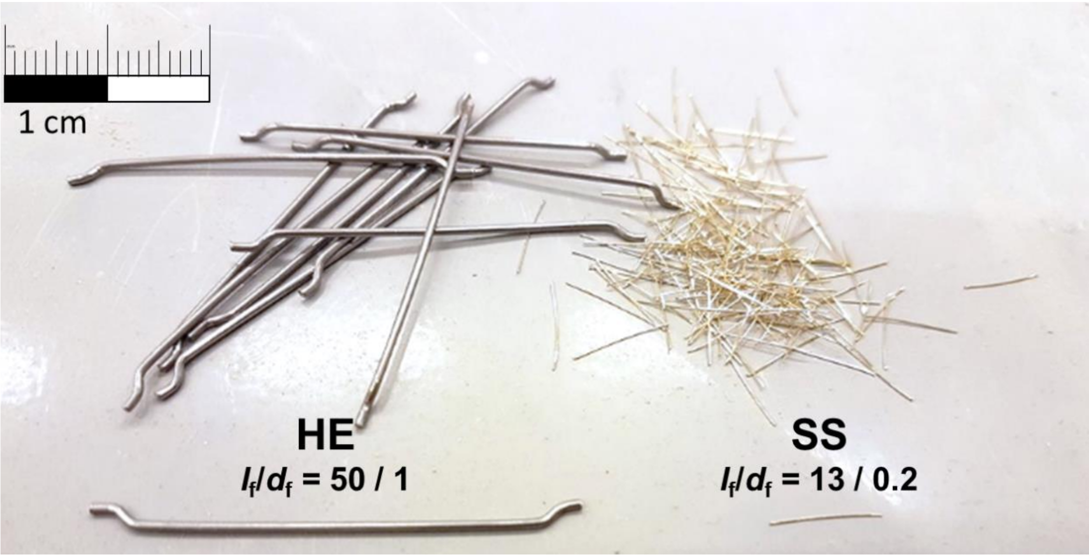


Fig. 8 Typical hooked-end steel fibres (HE) in conventional fibre-reinforced concrete (left side) and typical straight micro steel fibres (SS) in UHPC (right side). The fibre length (l_f) and fibre diameter (d_f) are in mm.

The inclusion of fibres is essential to impart the required ductility and so prevent the brittle behaviour of UHPC, which is a consequence of the special material composition. This differentiates UHPC from normal concrete. The fibres can improve several related material properties, such as provide usable tensile strength, sustained post-cracking strength, strain-hardening properties, and energy absorption capacity [48].

Micro steel fibres made from high-strength steel account for a substantial portion of the CO_2 emissions of UHPC. Typically, this is 48% of the total CO_2-eq. in a UHPC mix with 242 kg/m^3 of steel fibres and 752 kg/m^3 of cement [22]. Much of the CO_2-eq. from the production of micro steel fibres originates from the wet wire drawing process, which is necessary to achieve such small fibre diameters (0.15 mm in the investigation [22]). Micro steel fibres also account for a considerable share of the unit cost [22, 41]. Hence, a more efficient use of steel fibres is important for achieving a more sustainable UHPC.

Several approaches have been investigated to limit the CO_2 emissions from steel fibres. One is to use synthetic fibres with a lower CO_2 footprint [49]. Another approach is to use steel fibres with a larger diameter, allowing for production using less energy-intensive methods [22]. It is also possible to use steel fibres with better pull-out properties [50-52] or hybrid combinations of fibres with different properties [34, 35, 53]. The concept of hybrid fibre combinations in high-strength concrete was thoroughly investigated by Markovic [54]. The principle is to use the properties of each fibre type to generate synergetic effects [54]. As illustrated in Fig. 9, the short (micro) fibres bridge micro cracks, and the longer (macro) fibres prevent the propagation of macro cracks. The use of macro hooked-end steel fibres [33-35, 55-57] or long straight fibres [57, 58] in hybrid combination with micro steel fibres has been investigated.

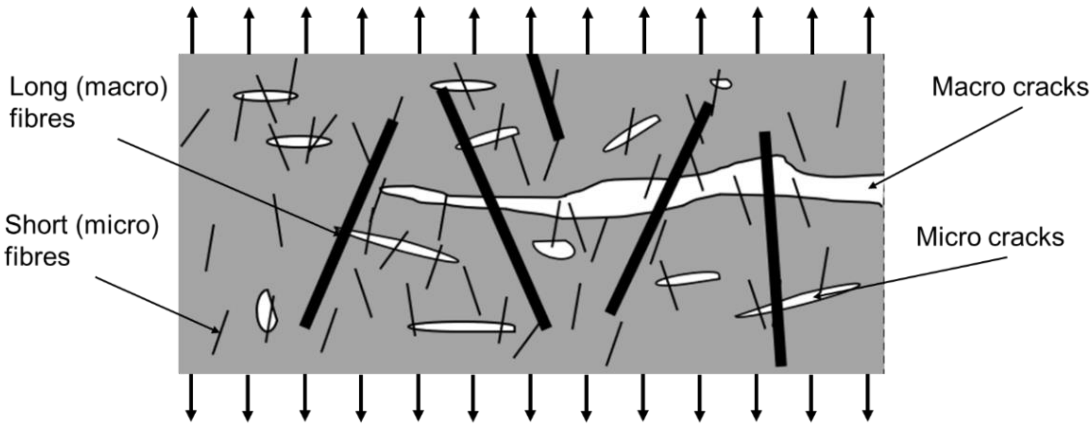


Fig. 9 Concept of hybrid fibre configuration for concrete subjected to tensile forces. Redrawn from Markovic [54].

2.4.2 Research approach

Research objective 3 (RO3): Investigate the potential for efficient use of steel fibres in UHPC was investigated in the studies described in Papers IV and V. The aim of both studies is to understand the influence of steel fibres on the mechanical properties of UHPC and to determine how steel fibres can be used more efficiently.

Paper IV describes the influences of steel fibres on the compressive and tensile strengths of UHPC by analysing existing experimental data from international research identified through a literature review. The parameters investigated include fibre content, type (shape and length), and hybrid combinations.

For the experimental part of the investigation (Paper V), the influence of steel fibre content, types (micro and macro steel fibres), and hybrid combinations of two different types were applied in different locally produced UHPC mixes. The micro fibre is a typical UHPC steel fibre, whereas the macro fibre is a locally available hooked-end steel fibre commonly used in normal fibre-reinforced concrete. Both types of steel fibres are shown in Fig. 8.

The influences on the behaviour and strength during compressive and flexural loading were studied (Fig. 10). For the flexural tensile behaviour, a DIC system was used to study crack propagation. The use of DIC allows a better understanding of crack propagation.

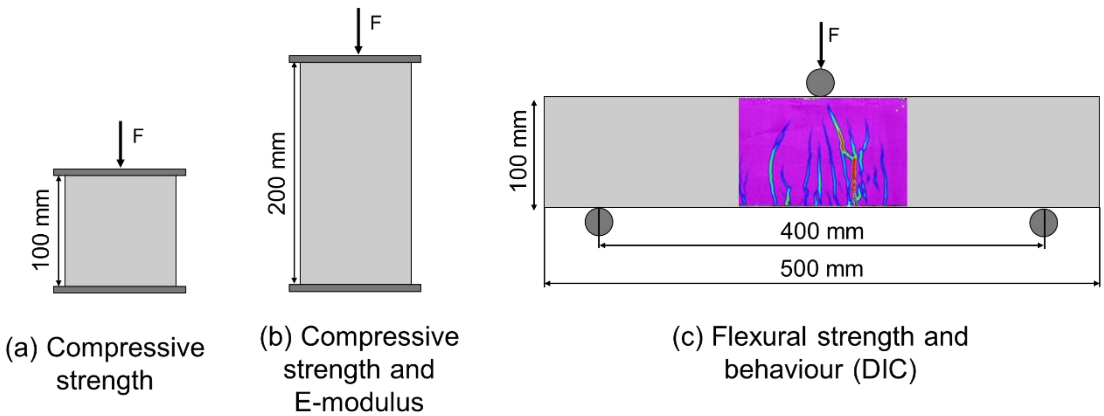


Fig. 10 Experimental test methods applied in the study reported in Paper V.

The methodological approach of first presenting a preliminary paper at a scientific conference and using the discussion for informing the subsequent journal paper was used for both Papers IV and V. The predecessor for Paper IV is referred to as Supporting Paper 7, and the predecessor for Paper V is Supporting Paper 8 (see *List of publications*).

2.5 Locally produced UHPC utilising by-products (RO4)

2.5.1 Problem description

UHPC is commercially available from a limited number of suppliers worldwide [39, 59] as a pre-bagged dry material that can be mixed with water, steel fibres, and admixtures [20]. In addition to the high cost [41] and CO_2 emissions of these products compared to normal concrete [22], there are CO_2

emissions associated with the transport of large volumes over long distances. Another weakness of this market without local capacity for producing UHPC is the lack of development of local competence, which would make the general concrete industry more versatile. This may delay the widespread use of UHPC, even for purposes where profitability is convenient to foresee and document.

Numerous studies have promoted the local production of UHPC worldwide [37-41, 60]. This opens several avenues for increasing the sustainability of UHPC production. The use of locally available materials is obvious in normal concrete. The arguments in favour may also be valid for UHPC production.

One opportunity to promote the sustainability of UHPC involves replacing the high-quality quartz sand normally used for the aggregate in UHPC [14, 42] with other materials, preferably different locally available industrial by-products or C & D waste [30-32]. A second opportunity is the availability of the most used SCMs (fly ash and blast-furnace slag), which will decrease in the future [2, 11], and there will then be a requirement for other cement-substituting materials. This might also create opportunities for the use of local industrial by-products. This approach is consistent with that of Scrivener et al. [11]. The use of locally available by-products is also a measure to minimise waste and reduce the need for virgin materials from a broader industrial perspective.

2.5.2 Research approach

Research objective 4 (RO4): *Demonstrating the potential for locally produced UHPC mixes using by-products and surplus materials* is addressed in the studies reported in Papers II, III, and V.

The feasibility of producing UHPC from local materials is investigated through experiments aimed at developing UHPC using available materials. Based on the approaches identified in the literature review, recommendations on mix proportions [41, 43] were pursued in conjunction with a modified version of the Andreasen and Andersen model for granular materials [61, 62].

Two fractions of filter-harvested dust from gravel production were used. The finest fraction was used to substitute for cement (Papers II and III), and the coarsest fraction (D_{max} < 1 mm) was used as an aggregate in the studies described in Paper V. Additionally, an unused fraction from the production of machine gravel (D_{max} = 6 mm) was used as an aggregate in a coarser-grained UHPC (investigations reported in Papers II, III, and V). The experimental program consisted of tests of the compressive and flexural tensile strengths (Fig. 7 and

10). Studies reported on in the literature on the application of by-products to substitute for cement were also investigated and are presented in Paper III.

Locally developed UHPC was used in the studies reported in Papers II, III, and V, concerning the efficient use of cement and steel fibres (RO2 and RO3).

2.6 Strategy for more sustainable UHPC (RO5)

2.6.1 Problem description

The research literature provides an increasing number of papers that present studies arguing to improve the sustainability of UHPC. However, these efforts do not appear to be primarily aimed at improving the sustainability of the industry. Rather, this appears to be a secondary effect, while a specific by-product, that is currently waste or has a negative value, seems to be gaining more focus. The use of by-products is an important measure for improving sustainability, however, the industry needs a clearer focus on sustainable development.

There appears to be an absence of comprehensive strategies for how UHPC can contribute to improving the sustainability of the concrete industry. Such a strategy may function as a guideline for both research and industry to make UHPC an alternative to normal concrete for certain applications.

2.6.2 Research approach

Research objective 5 (RO5) Develop an overall strategy for more sustainable UHPC is addressed in the final study (Paper VI). The approach is based on reviewing the existing research literature in a two-stage process: i) a study of the directions for more sustainable normal concrete, and ii) the transfer value of these to UHPC, followed by studies that directly investigate the contribution of UHPC (Steps 1 and 2 in Fig. 11). The work leading to Papers I–V is also used in developing this strategy. The result is a comprehensive strategy (Step 3 in Fig. 11), which is suggested as a guideline for future research.

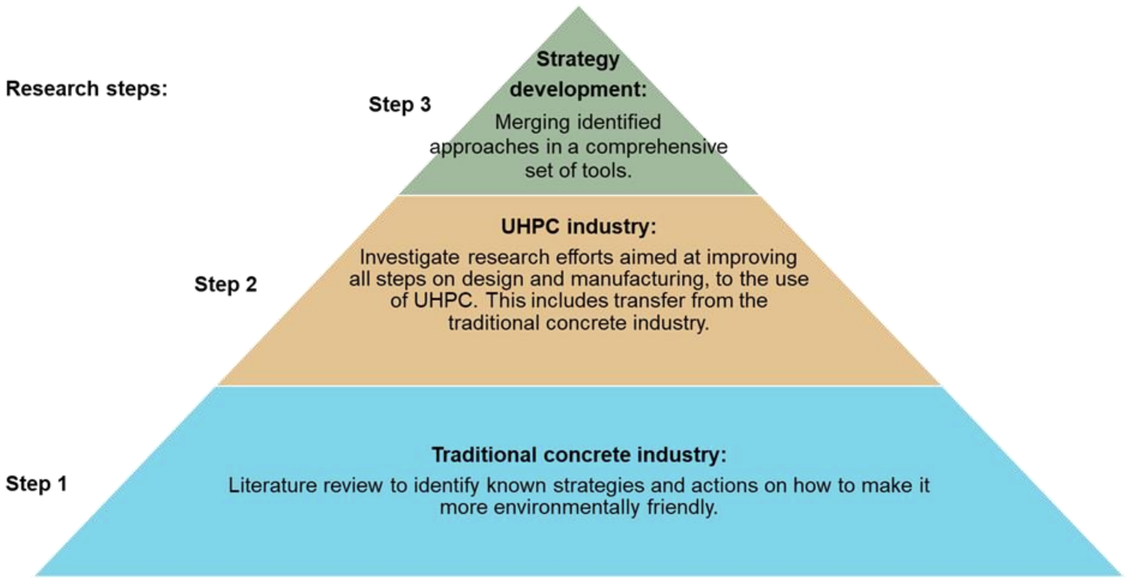


Fig. 11 Research methodology applied in the study reported in Paper VI.

3 Main observations

The conclusions of papers I–VI are presented and discussed in this chapter in the order of the research objectives (RO1–RO5) presented in Section 1.3. Full-text papers have been appended.

3.1 Directions for a more sustainable concrete industry (RO1)

Directions for a more sustainable use of concrete (RO1) are addressed in Paper I: '*Use of Concrete for Road Infrastructure: A SWOT Analysis Related to the three Catchwords Sustainability, Industrialisation, and Digitalisation*.

The study reported in this paper had a two-fold purpose. This was to identify the research direction for the two PhD candidates working with different approaches within the same project, *More Efficient and Environmentally friendly Road Construction'*. This study focused on the conventional concrete industry in its present state. Table 1 presents the results of the SWOT analyses on the sustainable use of concrete.

The smart use of high-performance concrete (HPC) and UHPC has been identified as a feasible approach. It originated from Mehta's [13] *Tool 1 Consume less concrete for new structures*. The smart use of UHPC involves the use of improved mechanical properties to limit material consumption and the enhanced durability properties to ensure that structures have an extended service life with minimal maintenance and repair. Increasing the service life of structures is considered an efficient long-term solution for improving the sustainability of the concrete industry [13]. A potential application area for UHPC is bridges and bridge rehabilitation [14, 16, 18-20]. The use of UHPC for bridge structures to reduce the environmental impact over their life cycle has been documented [49, 63, 64]. It was also found that for some applications, UHPC constitutes a competitive alternative to conventional methods in terms of cost [16, 18].

Table 1 SWOT analysis on sustainable use of concrete (points in bold highlight the relevant opportunities for this thesis), Paper I.

Strengths	**Weaknesses**
• The demand is increasing and will remain so due to population growth. • No material can replace concrete, due to required volume and availability. • Several advantages, like the simplicity of use, local part materials, flexible in design, cost-effectiveness and durability.	• Resource demanding locally and globally. • Causes substantial CO_2 emissions. • Conflicting timespan considerations for varying environmental goals.
Opportunities	**Threats**
Reduction of environmental loads through: • **Reduced material consumption through innovative design, prefabrication and use of HPC and UHPC.** • **Clinker reduction by use of SCMs and fillers.** • **Cement reduction by optimising grading and shape of aggregate particles.** • Utilising potential in extended maturity considerations (91 days hardening time, and innovative hardening technology). • **Increase the use of waste and recycled materials.** • **Enhancement of durability.** • CCS/CCU.	• Climatic changes. • Resource demanding. • Rigid regulations. • Availability of SCMs.

Some opportunities at the material level have been identified for normal concrete. One is the efficient use of cement in concrete. This originated from Mehta's [13] *Tool 2 Consume less cement for making concrete* and *Tool 3 Consume less clinker for making cement*. Measures within these tools continue to be emphasised frequently [2, 4, 5, 11]. Several different materials have been determined to be appropriate for use as SCMs in normal concrete. These include numerous by-products of other industries, such as fly ash, and blast furnace slag [2, 5, 11]. The availability of the SCMs that are used most is decreasing. Therefore, it is imperative to document and obtain formal approval for the use of new alternatives. Using inert fillers might be an alternative method of reducing the cement content while maintaining particle packing [11].

Another approach is to use C & D waste and other by-products, thereby promoting circularity in the concrete industry. The use of locally available by-products is vital for a circular economy.

The abovementioned opportunities for normal concrete may also be applicable to UHPC. This was investigated in studies reported in Papers II, III, V, and VI. As normal concrete does not include micro steel fibres, measures to reduce their environmental impact were not identified in the study reported in Paper I.

3.2 Efficient use of cement (RO2)

The investigation of the potential for more efficient use of cement in UHPC by reducing the consumption of cement (Portland clinker cement) (RO2) is addressed in the studies reported in Paper II '*Lowering environmental impact from ultra high performance concrete, utilising industrial by-products*' and Paper III '*Towards Efficient Use of Cement in Ultra High Performance Concrete*'.

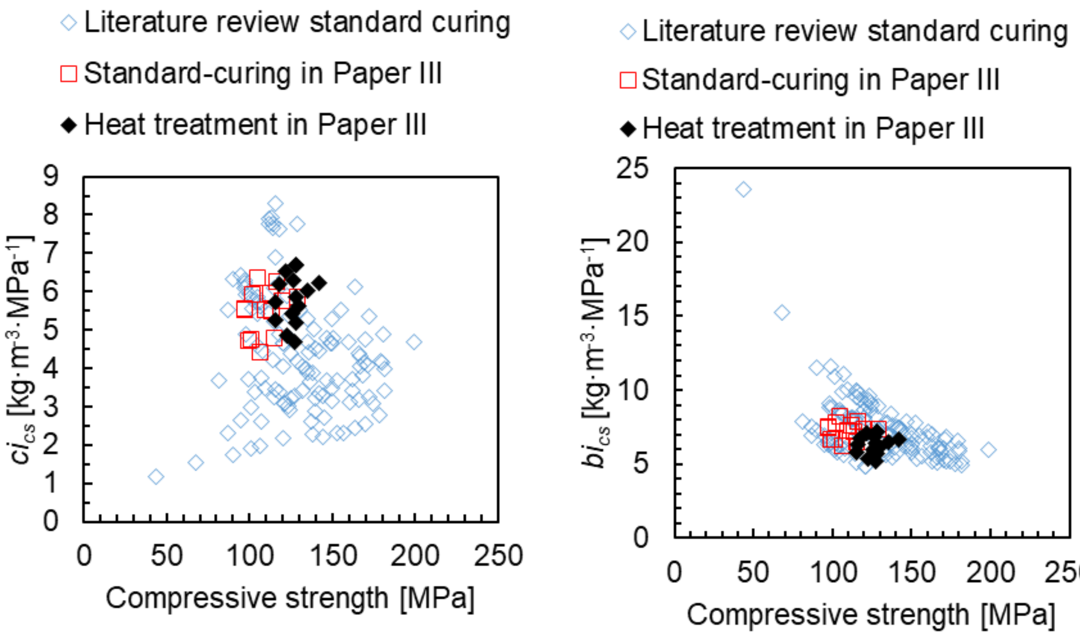
These studies investigated how different approaches to reducing the consumption of Portland clinker cement influence the mechanical properties of UHPC.

Based on the results of Papers II and III, several approaches have been proposed for the efficient use of cement in UHPC. The main approach was the partial substitution of Portland clinker cement with a range of other materials. Most materials used in the studies identified in the literature review have binding properties, and only a few are inert. The use of inert fillers in combination with particle packing models represents an additional approach.

The experimental results revealed the feasibility of substituting up to approximately 40% of the cement with an inert filler, with only a small reduction in the compressive strength. Simulations were used to maintain the particle packing through cement-substituting experiments. In most cases, the reduction in compressive strength was limited to a maximum of 15%. The experimental results were observed to be consistent with the corresponding results from the literature [21, 23, 24, 29, 65]. The flexural tensile strength was not influenced by the replacement of some of the cement with an inert filler.

Several methods exist for evaluating the efficiency of measures to reduce emissions. Two of these are the indices 'binder intensity' (bi_{cs}) and 'CO_2 intensity' (ci_{cs}). It is noteworthy that both indices can be manipulated through approaches other than cement or binder substitution, such as through approaches to increase the compressive strength.

In Fig. 12, the results for both indices from our experiments are compared with those reported in the literature. One conclusion is that the CO_2 intensity index could potentially be reduced through smart reductions in cement consumption.



(a) CO_2 intensity (ci_{cs}) (b) Binder intensity (bi_{cs})

Fig. 12 Compressive strength versus CO_2 and binder intensity indices compared with results from other investigations identified in the literature review (Paper III).

Another conclusion is that the ‘binder intensity’ (bi_{cs}) decreases when cement is substituted with inert materials. This implies that less binder is necessary to impart a compressive strength of 1 MPa. The ‘binder intensity’ (bi_{cs}) increases in most cases when active binders (SCMs) are substituted for (some of) the cement.

The accumulated results demonstrate the potential for improving sustainability through the substitution of a variety of inert and active materials for cement, while limiting the reduction in compressive strength. Because numerous materials have been determined to be appropriate, the recommendation is to aim for locally available and preferably inert materials to substitute for cement in UHPC.

3.3 Efficient use of steel fibres (RO3)

The investigation of the efficient use of steel fibres in UHPC (RO3) is addressed in Paper IV '*The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review*' and Paper V '*Locally Produced UHPC: The Influence of Type and Content of Steel Fibres*'.

A variety of measures for the more efficient use of steel fibres were identified in the literature review in Paper IV. Different fibre types ranging from micro fibres (l_f = 6–13 mm; d_f = 0.15–0.2 mm) to macro fibres (l_f > 30 mm; d_f > 0.3 mm) and different shapes (straight or deformed) were investigated separately and in hybrid combinations.

Fibres are generally included even when the material is only exposed to compressive loads. One objective is to prevent brittle collapse, which is a characteristic of the special material composition of UHPC. This is also concluded from both the literature review (Paper IV) and experimental investigation (Paper V).

The influence of the steel fibre content on the compressive strength is observed to be controversial. According to the literature review (Paper IV), the influence varies from low (< 10% increase [36, 38, 66]) to substantial (> 40% increase [52, 67, 68]). From the discussions in Paper IV, it is concluded that the test specimen geometry may influence the results for the compressive strength. This may explain some of the controversies. The results reveal a higher influence of the inclusion of fibres on small cube specimens than on larger specimens, and a lower influence on cylindrical specimens than on cubed ones. Although this is well known in fracture mechanics, it appears to be rarely addressed when experiments are analysed. Rather, conclusions are generally made without considering the specimen geometry.

The influence of steel fibre content on the compressive strength is observed to be low in the experiments executed on locally produced UHPC (Paper V). Conveniently available deformed macro fibres intended for normal concrete are observed to influence the compressive strength similar to micro steel fibres. This reveals the potential of replacing high-emitting micro fibres with a vol% equal to that of macro fibres intended for use in normal concrete (having a lower CO_2 footprint and cost) when compressive strength is evaluated.

For tensile properties, the effect of steel fibres is observed to be substantial (Papers IV and V). The influences are observed for the use of both different fibre types (Papers IV and V) and varying fibre content (Paper IV). The influence of steel fibres is also observed to differ between UHPC compositions (Papers IV and V). This can be explained by factors such as the mix design properties, curing, and rheology.

According to Paper IV, a few studies have shown that at low content deformed fibres can provide higher flexural tensile properties than straight fibres [55, 69] while they are less efficient at higher content (> 1.5 vol%) [34, 69, 70]. This might be explained by the fact that each fibre induces the formation of localised micro cracks (split cracks) in the cementitious matrix. At high fibre content, these split cracks might interfere with each other, reducing the pull-out capacity of each fibre (referred to as the *fibre-group effect*) [71]. Based on the results from Paper V, it is found that for flexural tensile strength, the sole use of long and wide macro hooked-end fibres (l_f = 50 mm; d_f = 1 mm) at 2 vol% appears unfavourable for the locally produced UHPC mixes. The use of such large fibres results in a small number of fibres bridging each crack, as well as being more sensitive to unfavourable fibre orientation. Smaller hooked-end steel fibres (l_f = 30 mm; d_f = 0.3–0.5 mm) are applied in several investigations identified in Paper IV. These are better alternatives for the efficient use of steel fibres in UHPC. Referring to Paper IV, some studies observe that the use of micro-deformed fibres (l_f = 13 mm; d_f = 0.2 mm) in small test prisms increases the flexural tensile strength [52, 72]. This reveals the potential for using lower micro steel fibre content while maintaining the mechanical properties of UHPC at constant levels. The application of long slender straight steel fibres (l_f = 19.5–30 mm; d_f = 0.2–0.3 mm) compared with straight micro fibres is observed to improve the flexural tensile strength [50, 69, 73]. This might be explained by the better bridging capacity of the long straight fibres compared with that of the shorter ones.

The impacts of hybrid combinations of different types of steel fibres are reported in some studies investigated in Papers IV and V. The objective is to achieve a higher influence from the synergy of different fibre types [54]. An overview of the influence of the hybrid fibre combinations is shown in Fig. 13. Several types of hybrid fibre combinations have been investigated (Paper IV). The accumulated results show that hybrid fibre combinations have the potential to increase the flexural tensile strength of UHPC [34, 35, 58]. However, this depends on the hybrid fibre combinations. Certain combinations are observed to enhance the flexural tensile strength of UHPC, whereas other combinations exhibit negligible or even adverse effects. Hence, the ‘correct’ hybrid combination can potentially increase the flexural tensile strength of UHPC. The experiments in Paper V with a hybrid combination of 50% straight micro fibres (l_f = 13 mm; d_f = 0.2 mm) and 50% macro hooked-end fibres (l_f = 50 mm; d_f = 1 mm) at 2 vol%, indicate similar and flexural tensile strengths to those achieved with straight micro fibres alone.

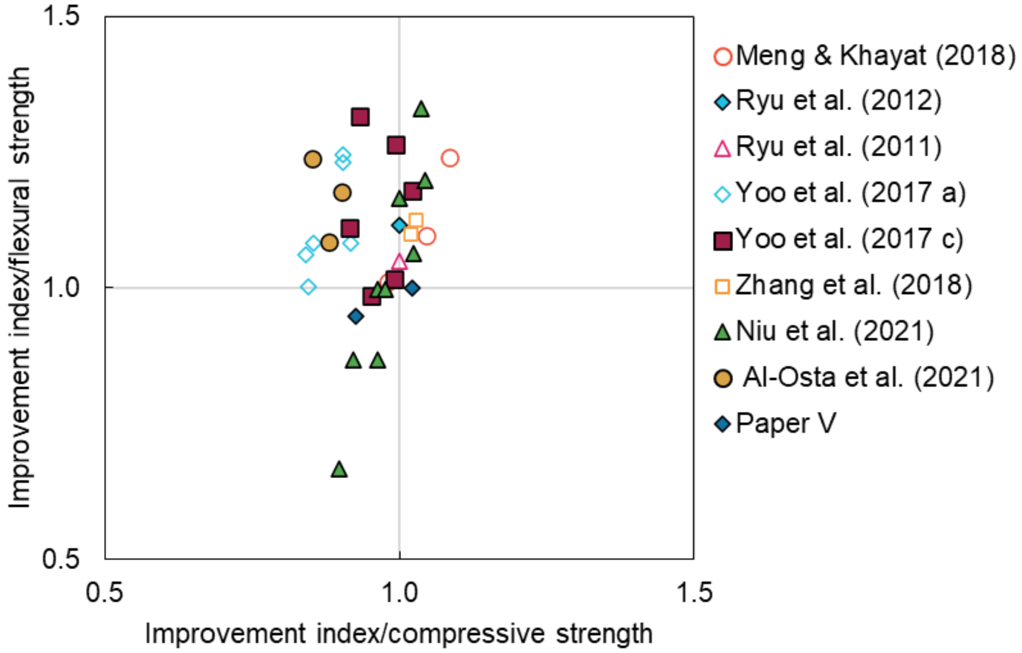


Fig. 13 Improvement index for flexural tensile strength (y-axis) and compressive strength (x-axis) of different UHPCs with hybrid reinforcement relative to 13 mm straight fibres.
The data is based on results in Paper IV [34, 35, 58, 70, 74, 75], in conjunction with an experiment by the author in Paper V and certain new publications [76, 77]. The fibre content is 2–2.5 vol%. The figure is an updated version of Fig. 8 in Paper IV.

From a sustainable perspective, there appears to be potential for using several combinations of hybrid fibres. This is feasible if the micro steel fibres are partly substituted with fibre types having a lower environmental impact and cost while maintaining the mechanical properties of the UHPC. Alternatively, if the hybrid combination or application of other fibre types improves the capacity, the steel fibre content can be reduced while maintaining the desired properties. However, the correct fibre type and combination should be identified in each case, considering factors such as the relevant mix composition, rheology, and curing regime.

Other opportunities that were not discussed further include the optimisation of the bond between the steel fibres and matrix and achievement of better fibre distribution and orientation. This might also make the use of steel fibres more efficient.

Approximately half of the environmental impacts in terms of CO_2-eq. per cubic metre of UHPC materials [22], and most of the cost [22, 41] is related to the consumption of micro steel fibres. The exploration of the above-mentioned efforts to identify efficient use of steel fibres for each specific UHPC product appears to have a high potential for improving the sustainability of UHPC at the material level.

3.4 Locally produced UHPC utilising by-products (RO4)

Investigations on locally produced UHPC mixes (RO4) were addressed in the studies reported in Paper II '*Lowering environmental impact from ultra high performance concrete, utilising industrial by-products*', Paper III '*Towards Efficient Use of Cement in Ultra High Performance Concrete*', and Paper V '*Locally Produced UHPC: The Influence of Type and Content of Steel Fibres*'.

A coarse fraction of the filter-harvest from the production of gravel and an unused fraction from the production of machine gravel are used as aggregates. The average compressive strengths of the locally produced UHPCs in Papers II, III, and V compared with certain proprietary mixes and certain mixes gathered from literature reviews are shown in Fig. 14.

For all the experiments, the composition recommendations identified in the literature review (Paper V) are used in combination with particle packing simulations. It is found that UHPC can be produced using locally available materials for aggregates.

However, the compressive strength achieved is, in some cases, limited by the properties of the aggregate material. When low-quality aggregates are used, fractures through the aggregate particles are observed (Paper III). In an additional experiment, a stronger material is composed to have the same particle size distribution (PSD) as that of the low-quality aggregate. This increased the compressive strength.

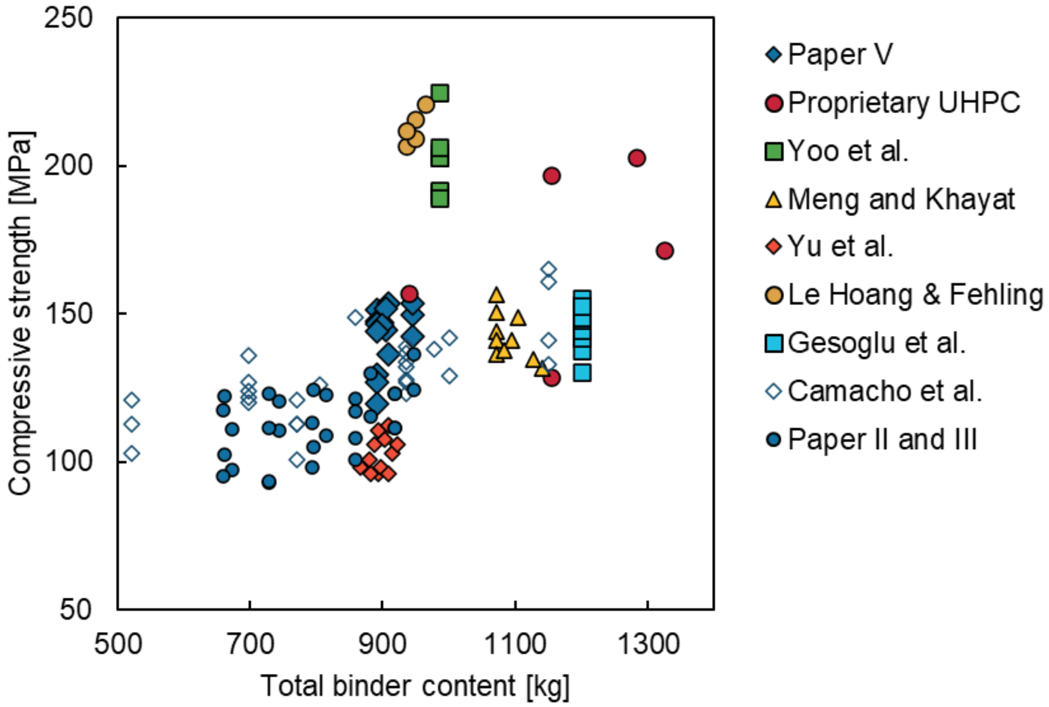


Fig. 14 Comparison between compressive strength (100 mm cube) and total binder content.

Differences in test specimen size were corrected according to Wille et al. [40]. Data points were obtained from Papers II, III, and V using local materials compared with proprietary UHPC [14, 78, 79] and certain UHPC mixes identified in the literature review in Paper V [23, 34-36, 51, 69]. The figure is an updated version of Fig. 12 in Paper V.

Some of the experimental results do not achieve a compressive strength above the limit for UHPC (papers II and III). This can be explained by the quality of the aggregates. However, the aim of these experiments is to investigate the influence of substituting non-hydrated cement particles with a locally available inert material, rather than to achieve a certain level of compressive strength. As presented in Section 3.2, partial substitution of cement in UHPC with inert fillers is observed to be effective.

All the by-products used are residues from the crushing of stones. This induces a higher water demand than that of natural sand, thereby reducing the workability of UHPC. Reduced workability may be a challenge for efficient use. This may cause insufficient compaction, resulting in poor mechanical properties. Better workability can be achieved using chemical additives specially designed to support UHPCs.

The widespread use of UHPC is a prerequisite for making it an alternative for certain applications in the concrete industry. Local production might increase interest and competence in this emerging material which might replicate one of the main success mechanisms of the conventional concrete industry.

3.5 Strategy for more sustainable UHPC (RO5)

The development of an overall strategy for more sustainable UHPC was addressed in Paper VI '*Comprehensive sustainability strategy for the emerging ultra-high-performance concrete (UHPC) industry*'.

The study reported in Paper I is used to identify directions for the more sustainable use of concrete. These directions and later additions are pursued in the work reported in Papers II–V through investigations of specific measures to improve the sustainability of UHPC.

The results of the work are concluded in a strategy consisting of five tools (Fig. 15): *Efficient use of cement* (addressed in Papers II and III), *Efficient use of steel fibres* (addressed in Papers IV and V), *Circularity: Utilise by-products* (addressed in Papers II, III, and V), *Local production* (addressed in Papers II, III, and V), and *Efficient use of UHPC in structures* (identified in Paper I).

The *Efficient use of cement* tool involves its reduction through the replacement of cement with other materials with lower CO_2 emissions and dense packing of particles.

With the *Efficient use of steel fibres* tool, multiple approaches have been found, such as hybrid fibre reinforcement, the use of steel fibres with better pull-out properties, using fibres with lower CO_2 emissions, or more efficient use through improved fibre distribution and orientation.

The *Circularity: Utilise by-products* tool includes industrial by-products or C & D waste, to reduce the need for virgin materials. Both cement and natural aggregates can be substituted with waste or by-products.

The *Local production of UHPC* is also considered a vital tool for a more sustainable UHPC industry, limiting the cost and emissions of transporting premixes over long distances. Local production might also contribute to wider use of UHPC.

The *Efficient use of UHPC in structures* aims to identify application areas where the use of UHPC is favourable, in terms of both cost and environmental impact. The use of UHPC for bridge rehabilitation and as a primary material in new bridge applications has been identified as promising areas.

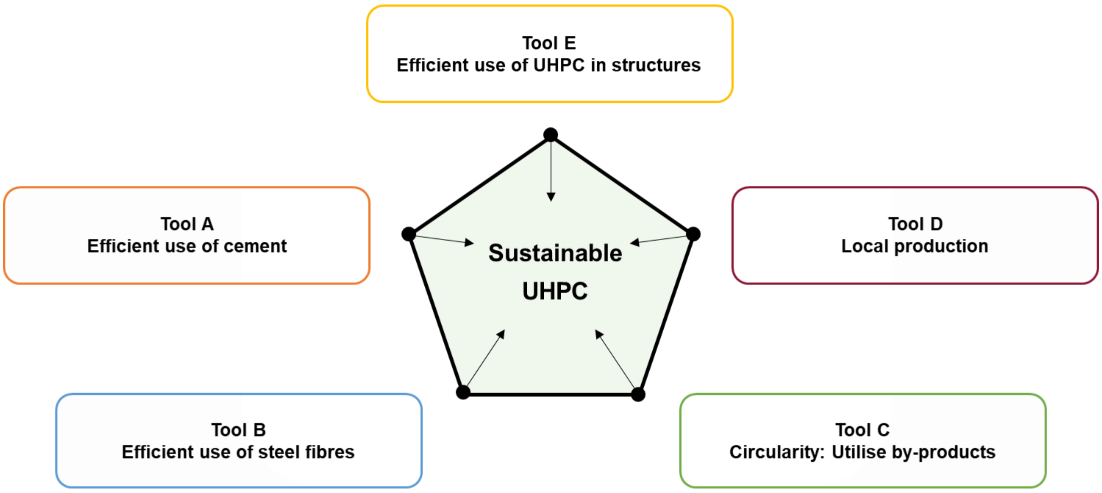


Fig. 15 Strategy for making UHPC more sustainable (Paper VI).

This five-tool strategy is my recommendation for addressing the main research topic in this thesis: to investigate identified approaches to developing a comprehensive strategy on how the UHPC industry can contribute to improving the sustainability of the concrete industry.

4 Conclusions

The main research objective of this thesis is to investigate identified approaches to develop a comprehensive strategy for how the UHPC industry can contribute to improving the sustainability of the broader concrete industry. To address the research objective, literature reviews and experiments were conducted by the author to accumulate knowledge. The main conclusions of this thesis for each research objective are as follows.

RO1: Identify directions for a sustainable concrete industry

A SWOT analysis was conducted to identify directions for the more sustainable use of concrete (Paper I). The conclusions are:

- A set of opportunities for a more sustainable concrete industry has been identified. One of these opportunities is to use less concrete for new structures by using durable and strong materials such as UHPC.
- Other opportunities for normal concrete are also observed to be relevant for future research to develop UHPC as a more sustainable material. These include the more efficient use of cement in concrete such as through better particle packing and partial replacement of cement, and the use of C & D waste and recycled materials to partly substitute for cement clinker or to use these as aggregates.

RO2: Investigate the potential for reducing the consumption of cement in UHPC

A collection of the results of international research was analysed (Paper III). A series of experiments was also conducted (Papers II and III). The following conclusions are drawn.

- Efficient use of cement can be achieved by using different materials, ranging from common supplementary materials such as fly ash and blast-furnace slag to different locally available C & D waste or industrial by-products. It is observed that it is feasible to use considerably less cement than typical UHPCs while maintaining compressive strength, thereby reducing the CO_2 intensity index (Paper III).
- In the locally developed UHPC, an inert filler (a by-product of gravel production) can be used to replace some of the cement. The cement

content can be reduced by approximately 40% without reducing the strength substantially.

RO3: Investigate the potential for efficient use of steel fibres in UHPC

This potential was investigated through a literature review (Paper IV) and experiments (Paper V). The main conclusions are as follows:

- The influence of the steel fibre content on the compressive strength is observed to be controversial. Some studies observed a considerable increase in strength from steel fibres (Paper IV), whereas others observed a negligible influence (Papers IV and V). Variations in fibre properties (shape and length) and hybrid combinations are observed to have a low effect on the compressive strength.
- The tensile strength is determined to be influenced considerably by the steel fibres. The influence is dependent on the fibre properties and content. The efficiency of a steel fibre type may differ between mixes (Papers IV and V). Steel fibres with better pull-out properties such as longer length and deformed shapes, can impart a higher flexural tensile strength. For deformed fibres, the effect appears to be dependent on the fibre content: straight fibres can perform better at higher content levels (Paper IV). A single use of large and hooked-end fibres (l_f = 50; d_f = 1 mm) appears unfavourable at 2 vol% in the locally developed UHPC mixes (Paper V). Hybrid combinations of steel fibres have the potential to increase the efficiency of steel fibres in UHPC (Papers IV and V). However, the effect depends on the combination of fibres in the specific UHPC mix (Paper IV).
- Targeted inclusion of different fibre types, including hybrid combinations, might be used to increase the sustainability of UHPC. However, the correct fibre combination should be identified in each case, considering factors such as the relevant mix composition, rheology, and curing regime.

RO4: Demonstrating the potential for locally produced UHPC mixes using by-products and surplus materials

The potential for developing UHPC with the available materials was investigated experimentally (Papers II, III, and V). The main conclusions are as follows:

- Locally produced UHPC materials can be developed by following recommendations on mix proportions and using a particle packing model (modified Andreasen and Andersen model) (Papers II, III, and V).
- Unused fractions of crushed aggregates and filter-harvest from gravel production can be used as aggregates (Papers II, III, and V).
- An inert filler (a by-product of gravel production) can be used as a substitute for up to 40% of the cement without considerably compromising the strength (Papers II and III).
- The compressive strength depends on the quality of the aggregate. The use of by-products from crushed materials may influence workability (Paper III).

RO5: Develop an overall strategy for more sustainable UHPC

An overall strategy for more sustainable UHPC was developed in Paper VI by reviewing the literature and using observations from Papers I–V:

- A comprehensive strategy for more sustainable UHPCs has been developed, consisting of five tools: *Efficient use of cement*, *Efficient use of steel fibres*, *Circularity: Utilisation of by-products*, *Local production*, and *Efficient use of UHPC in construction*.
- This is suggested as a strategy for directing and supporting targeted efforts in both industry and research to increase the sustainability of the concrete industry through the use of UHPC.

5 Future research

This thesis concludes by suggesting how the UHPC industry can contribute to improving the sustainability of the concrete industry. Although several approaches have been addressed, further research is required to improve the sustainability of UHPC and to determine whether UHPC can be a sustainable solution in the concrete industry.

At the material level:

- Only the strength-based properties were investigated in this study. For UHPC with a reduced cement content, the durability properties such as chloride ingress, and carbonation, should be tested to ensure that this characteristic is maintained.
- Simultaneous application of approaches for more sustainable UHPC at the material level, including the reduction of cement content using mostly locally available materials, efficient fibre application such as fibres with better pull-out properties, or hybrid fibre combinations, and use of by-products.
- The development of superplasticisers specially designed for UHPC and the use of these additives is important to improve workability. This is particularly critical when machine gravel or inert powders obtained from gravel production are used.
- Investigations on different mix designs combined with different steel fibre types and combinations to determine and use synergetic influences.
- Full-scale production of UHPC at concrete plants to expand the knowledge on material properties from the laboratory-scale to the real world.

Research at the structural level is not included in this thesis. The research presented involved laboratory-scale material testing on small test specimens. However, more research is required on a larger scale, such as:

- Large-scale testing of structural elements using sustainable UHPC mixes.
- Investigations of structural applications in which UHPC is expected to perform favourably compared to normal concrete.

In general, the widespread use of UHPC has been delayed for several reasons. For UHPC to be a sustainable solution for the concrete industry, its application must be increased, and potential areas for the efficient use of UHPC in structures must be identified. Broader use can be achieved by the following:

- Developing design and production standards and codes.
- Increasing local availability and competence.
- Life cycle assessment and costs of real UHPC structures compared with conventional ones to broaden and document the knowledge on when and how UHPC can contribute positively.

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Paper I – VI

Paper I

Use of Concrete for Road Infrastructure: A SWOT Analysis Related to the three Catchwords Sustainability, Industrialisation and Digitalisation

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Use of Concrete for Road Infrastructure: A SWOT Analysis Related to the three Catchwords Sustainability, Industrialisation and Digitalisation

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ABSTRACT
This paper aims at identifying the direction for more sustainable development of the use of concrete in road infrastructure in an industrialised context.

The increase in the global mean temperature is one of the most severe challenges today. The concrete industry is responsible for significant emissions of greenhouse gases, most attributable to cement production. However, concrete is one of the most important building materials in the world and indispensable for the societal development in countries at all development stages. Thus, the concrete industry needs to take measures for reducing emissions.

This paper investigates possible directions for the development of the concrete industry, to reduce climatic impact and accommodate positive societal growth. The investigation is carried out as a SWOT analysis, focusing on three terms dominating the present discussion on any development within the construction industry; sustainability, industrialisation and digitalisation. The result is a thorough discussion and a set of recommendations for the direction of future research and innovation on sustainable use of concrete in the construction of road infrastructure. The major opportunities and threats are summarised in the conclusions, and future research to be carried out in two of the authors' PhD-projects are described.

Keywords: Concrete infrastructure, Sustainability, Digitalisation, Industrialisation, SWOT analysis

1. INTRODUCTION

In a world striving towards sustainable development, economic, societal and environmental perspectives have to be implemented simultaneously. All these issues are challenging to the construction industry. The development of road infrastructure is fundamental to the growth of the economy and welfare.

The increase in the global mean temperature is currently one of the most severe sustainability issues [1]. According to the Intergovernmental Panel on Climate Change (IPCC), the global mean temperature has increased rapidly during the last 50 years and is projected to rise [2], clearly influenced by anthropogenic emissions of greenhouse gases. The prospects of continued emission are further global warming and long-lasting changes in climate systems, increasing the severe, negative effects for people and ecosystems [2]. In order to limit these climate change risks, substantial reductions in greenhouse gas emissions are required. Consequently, IPCC has established global reduction goals on CO_2 emissions for all nations. Norway has committed to reduce the greenhouse gas emissions of at least 40% compared to 1990 levels within 2030 [3]. Other authoritative sources define different goals and different deadlines for when these goals are to be met. Accommodating different time span requires implementation of different strategies. Some of these strategies might even be conflicting [4].

Concrete is indispensable for the development of countries at all development stages. The annual growth in consumption of concrete in highly developed countries has diminished. However, densely populated countries are still rapidly evolving, consequently experiencing rapid growth in the use of concrete. Hence, the world's demand for concrete is growing. The development of societies and climatic changes lay premises for the development and use of concrete. Three topics are presently dominating most discussions on industrial and societal development; i) sustainability, ii) industrialisation and iii) digitalisation. These terms are widely used, and each user tends to define the contents slightly differently.

In this article, a functional definition of the three catchwords is stated, and SWOT analysis is executed for each of them to help identify the direction of sustainable development for the use of concrete in road infrastructure in an industrialised context. The main opportunities and threats are summarised and used as a basis for future research in the first and second authors' PhD-projects.

3. RESEARCH METHODOLOGY

A SWOT analysis is executed to investigate premises for sustainable growth in the use of concrete in road infrastructure, and to identify research needs. SWOT is an abbreviation for the four terms Strength, Weaknesses, Opportunities and Threats, and is a well-known tool in economic and strategic management. The usage is not equally widespread in the construction industry. However, successful implementation is emerging. Jiang et al. [5] applied a SWOT analysis to study off-site construction in China. Yuan [6] correspondingly investigated successful construction waste management. Both gathered data for the SWOT analysis through interviews or meetings with experts, combined with literature reviews including research, regulations, and government reports [5, 6]. Inspired by these researchers, we applied a model for research methods, as illustrated in Figure 1. In this study, SWOT analysis is executed on the three topics; i) sustainability, ii) industrialisation and iii) digitalisation.

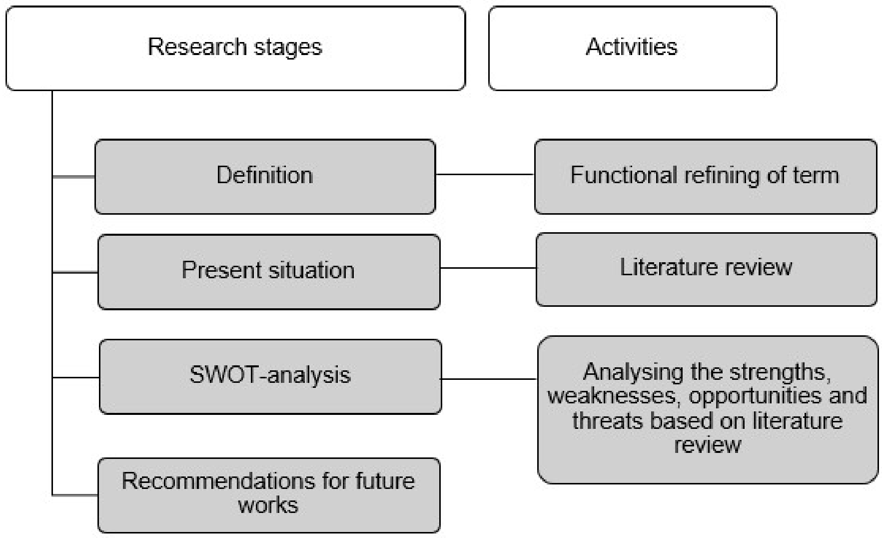

Figure 1 – Applied research methodology, similar to Yuan [6].

4. RESULTS AND DISCUSSION

4.1 Sustainable use of concrete

Functional refinement of the term
Sustainability is a broad term, often defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition origins from *Report of the World Commission on Environment and Development: Our Common Future* from 1987 [7]. Different professions tend to define sustainability in either economic, societal or environmental terms. All of these are necessary preconditions to support the needs of future generations. In the book *Concrete and Sustainability*, Jahren and Sui [4] define sustainability as the overlapping field between economy, social development and environment. This definition is applied in the following discussion. However, "environment" is in this paper limited to climate issues only.

Figure 2 – Sustainable development, according to [4].

Present situation
According to the European Cement Association CEMBUREAU, the total cement production in the world was 4.65 billion tonnes in 2016 [8]. Anticipating an average world consumption of 300 kg cement per cubic meter concrete, the present cement production corresponds to almost 2 cubic meters of concrete per capita in the world is built into new structures every year. Scrivener et al. [9] illustrate the consumption of concrete relative to other conventional building materials (Figure 3, left part), according to a report based on the efforts from the UN Environmental Program Sustainable Building and Climate Initiative. Without even arguing on the mechanical and durability properties, price or geographic availability of various materials, it is evident from a pure volume perspective that no other material can fully substitute concrete.

According to Jahren and Sui [4], Asia is responsible for approximately 80% of the world's cement production. The major part of the growth is due to countries outside China, India and Japan [4], mostly in low-income countries with strong growth in population and economy. In 2017 the world population was 7.6 billion, expected to grow to nearly 10 billion within 2050 [10]. Assuming cement consumption per capita remaining at today's level, the production of cement will have to grow to 6 billion tonnes in 2050, only considering the population growth. This result corresponds to an estimate made by the International Energy Agency [9].

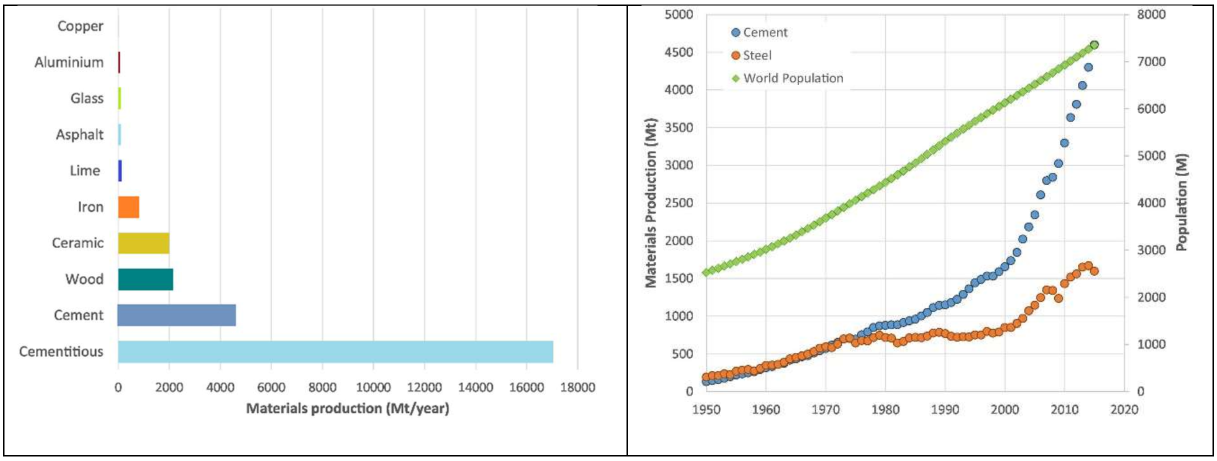

Figure 3 – Left part: Estimated consumption of common materials 2002-2005 [9]. Right part: Correlation on growth in world population and cement production 1950-2015 [9].

The World Bank estimates that around 40% of the world's population lives in low-income countries and that more than 60% of those living in slums without access to simple infrastructure like sanitation [9]. To accommodate the needs for a decent level of societal infrastructure for both the existing world population and the expected growth, the above estimate for cement consumption seems conservative. Scrivener et al. [9] showed that while the world population grew by 15% during the period 2000-2015, the cement production grew by 150% (Figure 3, right part). This unproportional growth in cement production probably illustrates welfare growth exceeding population growth.

According to CEMBUREAU [8], the cement and concrete industry generated more than 380 000 direct jobs within the EU in 2012. Also estimating indirect effects, this number grows to more than 1 million. EU is far more industrialised than most low-income countries, where concrete consumption is expected to grow. Hence, the importance of employment and economic growth is huge.

The social and economic impact stemming from the consumption of concrete seems indispensable, both due to material properties for creating necessary infrastructure and for the role of the related industry to generate personal employment, security and welfare for the citizens. Additionally, the structures being built through the concrete consumption constitute infrastructure and arenas necessary for future growth in industrial and social activities, economy and welfare.

SWOT analysis

As argued above, cement and concrete are indispensable for sustainable development of society. Consumption will grow substantially, especially in low-industrialised countries. Cementitious materials are favourable for availability, cost-effective and flexible design, simplicity of use, high strength/cost ratio and high durability. However, the concrete industry is responsible for a considerable demand for resources and greenhouse gas emissions. Production of cement is most significant, accountable for approximately 5-7% of the global anthropogenic CO_2 emissions [11-13].

A major measure to reduce CO_2 emissions would be carbon capture and storage (CCS) or even better than storage; use (CCU). A project on CCS is under development in Norway, including a full-scale pilot on Norcem's factory in Brevik expected to be realised in 2020-21. However, CCS is expensive, and unless disruptive technology is emerging, CCS/CCU is not expected to solve the climatic challenges of the cement industry worldwide. This was the origin of a UN initiative to find alternative solutions on CO_2 reduction from the use of cementitious materials, recently reported by Scrivener et al. [9]. Mehta [1] proposes three tools for making the concrete industry more sustainable; i) consume less concrete for new structures, ii) consume less cement in concrete mixtures and iii) consume less clinker for making cement. Scrivener et al.'s conclusions are in harmony with Mehta's approach, and this logic is followed in the discussion below. Several measures are essential for global solutions, without being central to development in highly industrialised societies. A fourth tool – spanning wider than just within the cement and concrete industry is related to utilising resources that are waste from other industrial processes (often referred to as by-products) –; iv) circular economy.

<u>i) Consume less concrete for new structures</u>

Improved durability – reducing the need for replacement of structures – is unarguably an effective mean to reduce consumption of resources in a long-time perspective. The designed service life of infrastructure members such as bridges and tunnels in Norway is 100 years [14, 15]. The designed service life is the period a structure is expected to be in use fulfilling its intended purpose with predicted maintenance, without extensive repairs [14]. Jahren and Sui [4] emphasise that designing structures for enhanced durability has a significant positive effect on emissions when considering long-time span, but might conflict towards short time focus.

Several strategies support durability enhancement. Two of those are careful design of structures to reduce degrading loads (e.g. avoiding surface water accumulation) and careful execution of construction work (e.g. avoiding reinforcement corrosion due to lack of cover). A third measure is careful inspections and maintenance, to stop degradation before it has propagated to a level where replacement is favourable to repair.

A fourth measure – emphasised by Mehta – is using highly durable concrete materials. Ultra High Performance Concrete (UHPC) is an emerging material presently being subject to massive research efforts. In addition to having higher strength than standard concrete, UHPC is also defined by having enhanced durability. This eliminates reinforcement corrosion caused by carbonation or chloride migration [16, 17], within any service life expectancy. Pilot projects are being built worldwide, and some early design codes have even been introduced [18, 19]. Using UHPC in the rehabilitation of existing concrete bridges is also investigated by several researchers [12, 20]. Habert et al. [12] showed that it is possible to lower the impact over the life cycle by using UHPC solutions rather than traditional methods.

Design optimisation offers several strategies to reduce concrete consumption. One is designing structures with flexibility for future changes in use. Another is the optimisation of cross sections. Prefabrication might support this, e.g. by offering slender beams with optimised cross sections, that would not be economically favourable for on-site production. Traditionally, concrete design utilises the lower part of the strength span allowed by design codes such as EN 1992 (EC2) [21]. Traditional use of concrete in structural design has rarely aimed at reducing CO_2 emissions. Investigating potential in the exploitation of high strength concrete and concrete having high targeted performance in other areas, might be fruitful.

Utilising the unique mechanical properties and the possible enhanced service-life of UHPC can drastically reduce the material consumption of concrete for some types of structural members [22]. Several studies [23-25] have shown that using high and ultra high performance concrete for construction can give more environmentally friendly solutions. A study aiming at innovation in traditional building design, focused on the utilisation of high strength concrete still within the limitation of EC2, in combination with biaxial hollow decks [26]. Potential for 60% reduction of CO_2 and at the same time 20% reduction of the cost was indicated, utilising today's formal regulations and commercially available products. Scrivener et al. [9] also concluded that using high strength concretes in suitable applications can be more efficient and decrease the total material consumption.

ii) Consume less cement in concrete mixtures

It is known that the amount of cement used to produce concretes of given strength and workability, varies enormously. Utilising pozzolans or other supplementary cementitious materials (SCM) to partly substitute cement in ready-mix production, is a well-implemented measure to use less cement. A drawback is the extended hardening time. Utilising 56- or 90-days strength instead of 28-days strength in structural design makes it possible to exploit the potential of these concretes [1]. However, this practice is often conflicting with design standards. According to the preliminary version of EC2 (2021), it will be possible to utilise 91-day compressive strength.

Another possibility to use less cement is to minimise the amount of water needed for obtaining the required consistency of fresh concrete. When keeping w/c-ratio constant, reduction of water consequently reduces the amount of cement. Superplasticisers can be utilised to reduce the amount of water required, still maintaining workability [1]. However, this strategy is well utilised in industrialised countries.

Further development to reduce water content is related to the functions of paste in concrete. The primary function is to fill the voids between aggregate particles; to envelope each particle in "glue" to obtain the required strength and durability of hardened concrete. The volume of voids is a function of particle packing. Scrivener et al. [9] claim that packing the particles of aggregate by carefully selecting the dosages of different fractions is an effective measure to reduce water and cement content in concrete. Mehta [1] also mentions the possibilities lying in optimised aggregate size and grading, without in this connection making an issue of the extra resources this would request. A secondary function of the paste in concrete is to reduce friction between aggregate particles to enhance the workability of fresh concrete. This is obtained by adding a surplus of paste exceeding the volume of voids to separate aggregate particles from each other, and hence increasing the consumption of cement. The shape of the particles also rules the friction within aggregates, as the content of flaky shaped particles creates more friction. Consequently, reducing the share of flaky shaped particles reduces the need for paste in the concrete.

Additionally, there is an emerging focus on the effect of small particles in concrete; the fillers. Scrivener et al. [9] claim that "engineering particle size distribution combined with the use of dispersants allow a binder replacement of up to 70% by inert fillers without the negative effects of dilution." Properties and grading of aggregates vary with location, which might explain variations in cement consumption. The consumption of cement, and hence also the price, can effectively be reduced by increasing focus on the composition of aggregates and the use of fillers. These measures are also location independent.

iii) Consume less clinker for making cement

Consume less clinker for making cement can be obtained by utilising other cementitious materials for partly substituting Portland clinker [1]. Depending on properties, these materials can be added into the cement production prior to, or after the calcination process – thus ending up as SCMs. Some examples are fly ash, silica fume, ground granulated blast furnace slag, rice husk ash, lime filler and several other natural pozzolans [9, 24]. This is considered to be one of the key strategies to reduce greenhouse gas emissions from concrete production [9] having an effect both on a short time horizon and lifetime perspective [4]. The availability of these materials depends on other productions, as they are often by-products from industrial processes. Some SCMs have shown to mutually affect each other positively. These synergetic mechanisms of ternary and quaternary binder blends are not yet fully investigated. If the particle size distribution and combinations of cement, fillers and SCMs are fully optimised, an average clinker substitution level of above 40% is realistic worldwide [9].

Often, SCMs have slower strength development than cement clinker, and resistance towards migration develops correspondingly. This slower development might require intermediate measures towards the migration of harmful components into unmatured concrete. Additionally, the availability of SCMs differ locally, and some require costly processing to obtain acceptable quality [9].

iv) Circular economy

Circular economy is gaining increased attention. The aim is to improve utilisation of resources, decrease waste and improve sustainability. This philosophy has several applications within the concrete industry. The most obvious would be the reuse of structures or elements for other purposes than they were designed for. Use of SCMs stemming from industrial processes to substitute cement is another example.

The construction industry produces large amounts of materials that are presently deposited or used for landfill; some from construction works and demolition of old structures, others from excavation or blasted rock. Xuan et al. [13] suggest one way of making the concrete industry more sustainable by increasing the use of waste from ready-mix concrete plants. Another study showed that it is possible to produce UHPC with reduced cement content [27] by utilising a by-product from the production of gravel. Often, these surplus masses are produced on-site, where aggregate for concrete is required. However, they fail to fulfil quality requirements according to concrete standards. For some materials, the quality requirements can be obtained by simple processing. However, tests also show that it is possible to produce high-quality concrete from aggregates that fail to meet some standardised quality requirements.

The concrete industry is ruled by formal regulations. Severe efforts are put into harmonising standards internationally, to simplify execution and to take advantage of existing competence. The existence of clear, authoritative guidelines are guarantors for quality and safety. However, standardised solutions might prevent innovation. Scrivener et al. [9] emphasise that avoiding the prescriptive regulations in traditional standards and instead allowing for flexibility to exploit local opportunities for raw materials can only be achieved with performance standards specifying properties that must be met (like strength, E-modulus and durability).

The above findings are organised by strength, weaknesses, opportunities and threats (SWOT) and presented in Table 1.

Table 1 – SWOT sustainable use of concrete

Strengths	Weaknesses
• The demand is increasing and will remain so due to population growth. • No material can replace concrete, due to required volume and availability. • Several advantages, like the simplicity of use, local part materials, flexible in design, cost-effectiveness and durability.	• Resource demanding locally and globally. • Causes substantial CO_2-emissions. • Conflicting timespan considerations for varying environmental goals.
Opportunities Reduction of environmental loads through • Reduced material consumption through innovative design, prefabrication and use of HPC and UHPC. • Clinker reduction by use of SCMs and fillers. • Cement reduction by optimising grading and shape of aggregate particles. • Utilising potential in extended maturity considerations (91 days hardening time, and innovative hardening technology). • Increase the use of waste and recycled materials. • Enhancement of durability. • CCS/CCU.	**Threats** • Climatic changes. • Resource demanding. • Rigid regulations. • Availability of SCMs.

4.2 Industrialisation of the construction process

Functional refinement of the term

The term "industrialisation" is traditionally used to characterise the transition of economies from being dominated by agriculture, towards being dominated by manufacturing. Development of new technology, including the steam engine, was the vital driving force for the European transition. The term is still frequently used even in highly developed economies, now to describe the transition of industrial sectors away from craftsmanship and one-of-a-kind solutions, towards standardised and automated production. The gaining is efficiency; a higher volume of production per time and at a lower cost. Once again, new technology is a major driving force. However, the organisation of processes and data to promote human interaction is considered equally important.

The present situation

The construction industry is still dominated by one-of-a-kind design and low level of automation in management, design and production. Although changes as increased use of innovative formwork technology, self-compacting concrete, fibre reinforcement, grinding- and surface treatment machinery, and sprayed concrete robots are emerging, it is widely accepted that construction lags behind manufacturing industry on productivity. The Norwegian construction industry and the government have established a joint effort to improve productivity and sustainability, named Bygg21. In a recent report from Bygg21, the following definition is given: "Industrialising construction projects is to plan and execute processes; maximising repeated use of standardised solutions, industrial methods and digital tools" [28].

The well-known "Lean Construction" (LC) philosophy, adapted from Toyota's "Lean Production", has inspired this definition. Most major contractors have been struggling to implement LC for many years already, often adopting company-specific names like Veidekke's "involverende planlegging" (participative planning). LC-implementation has often originated on-site to manage logistics and fabrication, but efforts are now spanning the entire process from planning and design, throughout deliverances that support operation and maintenance. Several "models" or "schools" have been developed to support these processes; like "Integrated Project Delivery" (IPD) and "Virtual Design and Construction" (VDC).

SWOT analysis

Three basic principles central to LC are: i) to improve flow in processes, ii) to reduce waste and iii) to continuously learn from experiences. These three principles are used for facilitating the SWOT analysis below.

i) Improve flow in processes

The most important "flow" in construction processes, is the flow of information relevant for each actor to execute his/her part as efficient as possible. All actors in the construction process must be involved early enough to influence actions laying premises for their own deliverance. All must also have access to correct and required information prior to executing any action, and uncertainty must be adequately handled. IPD is developed as a method utilising early involvement to focus on producing maximum value for the customer through building alliances between all people and "systems" vital for production, avoiding individual stakeholders to sub-optimise own gaining.

Though theoretical approaches to LC emphasise manual tools like "PostIt-technique", the industry soon called for computer-based LC implementations, due to the amount of information to be handled and the number of actions necessary for keeping the system updated [29]. IPD clearly defines seven sequences in a construction project, identifying vital actors in each sequence. This clear structure facilitates the use of digital solutions. Building Information Model/Modelling (BIM) is emphasized as "one of the most powerful tools supporting IPD" [30]. This is argued by BIM being able to combine all information and support all phases in a construction process, from design through the entire life-span. This is correctly the idea of BIM. However, there are still some shortcomings in the present use of BIM. Some of these are discussed in the section "Digitalisation" further down in this paper.

Another important "flow" in construction processes is the fabrication. Traditional thresholds include uncertainty; related to logistics, lack of drawings or staffing, unwanted events, etc. Prefabrication might be a strategy to reduce uncertainty. A state-of-the-art report by the Fédération Internationale du Béton (fib) from 2004 [31] reports that there are significant differences in the development and application of precast bridges in various countries. In the report, it is claimed that "Especially in the Scandinavian countries, there are few precast bridges, although the climatic conditions would logically incite to an opposite attitude". According to an investigation amongst practitioners on the use of precast bridge elements [32], there seems to be a widespread opinion that precast bridges are more prone to damage due to degradation mechanisms. These problems are recognised for bridges dated before 1990. However, in an investigation based on the NPRA database "Brutus", it was found that this is not correct – at least for bridges designed according to standards dated after 1990 [33].

Figure 4 (left part) shows the results of an investigation mapping the bridges related to four-lane national highways in the south of Norway [32]. As shown in the figure, there is a tendency that highway bridges are limited to a low number of typical lengths, clearly indicating a large potential for standardisation. NPRA has recently initiated two projects to use more prefabricated elements in road construction. One of them has resulted in standardised solutions for prefabricated concrete culverts. The other project aims to develop new pre-accepted precast bridge solutions utilising up to 40 meter long beams [34].

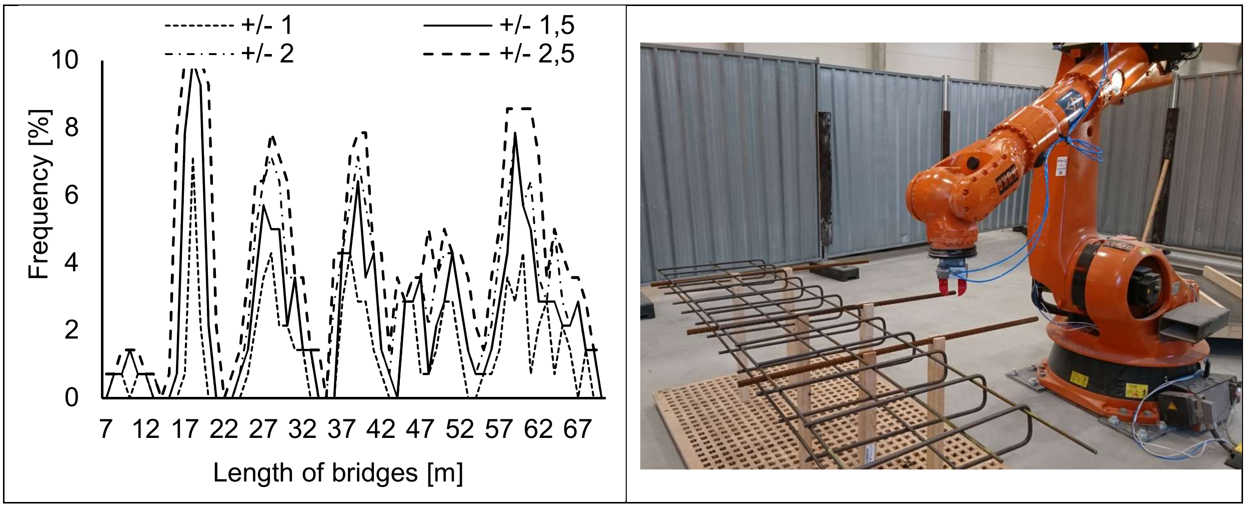

Figure 4 - Left part: Frequency of length of bridges on four-lane national highways in the south of Norway (a total of 140 bridges were included) [32].
Right part: Robotised placement and welding of prefabricated reinforcement.
Photo: Rebartek – Maximilian Trommer.

According to [32], some interviewed experts highlighted that there are challenges for precast bridges related to requirements in the regulation for bridge constructions by NPRA [14]. The Norwegian topography can also limit the use of straight precast elements. Transport on Norwegian roads can limit the span length both due to regulations and due to the road geometry (roundabouts define the maximum bridge lengths). Additionally, prefabricated (standard) elements are straight, limiting the road geometry, horizontal and vertical curvature, transverse inclination and inclining abutments. However, most agreed on the benefits of prefabrication regarding Health, Safety and Environment (HSE). Higher production speed, improved quality, reduction of traffic interrupts and potential reduction of production cost were other benefits emphasized in the interviews. These are major indicators of higher efficiency.

ii) Reduce waste

Improving flow inevitably leads to reduction of waste, as time is saved for involved personnel and equipment. Time is valuable both to business (personnel and equipment) and to the social economy (e.g. reducing traffic interruption).

Waste can also be reduced by implementing new technology like automated production of reinforcement cages (Figure 4, right part). In addition to the reduction of production time and material consumption it opens for more advanced design, e.g. by welding the minimum required the amount of reinforcement, omitting lap joints and reinforcement design optimised for production rather than structural needs. VDC is another process model heavily focusing on BIM and visualisation; including 3D models and further dimensions (time, cost, progress, risks, etc.). Once again, the primary driving force is to secure interaction and information access through organisation and the use of technology creating a work zone where all construction activities take place.

Standardisation is expected to promote industrialisation in road construction by reducing the number of alternative solutions, e.g. for fixation of railings. Reduction of the alternative solutions increases reuse of formwork, scaffolding and production techniques. Learning by repeated doing is a consequence of standardisation of production, resulting in reduction of process time, increased predictability and reduction of errors. Also, the reduction of work hours related to design processes and quality control are positive outcomes.

Standardisation inevitably leads to repetitive use of structural solutions, which might be perceived as aesthetically monotonous, limiting architectural expression. Traditionally, aesthetics is considered vital for Norwegian road infrastructure governed by an NPRA report [35]. Another drawback is that standardisation may act to conserve today's solutions. The regime of standardisation offered by today's formal regulations is frequently criticised for being conservative and counteracting new solutions and cost reductions. The urge to standardise for promoting leaner production today might prevent innovation and be a threshold to cost-efficient changes in the future. Additionally, the basic purpose is to ensure solutions that have proven their durability in practice. If opening the rigidity of standards to promote innovation, measures must be taken to make sure that the durability aspect is still attended.

iii) Continuously learning from experiences

Seen in the light of hindsight, some parts of a construction process could always have been improved. Individuals often claim to learn from experiences, however organisations like companies are known to struggle to avoid repeating mistakes. Explicit measures for organisations to learn from experiences calls for systematic registration, analysis, alternative investigation, storing and active education. Formal initiatives, processes and systems to promote this kind of organisational learning, are not always well developed. Digitalisation provides powerful tools supporting this development, but still the organisation of humans and processes is needed. One obvious reason why this is still often lacking is that these processes are time-consuming. However, the overall goal is to reduce time consumption by learning systematically from experiences.

Another measure to promote learning is the use of formerly approved solutions and practices. This might be formal standardisation through legal regulations and design codes, or restrictions given by building client (like the above-mentioned restrictions for fixation of railings along highways). However, it might also be the reuse of former design, proven to be successful. Once again, the use of digital solutions like BIM supports this kind of "standardisation" through easy access and reuse. However, also this kind of standardisation might prevent innovation.

Table 2 – SWOT industrialisation of the construction process

Strengths	**Weaknesses**
• Improved productivity by reducing the time for design and production. • Consequently, reduced cost (per unit). • Reduce climate impact (by reducing waste).	• Depending on successful implementation of interaction between numerous actors.
Opportunities	**Threats**
• Early involvement improves the possibility to influence at early stages, avoiding changes at later stages when the cost of changes rises. • Correct information required for prerequisite available for all – at any time. • Consequences of choices understood through analysis including all existing prerequisites, and easily available through visualisation. • Advanced/automated production methods open for design optimised for structural performance rather than for easy manual production. • Standardisation allows for reuse of design, equipment and production techniques. • Prefabrication allows for cost reduction, sustainable solutions and improvements on HSE. • Improved quality through systems for continuously learning.	• Aesthetics – promotes monotony. • Standard prefabricated elements limit road geometry and adaptation to terrain. • Complicated and demanding handling processes (lifting, transport and assembly).

4.3 Digitalisation of construction and management processes

Functional refinement of the term

Digitalisation is the process of using digital methods to achieve results that would not be available without these methods. The enablers are high capacity for accessing, storing, processing and presenting data. In this paper, digitalisation refers to digital information of the structure that is applied in all stages throughout the life cycle of the structure, from design until the end of service life. Digital information in the form of models including metadata may be used at the design stage, for structural analysis and dimensioning, for construction at the building site, for operation, maintenance and management and finally for demolishing, recycling and deposition of waste materials at the end of service life.

Present situation

There is an emerging interest in the opportunities related to a more digitalised construction industry. The most used development within digitalisation is BIM. By using BIM, it is possible to replace structural drawings with virtual, 3-dimensional digital models of the structure and construction site, and assign more information to the different parts than just the geometry [36]. In addition to the description of the structure and the applied materials, this may include information needed for technical and quality control, and extraction of quantities necessary for pricing. Digitalisation and BIM-models can be used throughout the life cycle of a structure. However, presently the information is often modelled in different ways and by various software tools and platforms from phase to phase, which is a serious hindrance for future development.

According to Azhar [37], BIM can be used for 3-D visualisation, fabrication of drawings, estimation of cost, automatic extraction and updates of material quantities, construction sequencing (coordinate material ordering, fabrication, and delivery schedules for all building components), conflict situations, and collision detection, to mention some. The same author also mentions that BIM may give benefits in terms of faster and more effective processes, better design (as the design of the buildings can easily be analysed and changed in the digital model), control of the lifetime costs and environmental data, and improved production quality. It is possible to achieve substantial reductions in time consumption related to generating cost estimates and utilise lifecycle data for facility management. More recently there has been increased interest in using BIM to achieve more sustainable solutions by including EPDs (Environmental Product Declaration) in the BIM-model and carry out optimum design [36].

An important part of digitalisation in the construction industry is to use modelling tools and software for structural analysis and dimensioning. Direct application of BIM and the growing sophistication of computer programs, increasing computer capacity and decreasing costs, give great possibilities for better design. Table 3 presents today's practice and two possible future scenarios for structural analyses and design, which both may facilitate more efficient material use and therefore more sustainable solutions.

Table 3 The structural design process

Solution	Date	Drawings/Design	Structural Analysis	Dimensioning/Design
I	Today	Drawings or BIM	Linear elastic methods, Finite Element Analysis (FEA) occasionally. Supported by human competence and special purpose program accounting for cracking, creep, shrinkage, relaxation and temperature effects, and construction history. Nonlinear analysis rarely used in practice.	Manually in critical sections, often using special purpose programs.
II	Future scenario, alt I	BIM	Linear elastic FEA based on the BIM, occasionally nonlinear and time-dependent. Modification of linear FEA to account for cracking, creep, shrinkage, relaxation and temperature effects, and construction history.	Computerised checks of all sections.
III	Future scenario, alt II	BIM	Numerical simulation of structural behaviour based on BIM-model. Nonlinearities and time-dependent behaviour well accounted for. Probabilistic safety-formats. Structural analysis and dimensioning fully integrated.	

In today's structural design, it is most common that the design of each structural member is done manually in critical sections using special purpose programs. This is time-consuming, and in a market with great competition and economy focus for both designers and contractors, the approach does not always give the optimal solutions and sustainable design.

Compared to today's practice, future scenario I will utilise BIM to make more accurate linear finite element analysis (FEA) of structural systems. Still, care must be taken to distribute stress concentrations, account for time-dependent effects, and in some cases also nonlinear behaviour. This, together with computerised design of all sections in a member, may contribute to more optimal and sustainable solutions. For instance, industrialising the process of prefabricating beams by placing the exact amount of shear reinforcement required by the design code, precisely fixed in position by robots. Hence, industrialising open for flexible production by standardising processes, not products.

Future scenario II assumes frequent use of advanced numerical simulations of the structural behaviour based on the BIM. The preferred method will be Non-linear Finite Element Analysis (NLFEA), including accurate material models. These tasks are challenging and require development of guidelines and regulations to be able to achieve the right structural safety concerning design resistance and robustness, and quality control of the results. NLFEA is used already today, but only in special cases, e.g. for existing structures (remaining/rest-capacity), or when there has been a structural collapse (accident) and investigations to explore the causes are required.

To fully utilise the advancement in digitalisation, to achieve future scenario II, should be one goal to achieve more sustainable solutions but, as mentioned above, further research and development of regulations and guidelines are required.

SWOT analysis
As illustrated in Figure 5, digitalisation may facilitate communication, information sharing, innovative thinking, design adjustments and construction planning. The different sub-processes work together towards a better and sustainable design.

First sub-process, denoted building opportunities (Gear 1), is constantly moving and must be checked with preliminary and advanced models to obtain the best design. This sub-process also requires feedback from the other sub-processes to improve. If one process works alone and does not communicate, it will hinder the abilities for the other sub-processes to work together.

The authors agree with the statement from Azhar [37] that BIM contributes to a better design, but the authors would like to address this broad term. Among the conclusion for a better design, one is that the building proposals can be rigorously analysed, and simulations performed quickly.

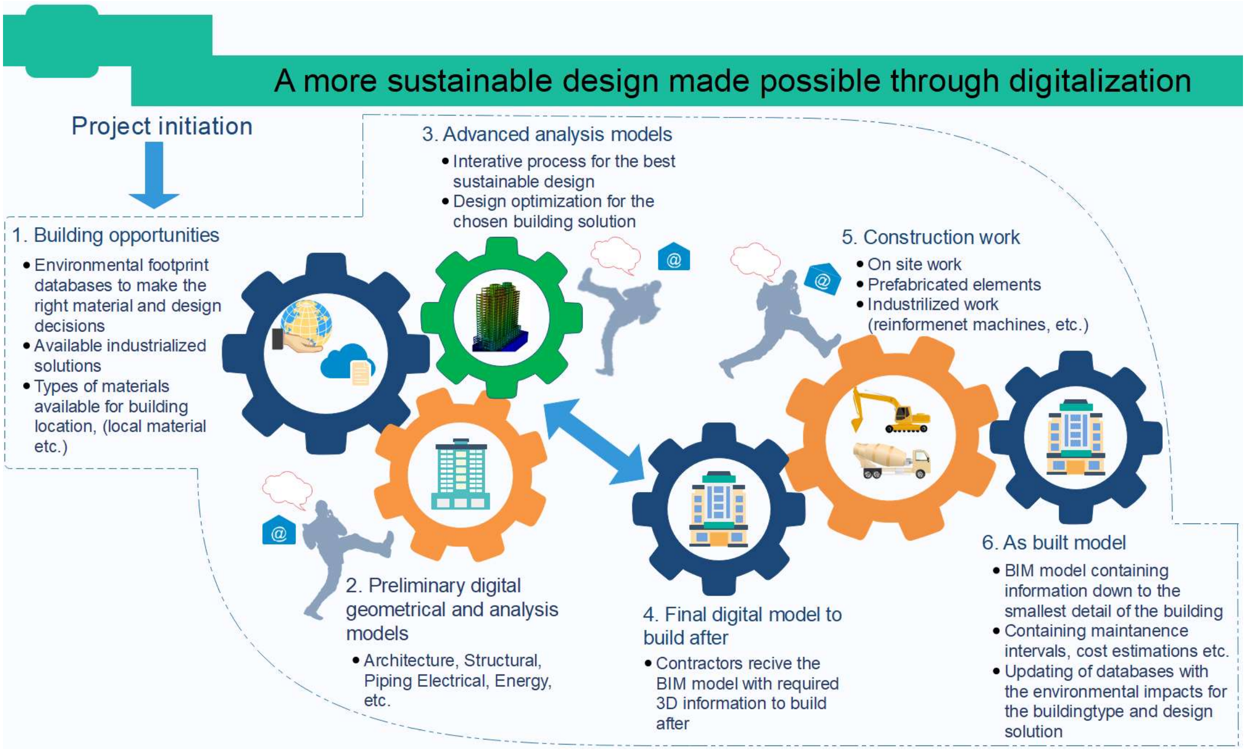

Figure 5 – A more sustainable design made possible through digitalisation (own design of illustration).

A risk when using more advanced software is that complex structures may become too simple to handle in the software's environment. In worst-case, this can lead to serious faults, and also structural failures with large consequences. Therefore, it is of vital importance that engineers understand and maintain competence within their field. Some of the advanced structural analysis programs now available for the industry were previously only available in the academic environments.

Table 4 shows the results from the SWOT analysis in digitalisation of construction and management processes.

Table 4 – SWOT Digitalisation of construction and management processes

Strengths	**Weaknesses**
• Faster and more effective processes. • More efficient design process and better quality of the design. • Faster and more correct cost estimates. • More accurate geometry and material modelling for structural analysis. • More accurate descriptions of the construction history.	• Information may be modelled in different ways and using different software tools and platforms from phase to phase. • The computer programs may use different theory and algorithms than those known to the designer, which may lead to misunderstandings and faults. • Too large amount of information creates unnecessary complexity.

Opportunities	**Threats**
• More efficient (economic and sustainable) use of materials. • Interaction of BIM and LCA-software/EPDs. • More optimal design (easier to improve the design of a structure). • More optimal and sustainable solutions.	• Changes in data-formats and platforms over time. • Robustness of systems (data storage, hacking, etc.). • Loss of competence due to phasing out valuable computer programs. • Lack of understanding of how the structural systems work – may lead to possible faults. • Import of geometrical 3D models for structural analysis– possibly wrong connections between elements due to different formats. • Too much information in the models related to the necessary task at hand.

5. DISCUSSION

The aim of this paper is to identify and discuss directions for more sustainable development of the use of concrete for road infrastructure, in an industrialised context. The term “sustainable” is defined to embrace not only environmental issues, however also the economy and social development. Hence, issues regarding HSE and productivity are included. The term “industrialised context” reflects that the discussion regards highly industrialised societies, where advancements in digitalisation and automation are natural traces of development.

Substantial growth in the use of concrete is inevitable. Consequently, measures must be taken to avoid a corresponding growth in CO_2 emissions, and to reduce the anthropogenic influence on climate change. Future solutions might involve CCS/CCU, however widespread use of these solutions requires disruptive technology that substantially reduces cost. Hence, CCS/CCU is not further discussed in this article.

The three terms sustainability (in a threefold understanding), industrialisation and digitalisation are separately discussed in SWOT analysis above. No cross-disciplinary conflicts have been identified. On the contrary, synergies are described, and simultaneous utilisation of the three considerations is necessary for realising the full potential in each. A fundamental approach to reduce the use of natural resources, emissions, time and money, is to secure flow in all processes. Flow is pursued by taking all preconditions into account in all processes and choices, including design and production. This calls for sharing information and evaluating each choice real-time, enlightened by all relevant information in the project.

Concepts like “flow”, “early involvement” and “sharing information” are all vital in different approaches towards industrialisation, e.g. LC, IPD and VDC. The use of digital methods is another important measure in industrialisation; to achieve results that would not be available without these methods. Hence, further industrialisation requires both organisation of processes and the use of digital methods. Digitalisation on the other hand, will only produce gaining if all relevant information is available. Hence digitalisation requires industrialisation.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The paper considers the three frequently used catchwords; sustainability, industrialisation and digitalisation, and gives a functional refinement of them related to their application within the construction industry. As a contribution towards more sustainable solutions within the road infrastructure a SWOT analysis is carried for each term. Several opportunities for sustainable development of the use of concrete have been identified. A prerequisite for taking advantages of these opportunities is that processes for further industrialisation and digitalisation are carefully implemented. Some of these identified opportunities are:

- More efficient use of materials through innovative design, utilisation of advanced and automated production, prefabrication and investigation into smart use of HPC/UHPC.
- More optimal design made possible by early involvement of stakeholders, the interaction of BIM and LCA software, and digital visualisation, allowing for better informed decision processes.
- Improved quality in processes, decisions and products, supported by operational systems for continuous learning; including both explicit actions and knowledge tacit in the reuse and standardisation of solutions.

Several important threats to the sustainable development of road infrastructure have also been identified:

- The main threats towards future sustainable development of the concrete infrastructure are the lack of natural resources, too rigid regulations and availability of SCMs.
- Concerning industrialisation, a threat to be avoided is making solutions that are rational when implemented but may act preservative in the longer run, preventing future innovations.
- Related to digitalisation the major threats are due to changes in data-formats and platforms over time, the robustness of systems (data storage, hacking, etc.), loss of competence due to phasing out valuable computer programs, and finally lack of understanding of how the structural systems work – which may lead to possible faults.

The paper is a part of two ongoing PhD-projects, and the findings in this paper will be followed up. One of these will focus on the development of production of Ultra High Performance Concrete (UHPC) from local constituents and investigate the structural behaviour of this material. The other one will study industrialised sustainable concrete bridges in Service Limit State (SLS). The objective is to improve structural analysis and design of concrete bridges in SLS that are adapted to new sustainability-requirements, industrialisation and digitalisation.

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Paper II

Lowering environmental impact from ultra high performance concrete, utilising industrial by-products

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Lowering environmental impact from Ultra High Performance Concrete, utilizing industrial by-products

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Abstract

Ultra High Performance Concrete (UHPC) is a material having some properties superior to ordinary concrete, such as strength and durability. Production of UHPC often includes large amount of cement, leading to high cost and environmental footprint. This study aimed at demonstrating the potential of reducing both cost and environmental impact from production of UHPC, by reducing cement content through substitution with inert materials. Locally available industrial by-products were utilized as aggregates, as another mean to reduce cost and environmental impact. It has been proven possible to substitute 40% of the cement with inert materials, without significantly reducing the compressive strength. It has also been demonstrated how different superplasticizers strongly influence properties of UHPC, and hence must be controlled in experiments aiming solely at measuring effects of variations in cement content.

1 Introduction

Concrete has remained by far the most commonly used building material for decades. However, concrete industry is commonly accepted to produce 5-8% of the global CO_2 emissions. This is mostly due to the production of cement, understood as Portland clinker [1], [2].

A variety of industrial by-products has shown to be chemically active, able to not only successfully substitute Portland clinker as binder in concrete, but also improving qualities of concrete [3]. Such materials are often referred to as “Pozzolanic binders”, due to that special hardening process.

Ultra High Performance Concrete (UHPC) is emerging as an advanced cementitious material with high strength and durability properties [4], [5]. UHPC is suitable for substituting ordinary concrete for some purposes and at the same time reducing cost and environmental impact [6]. Development of material science, design rules, and application examples are rapidly ascending. Reasons for this are multiple, including the struggle to reduce environmental impact from construction. UHPC is also expected to reduce the weight of structures, still retaining the desirable properties of concrete.

Traditionally, production of UHPC includes a large amount of binders. It might seem as if a practice of high binder content has emerged, without always putting effort into minimizing the binder content. UHPC is typically characterized by high cement content and low water content, leading to large amounts of unhydrated cement in the hardened product [7]. Particles of unhydrated cement have high compressive strength, and will consequently work as filler in the particle skeleton. However, using cement as filler represents both waste of resources, unnecessary environmental load, and high cost.

Recently, several investigations on UHPC has been published, where high amounts of cement have successfully been substituted with pozzolanic binders, e.g. [8] and [9]. This will certainly reduce the environmental footprint. However, it is questionable whether these high amounts of pozzolanic binders will be able to react as binders, due to lack of other reactants. If pozzolanic materials remain as particles in the concrete, the cement might rather be substituted with inert materials having a lower cost.

2 Research question and significance

Based on the assumption that UHPC often contains high amounts of unreacted particles from cement and pozzolanic binders, this investigation aimed at demonstrating the potential for partly substituting cement in UHPC with an inert material having the same morphology. The substituting material was expected to replace unreacted binder particles in the particle skeleton, without reducing the creation of the calcium-silicate-hydrate (C-S-H) phases in hardened UHPC.

Cement is expensive, constituting price as one barrier towards the widespread application of UHPC. Hence, from a cost perspective, it would be favourable to reduce the content of cement. The potential for substitution of cement by pozzolanic binders has been successfully demonstrated by several researchers. However, the cost of pozzolanic binders is often higher than that of cement, making this substitution irrelevant from a cost perspective.

CO_2 emissions from the production of cement is high. Pozzolanic binders are often by-products from other industrial processes. Even if the industrial processes in which the pozzolanic by-products are created cause CO_2 emissions, this environmental load is usually allocated to the primary product. The by-product is thus considered to be carbon neutral. Hence, according to standardized LCA-models, substituting cement with pozzolanic binders will lower carbon footprint. However, as by-products are established as commercial products, the LCA-model should be altered to distributing the CO_2-burden between the primar product and the now commercialized by-product – corresponding to the distribution of economic surplus.

If the pozzolanic materials remain as particles in the hardened UHPC, the cement might rather be substituted with an inert material. Pozzolanic materials should then be spared to replace cement in situations where the binding properties are utilized. Hence, also from an environmental perspective, substituting cement with the inert material is favourable – and more favourable than substituting with pozzolanic binders, even if the latter is not visualized through today's LCA-models.

Reducing cost and environmental impact will contribute to further widespread of UHPC.

3 Materials and methods

3.1 Experimental design

A reference mix for UHPC was composed, utilizing surplus sand from local production of machined gravel, as aggregate. This aggregate was included "as is", without manipulating particle size distribution to optimize properties of UHPC through particle packing. Controlling particle packing is an essential step for optimizing properties of UHPC, however not the scope of this investigation. It is also undesirable from a cost perspective.

To obtain the high performance properties characterizing UHPC, it is generally accepted that the water content must be kept low; typically having water/binder ratio (W/B-ratio) of 0.2 [4].

Other characteristics of UHPC are keeping particle size down, and use large amounts of microsilica (MS) [10]. Achieving workability at these low water levels in mixtures exclusively containing fine particles, is only achievable through high dosages of superplasticisers (SP) [10].

To reduce variations due to choose of SP, a limited investigation was performed on impact of different brands of SP commercially offered. Four different brands (MAP1-4) were tested in the reference UHPC-mix. Dosages were chosen on basis of earlier investigations, and are shown in Table 1. The resulting average level and in-series variability of compressive strength were taken as indicators for selecting which SP to use in the main investigation; striving for highest level and lowest in-series variation. All series include three test specimens.

Table 1 Superplasticizers

Material	Properties	Solid content [%]	Density [g/cm^3]	SP/C-ratio [%]	Dry mass in mix [kg/ m^3]
MAP1	Modified acrylic polymers	19.5	1.05	5.4 %	8.1
MAP2	Modified acrylic polymers	23.0	1.05	5.4 %	9.5
MAP3	Modified acrylic polymers	18.5	1.06	5.4 %	7.7
MAP4	Modified acrylic polymers	22.0	1.06	6.4 %	9.1

As a third indicator for identifying the best performing SP, a visual control of specimen surfaces was applied. The level of entrapped air is influenced by workability. The vital point is to keep the content of entrapped air low and stable. It is anticipated that content of entrapped air is revealed also in the quality of the surfaces of specimens.

After concluding on the choice of SP, five mixes were composed, by stepwise substitution of cement with an ultrafine, inert filler (UF): 10%, 20%, 30%, and 40% by mass, compared to that of the reference mix. All other variables were kept constant through all mixes; MS, W/B-ratio, aggregate, retarder, and SP. W/B-ratio was kept 0,29 for all mixes, leading to different amounts of added water corresponding to the reduction of binder content. The W/B-ratio was kept relatively high, (and higher than that for evaluating brand of SP) to get acceptable workability even for the mixes containing least water. Table 2 shows the reference mix and the four substitution mixes (R1-5), investigated in the study.

Table 2 UHPC mix designs

ID	Substitution level	OPC	UF	A	MS	SP	R	W	W/B
	%	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	-
R1 (ref)	0	766.3	0	1204.3	191.7	41.4	0.77	277.9	0.29
R2	10	689.7	76.7	1204.3	191.7	41.4	0.69	254.8	0.29
R3	20	613.0	153.3	1204.3	191.7	41.4	0.61	232.0	0.29
R4	30	536.3	230.0	1204.3	191.7	41.4	0.54	208.9	0.29
R5	40	436.0	306.7	1204.3	191.7	41.4	0.46	186.1	0.29

OPC – Ordinary Portland cement, UF – Ultrafine inert filler, MS – Microsilica, A- crushed sand, SP – Superplasticizer (MAP3), R – Retarder (R/C=0.1%), W – Water, W/B – Water-to-binder-ratio

3.2 Materials

Table 3 shows the materials used. UF is a filter harvested dust, which is collected in the cleaning process from production of gravel. All materials are locally available.

Table 3 Material specification

Material	Characteristics
Ordinary Portland cement	Rapid hardening Portland cement, CEM I 52,5 N
Microsilica (MS)	Undensified silica fume SiO_2>90%, $D_{0.45}$<1.5%
Ultrafine filler (UF)	Filter harvest (dust) from production of gravel
Aggregate (A)	Surplus sand from local production of machined gravel, fraction 0-2 mm
Retarder (R)	Based on sodium gluconate, 20 % dry content
Superplasticizer (MAP3)	Modified acrylic polymers, 18 % dry content

The particle size distribution (PSD) of the cement (OPC) and the ultrafine inert filler (UF) used to substitute cement, is shown in Fig. 1. The two materials are close to identical in particle size distribution. The PSD for MS is shown to have D50 around 1/100 of that of OPC and UF. The PSD for all materials are determined by laser diffraction.

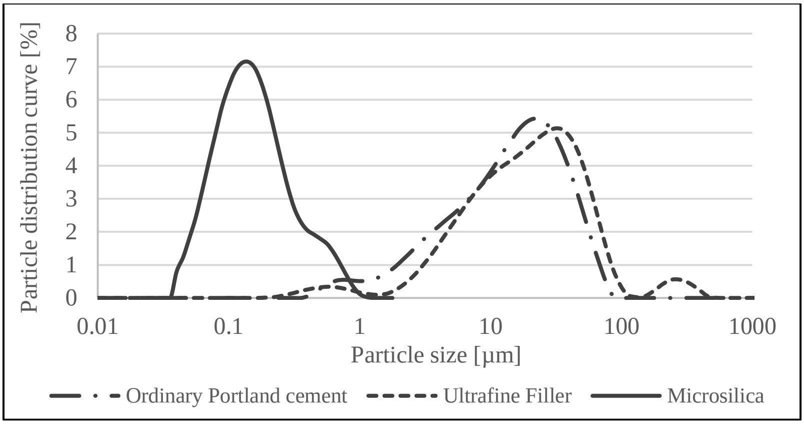

Fig. 1 Particle size distribution obtained by laser diffraction of the used Cement (OPC), Ultrafine inert filler (UF) used to substitute cement, and lastely the Microsilica (MS) (having the smallest particle size).

3.3 Mixing procedure

The UHPC was mixed in a planetary mixer (according to ASTM C305 [11]) at standard laboratory condition. For each batch, three litres of UHPC was mixed, using the following procedure:

1. Mixing all dry constituents for 30 seconds at low speed
2. Adding water, superplasticizer and retarder
3. Mixing for 30 seconds at low speed
4. Stopping the mixer for 90 seconds
5. Mixing for two minutes at medium speed
6. Mixing for 15 to 30 seconds at high speed

3.4 Mechanical properties

The UHPC was cast in cubes of 50 mm x 50 mm x 50 mm, by filling the forms halfway, manually compacting with ten strokes, completing filling, and finally compacting manually with another ten strokes. All specimens where demoulded 18 hours after casting. The test specimens were cured for 48 hours at 90 degrees Celsius in water bath. Testing of compressive strength was performed by ASTM C109/C109M [12].

4 Experimental results and discussion

4.1 Impact of variations in superplasticizer

The scope of the experiment was to investigate the impact on compressive strength when cement was gradually substituted with an inert material. However, air is always entrapped in UHPC, heavily influencing the compressive strength of specimens. The amount of entrapped air is closely associated to the workability of the fresh UHPC because variations in workability influence the quality of placement of UHPC in moulds. If the amount of entrapped air in hardened specimens is varying, changes in compressive strength cannot be claimed to be sole results of different cement content.

Producers of SP claim that different brands have an unequal impact on fresh and hardened properties, even when all are based on modified acrylic copolymers.

Impacts of alternative brands of SP were investigated, based on the assumption that different brands work differently in UHPC. The SP best fitted for this investigation, was identified by specimens having the highest average value in compressive strength and simultaneously lowest in-series variability. Results are shown in Fig. 2.

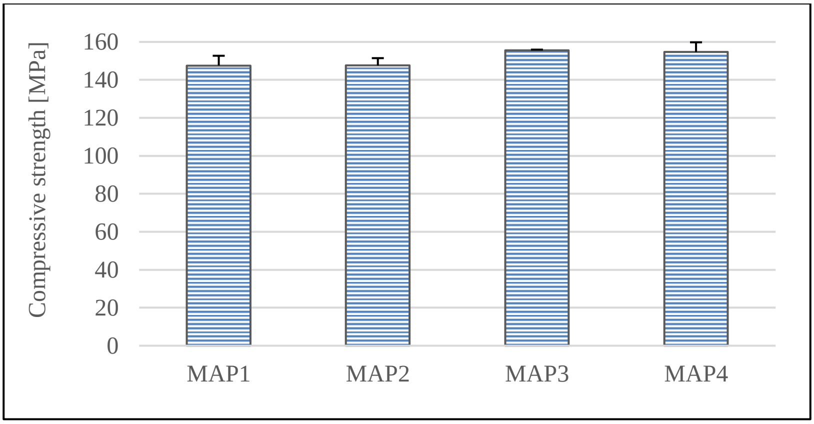

Fig. 2 Average results and in-series variability in compressive strength, for 50 mm x 50 mm x 50 mm cubes for the reference recipe using four different superplasticizers. In-series variability is characterized by standard deviation (SD), indicated on top of each column.

The average level of compressive strength varies up to 5.3% between series. Serie with MAP3 have the highest resulting compressive strength; 155.4 MPa. For evaluating brands of SP, the W/B-ratio was 0.23 leading to higher compressive strength than for the test results in Fig. 4.

The standard deviations between series are in the range 0.4 – 5.2, again leaving MAP3 as the one giving the best result.

As a third indicator for low and stable content of entrapped air, a visual inspection of the specimen surfaces was applied. In contradiction to average level and in-series variation of compressive strength, visual inspection of surfaces is a qualitative measure; only ranged – not quantified. Fig. 3 shows photos of the specimen surfaces. Also, this indicator concludes that MAP3 has the best result.

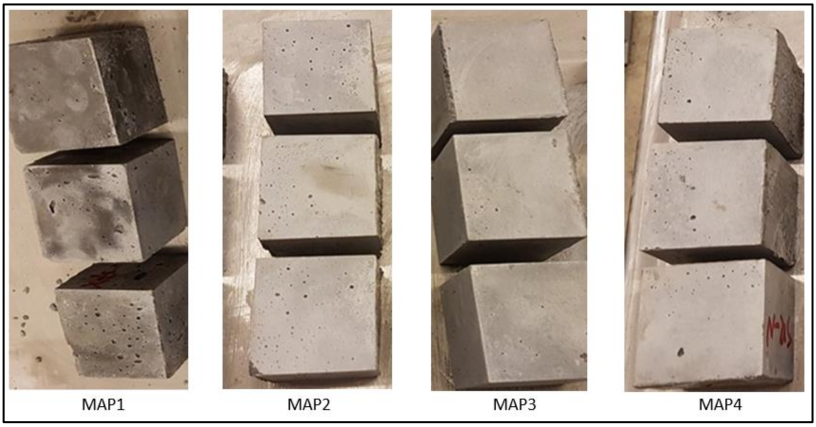

Fig. 3 Photos of specimen surfaces resulting from the use of four different SPs (MAP1-4) in the same UHPC mix (R1), for visual evaluation of content of entrapped air.

The chemistry regarding SP is complicated, and it is not unambiguously that variations in compressive strength is fully explained by the content of the entrapped air. However, porosity is known to influence compressive strength, and visual inspections of surfaces indicate that this is at least a part of the explanation. The importance of keeping such variation under control is demonstrated, e.g., in [2].

Both average level of compressive strength, in-series variations and visual apparent entrapped air identify MAP3 to be the best fit for this project. Conclusively, MAP3 was used in all mixes for the main investigation on the impact of cement substitution.

4.2 Impact on mechanical properties, from cement substitution

Following the fundamental work of Power and Brownyard [13], w/c-ratio above 0.42 is required for all cement to theoretically be able to hydrate. Thus, UHPC – being partly defined by having w/c-ratio far below this value, will comprise unhydrated cement particles in the hardened product.

The aggregate phase of conventional concrete is normally dominated by particles in the size range 2-30 mm. UHPC is typically constituted exclusively by particles <2 mm. A thin layer of water (2-3 molecules thick) is physically adsorbed on all surfaces, making this water unavailable for cement hydration. The specific surface of particle materials grows exponentially inversely proportional with particle size. Thus, the share of water in UHPC being available for cement hydration can be anticipated significantly less than that in ordinary concrete. High dosages of MS strengthen this effect, as MS particles are very small – in the range of 1/100 of the smallest of other particles present (Fig. 1). Further strengthening the water adsorbing mechanism is that MS usually is not in the state of «saturated, surface dry» (SSD), which usually aggregate is in controlled laboratory experiments. Thus, the aggregate will compete with cement hydration on available water.

Conclusively, a considerable share of cement particles can be expected to remain unhydrated in hardened UHPC. These cement particles will still contribute to strength and durability, due to their strength and role in particle packing [7]. A dense and strong particle skeleton is vital for strength and durability of UHPC [14].

Cement particles have normally higher compressive strength than the calcium-silicate-hydrate (C-S-H) created from both cement hydration and pozzolanic reactions [7], constituting the «glue» in concrete. The size of cement particles is smaller than most other particles present in concrete, making them valuable members of a dense particle skeleton. Conclusively, the presence of unhydrated cement particles in hardened UHPC is advantageous for strength and durability. However, it is disadvantageous for cost and environment.

The scope of this study is to investigate the potential for substituting cement with an inert material, having low cost and environmental impact. Hence, when aiming at substituting cement without changing its role in particle packing, it is vital that the substituting material has as close to the morphology of the substituted material as possible. The substituting material used in this investigation is dust from the crushing of stone, harvested in filters for air cleaning. The PSD of this material is near identical to that of cement, as visualized in Fig. 1.

Cement was partly substituted stepwise by 10%, 20%, 30% and 40% (by mass). The resulting reduction of compressive strength was measured to be limited within the range of 10%, according to Fig. 4 (left).

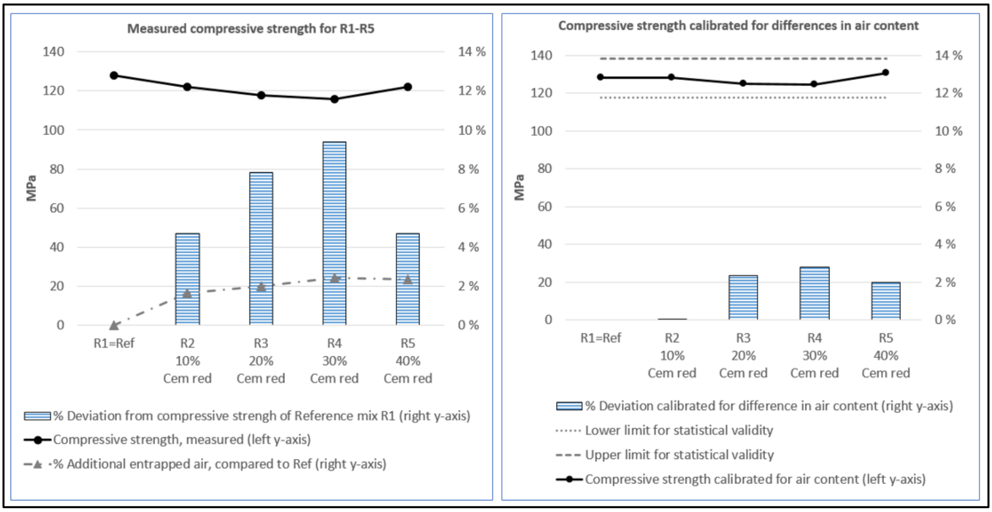

Fig. 4 Left: Measured values for compressive strength during up to 40% cement substitution. Right: Compressive strength calibrated for variations in air entrapped in specimens.

Achieving only 10% reduction in compressive strength when substituting up to 40% of the cement by an inert material, demonstrates high potential for economic and environmental gaining. However, it remains unexplained why the reduction in compressive strength for 40% substitution is less (5%) than for 30% substitution (9%).

The density of all specimens was measured before measuring compressive strength. The workability of the fresh UHPC varied through the levels of cement substitution. Variations in workability might influence placing of mortar in moulds, leading to more air voids entrapped as a consequence of low workability. Variations in density between specimens from different series (R1-R5) can be considered a measure on variations in the entrapped air. As shown in Fig. 4 (left), the amount of entrapped air was found to increase up to 2.4% of specimen mass, compared to the reference mix R1.

Entrapped air in concrete is known to reduce compressive strength significantly. A conservative estimate is that each 1% entrapped air reduce compressive strength by 3%. Fig. 4 (right) shows the resulting compressive strength when this model is applied to the measured results. The procedure of calibrating compressive strength due to variations in entrapped air, is corresponding to that utilized in [2]. When calibrated for variations in amount of entrapped air, the impact on compressive strength is found to be less than 3%, when up to 40% of cement is substituted with an inert material.

Still, there are some unexplained variations in results, where the impact of 40% cement substitution seems to be slightly less than from 20% to 30% substitution. However, the number of test specimens in the series are small, and small variations might be caused by uncertainty in the method. Variations in results due to uncertainty should not be understood as significant impact of variations designed in the experiment.

A very simplified statistical handling is applied: The largest in-series deviation from average compressive strength is 8%. Hence, results varying less than 8% should not be understood as statistically significant. In Fig. 4 (right), limitation lines showing +/-8% from compressive strength of the reference mix are shown. All variations in compressive strength within these limitations, is explained by uncertainty in method rather than being statistical significant results of the experimental substitution of cement.

Conclusively, it has been shown possible to reduce content of cement in UHPC from an ordinary used level 766 kg/m^3, down 40% to 460 kg/m^3 – by substituting with inert filler. Previous studies have also obtained low cement contents of about 400 to 600 kg/m^3, but by using pozzolanic or hydraulic binders for substitution, e.g. [8] and [9].

5 Conclusion

This paper presents the results of an experimental study on the effects of partly substituting cement with a locally available inert material having morphology close to that of the cement. The study showed that:

1. Brand of SP influences both level and in-series variability of compressive strength of UHPC, and porosity visible on specimen surfaces.
2. It is possible to make UHPC of local materials, using unmanipulated sand and achieving average compressive strength of 122 MPa. The sand used for aggregate was by-product from production of gravel. An inert filter dust stemming from corresponding process, was used to substitute cement (40%).
3. The workability was affected by the substitution of cement even if the morphology of these two materials were close to identical. This indicates that the water amount is sensitive to the type of materials used.
4. The compressive strength of UHPC were not significantly reduced, when substituting cement up to 40% (by mass) with an inert material having the corresponding PSD.

6 Further investigation

The further experimental investigations concerning this study should be done, including:

1. Finding the optimize microsilica content, as much of it may be unreacted when the amount of cement is decreased.
2. Investigate the amount of superplasticiser needed in each recipe.
3. Experimentally investigate if the durability properties are affected by the reduced binder content.

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Paper III

Towards Efficient Use of Cement in Ultra High Performance Concrete

Lande, I. & Thorstensen, R. (2021)

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Towards Efficient Use of Cement in Ultra High Performance Concrete

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ABSTRACT
This paper presents an investigation on substituting the cement content with an inert material, in a typical locally produced UHPC mix. A structured literature review was performed to enrichen the discussion and to benchmark the results towards already reported investigations in the research society. Investigations on cement substitution in UHPC are frequently reported. However, usually the cement is substituted with other binding materials – often pozzolanic by-products from other industries. Reports from investigations on the use of inert materials for cement substitution in UHPC seem scarce.

An experimental program that included a total of 210 test specimens was executed. This program included evaluating several questions embedded to the problem on how to substitute cement while keeping all other variables constant.

It is concluded that up to 40% of the cement can be substituted with an inert material, without significantly changing the flexural tensile strength or compressive strength of the hardened UHPC. Two preconditions were caretaken: the particle packing was maintained by securing that the substitution material had a Particle Size Distribution (PSD) near identical to the cement and that the water balance was maintained through preconditioning of the substitution material. Suggestions are made for improving benchmarking.

Keywords: UHPC, Cement substitution, Inert material, Circular economy, Cement and CO_2 efficiency indexing.

1. INTRODUCTION

The concrete industry is responsible for high CO_2 emissions, often claimed to constitute 5-7% of the global anthropogenic CO_2 emissions [1]. Concrete is by far the most applied construction material worldwide and the use is anticipated to still increase. This increase is not only due to population growth, but also due to the industrialisation of developing countries. Concrete is considered indispensable for societal development at all stages [2]. Actions need to be taken to reduce the CO_2 emissions from the industry.

Mehta (2009) [3] suggested three steps towards lowering the CO_2 emission from the concrete industry: (i) consume less concrete for new structures, (ii) consume less cement in concrete mixtures and (iii) consume less clinker for making cement. One strategy to reduce the consumption of concrete in new structures might be to apply stronger concrete types. This might also further reduce emissions in a lifetime perspective, due to increased durability [2]. Ultra High Performance Concrete (UHPC) has been considered a promising material for some structural purposes, especially for bridge structures [4] – both for new construction and for rehabilitation.

UHPC is defined as a cementitious composite material [5] with (i) compressive strength greater than 120 MPa, (ii) sufficient content of fibres to obtain post-cracking tensile strength and (iii) a discontinues pore structure that reduces permeability and increases durability [4]. High levels of both cement and high-strength steel fibres are consumed to obtain these properties. However, this content also contributes to high unit cost and environmental footprint. Figure 1 presents the typical composition of UHPC mixes, calculated from a number of sources reported in research [6].

According to Stengel & Schießl [7] and Graybeal [8], cement and binder are typically responsible for 17-22% of the cost of UHPC, while the high-strength steel fibres are responsible for 62-73%. The corresponding contributions to CO_2 emissions are approximately 45% from cement and 48% from fibres, while mainly superplasticisers and silica sand are responsible for the remaining CO_2 emissions (7%) [7]. The focus of this paper is on the cement content in UHPC. In a previous paper [6], the same authors have focused on how to achieve more efficient use of fibres through hybrid configuration of macro and micro fibres in UHPC.

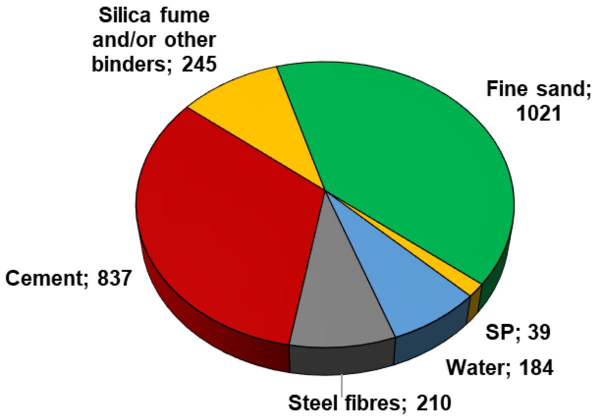


Figure 1 – Mean composition of UHPC kg/m^3, based on data from proprietary UHPC products and UHPC mixes reported in research papers [6].

Mehta's [3] second step for lowering the CO_2 emission from the concrete industry is to consume less cement in concrete mixtures. Considering the high content of cement in UHPC, this step seems even more important. Typical for UHPC is a low water to binder ratio (*w*/*b*-ratio), normally in the range 0.15-0.25. This contributes to two of the characteristics of UHPC, increased durability and improved strength. However, the low *w*/*b*-ratio leads to a large portion of the cement remaining un-hydrated, thus, simply acting as filler [9]. Cement seems an unnecessary valuable filler. Replacement of cement is usually done by active mineral additions, often in form of industrial by-products. The intention of this use of Supplementary Cementitious Materials (SCMs) is often driven by a desire to increase the circular economy within the construction industry. From this starting point, several SCMs have been found to increase properties of concrete, like microsilica which has evolved to a far more expensive product than cement, only applied when special properties are needed.

In contradiction to the use of various active SCMs, in a paper reporting from a UN initiative to reduce the CO_2 emission from the construction sector, Scrivener et al. [10] suggested (as one of many possible approaches) to substitute cement with inert or almost inert filler. The suggestion regards ordinary concrete, and reference is given to exactly this approach in the building of the still existing Arrowrock and Elephant Butte Dams, built more than a hundred years ago in 1912 and 1916. Considering the high amount of cement that remains un-hydrated in UHPC, this approach seems even more relevant.

This study reports from an experimental investigation on the effects on mechanical strength (compressive and flexural tensile strength) of UHPC, when cement is gradually substituted with granite powder, presumably acting as an inert filler. A systematic literature review was executed to enrichen the discussion and evaluate binder and CO_2 intensity through benchmarking indexes. These efforts constitute one part of a research project on understanding the material properties and behaviour of UHPC made from local materials, with the long-term goal of facilitating the use of UHPC.

2. MATERIALS AND METHODS

2.1 Literature review

The methodology for the literature review is thoroughly reported both to secure transparency and repeatability, and because this paper constitutes a part of a PhD thesis, which makes documentation on a structured methodology vital – in contradiction to just “cherry-picking” random sources. A systematic literature search was performed to obtain relevant journal papers concerning the influence of substituting cement with other materials. The methodology was structured into four steps: (i) Formulating the research question, (ii) Identifying papers and selecting relevant papers through a screening process (Figure 2) using pre-defined inclusion and exclusion criteria (Table 1), (iii) Extracting relevant data from the papers and (iv) Analysing the findings. The research questions of this study were:

- What types of materials have been used to substitute cement in UHPC?
- How is the compressive strength influenced by a reduction in cement content?

The strategy included structured searches in the Scopus database by building three blocks of keywords of three main concepts: (i) *UHPC*, (ii) *Cement replacement* and (iii) *Compressive strength*. For each concept, synonyms and related terms were found to create a block of keywords. The terms/synonyms were combined with the Boolean operator “OR”. The different block of keywords was searched separately and then combined with the Boolean operator “AND”, ensuring that at least one term for each search block is included in the paper. The search was performed first in June 2021 and then in September 2021. The searches were applied to Title, Abstract and Keywords.

Figure 2 shows the flow chart PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) [11], describing the steps from database search to the selection of relevant papers. The selection process follows four stages; (i) *identification*, (ii) *screening*, (iii) *eligibility*, and (iv) *inclusion*.

The papers identified in the search were exported to EndNote, and then to Ryyan QCRI [12] (a free web service) for screening of titles and abstracts. Inclusion and exclusion criteria (Table 1) were used to include only relevant papers in two steps. First, the title and abstract were *screened*, before the *eligibility* of the remaining papers were full-text assessed. The remaining papers in the last step were *included* in the analysis. Conclusively, a total of 33 papers was included. Extractions of these are presented in Section 3.

Table 1 – Exclusion and inclusion criteria.

Exclusion criteria	Inclusion criteria
- Non-English language - Other document types than journal research papers (e.g., books, book sections, reviews, conference papers). - Analytical and numerical studies. - Structural members (e.g., columns, walls). - Other loadings than compression (e.g., impact, blast, fatigue, shear). - Investigations of early-age strength, extreme conditions or curing conditions or autoclave curing.	- English language. - Journal papers from journals with cite score > 4. - Experimental research paper. - Investigating compressive strength. - Investigations on reduction of cement with a substituting material (with replacement percentage > 10%).

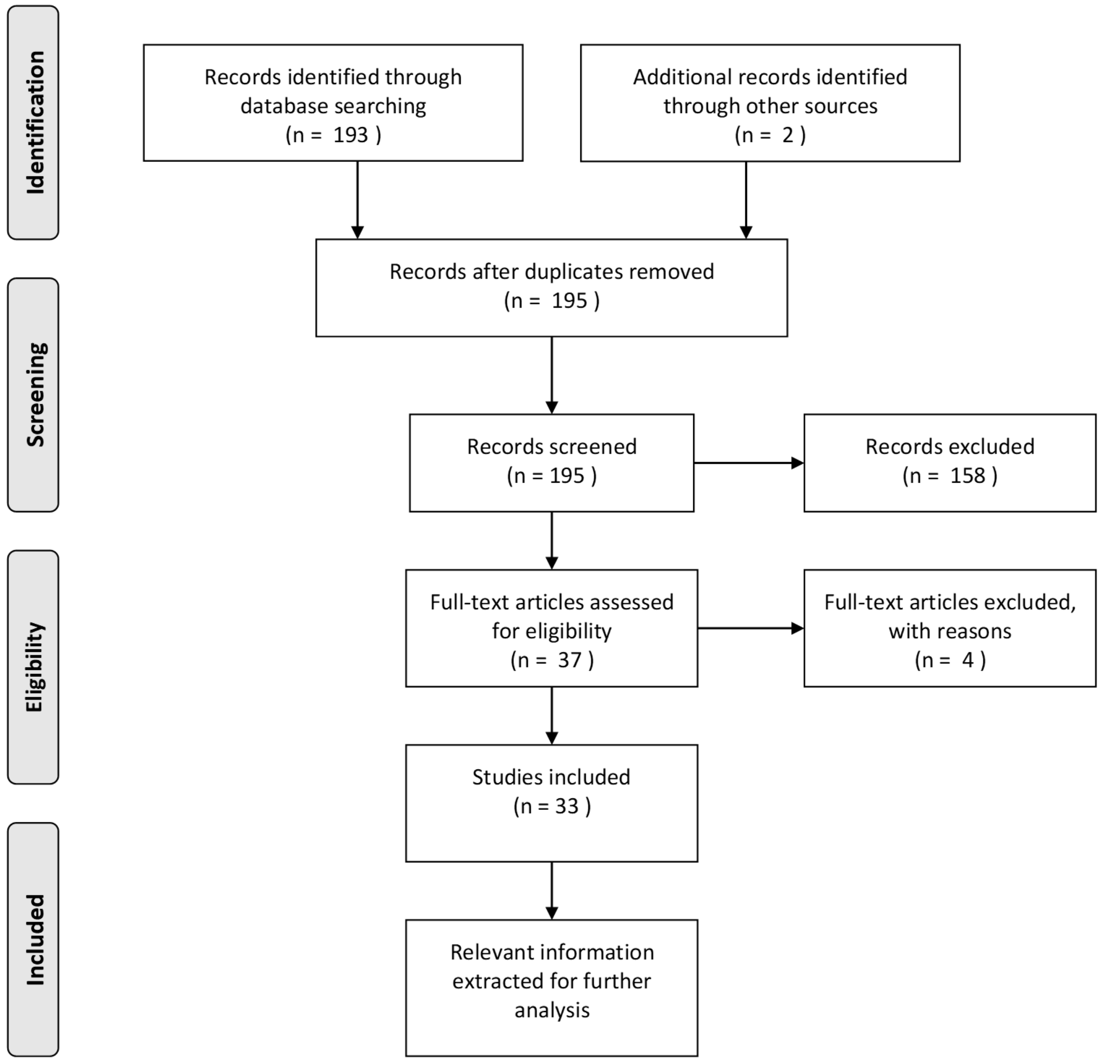


Figure 2 – The flow chart of the literature review process following the PRISMA [11].

2.2 Experimental investigation

Materials and mix design

The UHPC mixtures included the constituents described in Table 2. The largest particle size (D_{max}) of the aggregate is 6 mm, being a residue from the production of machined gravel. The fine filler material (UF) is a filter harvested powder from the production of gravel (mainly granite), used to partly replace the cement. The particle size distribution (PSD) of the cement and the UF is near identical. This can be derived from Figure 4 which reports the results of a laser diffraction investigation of the two materials. This conformity in PSDs is vital to obtain similar particle packing of the powder mix, securing that the changes in mechanical properties in the UHPC are due to changes in the cement content – not changes in particle packing of the powders.

Table 2 – Material characteristics of the UHPC constituents.

Material	Characteristics	Density [kg/m³]	D_{50} [µm]
Microsilica (MS)	Undensified microsilica	2200	0.14
Cement	CEM I 52.5 N	3100	14.1
Ultrafine filler (UF)	Filter harvest dust from production of gravel (D_{max} = 0.6 mm)	2590	16.4
Crushed aggregate (A)	Surplus aggregate from the production of machined gravel (D_{max} = 6 mm)	2770	299.2
Superplasticiser (SP)	Modified acrylic polymers, 18% dry content	1060	N/A
Retarder (R)	Based on sodium gluconate, 20% dry content	1100	N/A

N/A: Not applicable.

Figure 3 shows a SEM (Scanning electron microscope) image of the UF. The particle shape of the UF differs from the shape of the cement particles, potentially also influencing the particle packing. The filler has water absorption value of 10.7% and was pre-conditioned at least 24 hours before lab execution to ensure the Saturated Surface Dry (SSD) condition. This seems rather high and was consequently controlled in the university lab. The result was confirmed.

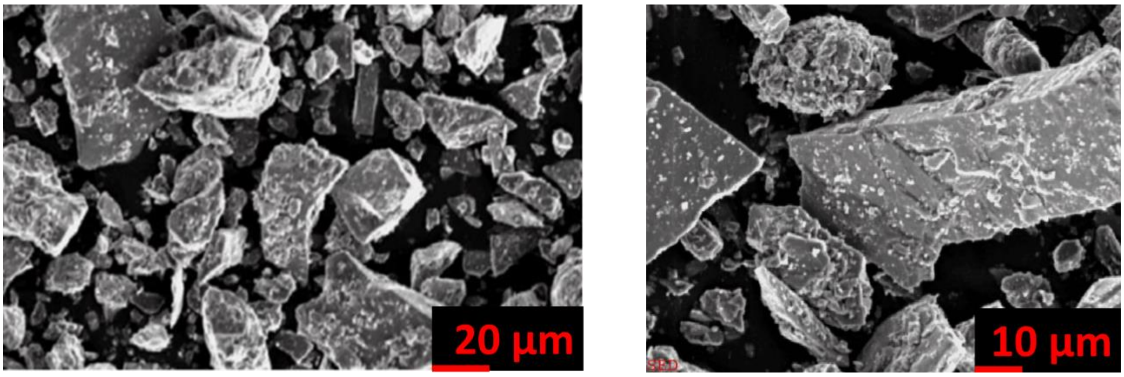


Figure 3 – Scanning electron microscope image of the inert ultrafine filler (UF) used to partly substitute cement in the UHPC mixes.

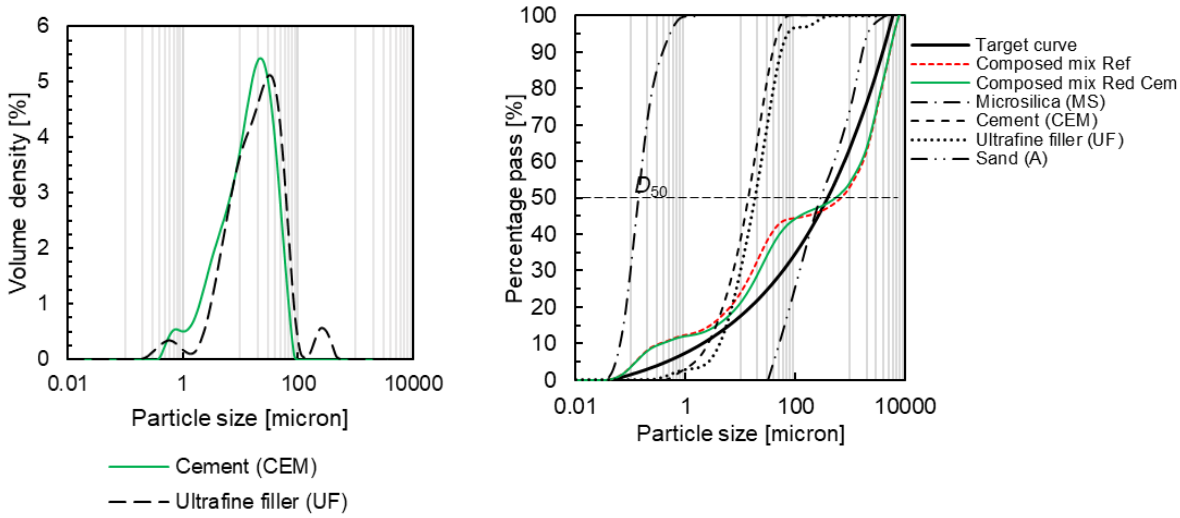
Figure 4 b reports the individual PSDs of cement, ultrafine filler, aggregate and microsilica. For materials with $D_{max} < 1$ mm, laser diffraction was used to obtain PSDs. A sieve analysis was used for the aggregate (A). There are disadvantages in combining measurements from indirect methods (laser diffraction) and direct methods (sieving). However, this is still applied in Figure 4 b due to the lack of one single method for measuring the total range in particle size, spanning 35 nanometer to 6 mm.

The composition of the reference mix was set according to [6], to include 700-800 kg/m³ of cement, and microsilica content corresponding to 25% of the mass of cement. The *w*/*b*-ratio was set to be either 0.25 or 0.29 in different mixes. Following numerous of the studies identified in the literature review, the modified version [13] of the Andreasen and Andersen model (AA model) for granular materials [14] was used to simulate the accumulated particle distribution of the mixes. The modified Andreasen and Andersen particle distribution curve (target curve) reads as follows (Eq. 1):

$$CPFT = \left(\frac{D-D_{min}}{D_{max}-D_{min}}\right)^q \qquad (1)$$

where CPFT is the cumulative per cent finer than size *D*, *D* represents the particle size, D_{min} is the smallest particle size of the distribution and D_{max} is largest. The *q-value* is the distribution coefficient that defines the curvature of the cumulative PSD. The target curve for the relative composition of powders was defined as the densest possible particle packing according to this model. The software EMMA (Elkem Materials Mix Analyzer, version 3.5.2), which is an operationalisation of the modified AA model, was used to simulate the target curve and the PSDs of the actual powder compositions. The target curve is represented by the solid black line in Figure 4 b, while the red and green lines represent the actual composition of the reference mix and one of the mixes with the highest cement substitution, respectively. From these curves, it seems clear that the particle packing remains stable through the substitution levels. All materials were included "as is", without any manipulation which might have been applied to obtain a better fit with the target curve.

The *q-value* is essential in the AA model, influencing the curvature of the target curve. In practice, the *q-value* is considered to rule the flowability of the mix. Following the practice of several papers identified in the literature search, a *q-value* of 0.23 was applied.



(a) *Cement (CEM) compared to the inert filler (UF).*

(b) *PSD of all dry materials individually, the accumulated PSDs of the composed mixes and the AA model (target curve) with q = 0.23.*

Figure 4 – Particle Size Distribution (PSD) of individual powders and accumulated mixes.

Cement substitution might follow different "rules", all potentially influencing the results. Approaches through different rules were identified through the literature review. One variation that might influence the results, regards the *w*/*b*-ratio. When cement is substituted with an inert filler while the *w*/*b*-ratio is set to constant, the water content is reduced as the substitution level increases. The reduced water content might govern other properties that influence the resulting mechanical properties. As an attempt to evaluate this effect, two different *w*/*b*-ratios were tested. Another variation that potentially influences the results, regards the SP content. The SP is designed to act on the surface of the cement particles. Hence, the SP/C ratio should be kept constant, meaning that the SP content should be reduced correspondingly to the cement reduction. However, it is not clear whether SP also acts on the surface of other particles. Thus, it might be better to keep the SP content constant. Both approaches are tested in this investigation.

Three groups of mixes were designed for cement substitution, following three different “rules”. A total of 14 mixtures was included (Ref. in groups 2 and 3 are the same). The cement was substituted with the ultrafine filler material (UF) in steps of 10, 20, 30 and 40% by mass. The three groups and “rules” for substitution is:

1. *w*/*b*-ratio of 0.25 and constant SP/C-ratio
2. *w*/*b*-ratio of 0.29 and constant SP/C-ratio
3. *w*/*b*-ratio of 0.29 and constant SP content

Table 3 shows the different mixes. The content of water includes the water content of the admixtures, excluding the water absorption in the aggregate and the filler.

Table 3 – UHPC mix proportions.

Group no.	CEM reduction [a]	CEM (C)	UF	A	MS	SP [b]	R	W (*w*)	*w*/*b*
	%	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	-
1	0 (Ref.)	756	0	1188	189	7.3	0.8	236	0.25
	10	690	77	1205	192	6.7	0.7	221	0.25
	20	623	156	1223	195	6.1	0.6	205	0.25
	30	553	237	1242	198	5.4	0.6	188	0.25
	40	482	321	1261	201	4.7	0.5	171	0.25
2	0 (Ref.)	728	0	1145	182	7.1	0.7	264	0.29
	10	667	74	1165	186	6.5	0.7	247	0.29
	20	604	151	1186	189	5.9	0.6	229	0.29
	30	538	231	1209	193	5.2	0.5	210	0.29
	40	470	314	1232	196	4.6	0.5	190	0.29
3	0 (Ref.)	728	0	1145	182	7.1	0.7	264	0.29
	10	667	74	1165	185	7.2	0.7	246	0.29
	20	603	151	1185	189	7.3	0.6	228	0.29
	30	537	231	1207	192	7.5	0.5	209	0.29
	40	469	313	1229	196	7.6	0.5	190	0.29

[a] by mass. [b] solid content. CEM: Cement CEM I 52.5 N. UF: Ultrafine filler. A: Surplus aggregate from production of machined gravel. MS: Microsilica. SP: Superplasticiser. R: Retarder. W (*w*): Total free water, including the water content of the admixtures, excluding the water absorption in the aggregate and the filler. *b*: binder (CEM + MS) content. *w*/*b* – Water to binder ratio.

Mixing and production

A Hobart A200 planetary mixer (with three mixing speeds) was used. Three litres of UHPC were mixed for each batch, following the procedure in Table 4. The fresh properties were measured using a flow table with an ASTM cone (*ASTM C230/C230M)* following *ASTM C1437*. After mixing, the initial flow was immediately measured by taking two diameters perpendicular to each other. Then, the table was dropped 15 times in 45 seconds, giving two new diameters (final flow).

The UHPC was cast in cubes of 50 mm for compressive strength tests, or prisms of 40 mm × 40 mm × 160 mm for both compressive strength and flexural tensile strength tests. The moulds were filled in two layers, both manually compacted. All moulds were screeded and covered with plastic sheets until demoulding about 18 hours after casting.

The 50 mm cube specimens were exposed to two different curing regimes. Curing at 90°C for 48 hours is an often seen manufacturer-recommended treatment for UHPC [15], but is difficult to apply in practical construction. The following curing regimes were applied, to evaluate the differences in effect:

a) *Heat treatment* in water at 90°C for 48 hours and tested after finished curing regime.

b) *Normal curing* temperature, in water at 20°C for 28 days.

Table 4 –Mixing procedure.

Step	Procedure	Time [sec]
0	Mixing all dry constituents at low speed	30
1	Adding water, superplasticiser, and retarder	-
2	Mixing at low speed (107 rpm)	30
3	Pausing the mixing	90
4	Mixing at medium speed (198 rpm)	120
5	Mixing at high speed (361 rpm)	15-30

Mechanical strength tests
Compressive testing was performed according to the *ASTM C109/C109M* on 50 mm cubes. All tests included three specimens tested in parallel, and the average value was calculated to represent the properties.

The mechanical behaviour of the UHPC mixes was also tested on prisms of 40 mm × 40 mm × 160 mm, using the European standard *NS-EN 196-1*. Following this standard, both compressive strength and flexural tensile strength are achieved. Three test samples were tested in flexure and the six half-samples obtained after finishing the flexural test were tested in compression. All these test samples were *heat-treated* (curing regime *a*) at 90°C for 48 hours.

Small cubes were used as test specimens in accordance with most of the experimental investigations identified in the literature review. The capacity of the test machine might conflict with the strength of larger specimens with high strength (e.g., UHPC). Hence, a practical solution is to use small test specimens [16]. For normal concrete, it has been shown that smaller test specimens tend to give higher compressive strength. However, previous studies have demonstrated that the effect of size and specimen geometry (cubes and cylinders) is very small for UHPC [16, 17]. Thus, it will not be discussed further in the present investigation.

2.3 Cement efficiency

The efficiency of cement replacement is evaluated based on two indexes; binder intensity (*bi*) representing the cost perspective, and CO_2 intensity (*ci*) representing the Global Warming Potential (GWP) perspective, as described by Damineli et al. (2010) [18]. The results are evaluated within the present investigation, and for comparing the results of this investigation towards the studies found in the literature review.

The binder intensity index measures the total content of binder required to give one unit of a performance, in this case, 1 MPa of compressive strength bi_{cs} (Eq. 2):

$$bi_{cs} = \frac{b}{p} \qquad (2)$$

where b represents the total content of binder materials (kg/m^3), and p is the performance requirement. In this study, the performance requirement is selected to be the compressive strength (in MPa) after 28 days of normal curing in 20°C. For the values representing the experimental investigation in this study, the compressive strength was obtained from the ASTM cubes (*ASTM C109/C109M*). The bi_{cs} index is often applied to measure the economic performance in concrete [18], as the highest cost in concrete compositions is the binders.

The CO_2 emissions of the UHPC mixes are calculated using the CO_2 intensity (*ci*) index. The intention is to measure the amount of CO_2 released to give one unit of performance, in this case, compressive strength ci_{cs} (Eq. 3) [18]:

$$\mathrm{ci}_{cs} = \frac{c}{p} \tag{3}$$

where c represents the total CO_2 (kg/m^3) emissions to both produce and transport the raw materials in the concrete and p is the compressive strength in MPa after 28 days of normal curing in 20°C. The main contributor to CO_2 emissions in normal concrete is cement [18, 19]. For UHPC, the main contributors to CO_2 emissions are cement (approximately 45%) and micro steel fibres (approximately 48%) [7]. However, only the cement content is evaluated in this investigation. The CO_2 emissions from industrial by-products are considered to have no contribution to the overall CO_2 emissions [19]. According to Damineli et al. (2010) [18], the CO_2 emission from cement production is set to 1 tonne CO_2 per tonne cement, considered to represent a world average. Norwegian production of cement (CEM I 52.5) is about 0.7 tonne CO_2 equivalents per tonne cement, according to the Environmental Product Declaration (EPD) from Norcem AS. The world average value is used to facilitate international comparison. An additional value of 125.7 kg CO_2 emission per m^3 UHPC is applied for the *heat-treated* test specimens, following Shi et al. [20].

3. RESULTS AND DISCUSSION

3.1 Literature review

Table 5 shows the papers identified through the literature search, which was included in the review process. The table shows the replacement material and reduction percentage by mass (vol.% is displayed if the reduction is given in vol.% in the paper). The total cement content is given in the reference mix, along with the compressive strength of the reference mix (σ_{cRef}) and the compressive strength of the highest reduction percentage ($\sigma_{cMaxsub\%}$).

Table 5 – Overview of the included papers on cement substitution in UHPC, with extracted data.

Authors (year)	Replacement material	CEM content in Ref. [kg]	% CEM replacement	σ_{cRef} [MPa]	$\sigma_{cMaxsub\%}$
Abdulkareem et al. (2021) [21]	GGBS	977.0	30, 50 and 80 vol.%	153.1 [a]	111.8 [a]
Aghdasi & Ostertag (2018) [22]	FA and GGBS	N/A	50 (25% FA and 25% GGBS)	144.8	133.8
Ahmed et al. (2021 a) [23]	FA	935.0	20, 40, 60, 70	198.9	106.9
Ahmed et al. (2021 b) [24]	GGBS	N/A	15, 30, 45, 60	180 [b]	151.0
Aldahdooh et al. (2013) [25]	Palm oil fuel ash	720.5	25, 50 vol.%	181.4	156.7
Alsalman et al. (2020) [26]	FA	1104.9 [d]	30, 40, 50	150.2 [c]	111.1 [c]
Ganesh & Murthy (2019) [27]	GGBS	960.0	20, 40, 60, 80	115.7	101.2
Hou et al. (2021) [28]	Red mud	750.0	20, 40, 60	159.7	81.3

Authors (year)	Replacement material	CEM content in Ref. [kg]	% CEM replacement	σ_{cRef} [MPa]	$\sigma_{cMaxsub\%}$
Huang et al. (2017) [29]	LP	1251.2	34, 54, 74 vol.%	145 [b]	112.5 [b]
Jing et al. (2021) [30]	FA (cenosphere)	965.0	10, 20, 30, 40 vol.%	107 [a, b]	96 [a, b]
Li et al. (2020) [31]	LP	1071.8	20, 40, 60, 80 vol.%	152.9	75.5
Li et al. (2019) [32]	Ternary/quaternary blends of cement or slag cement with LP and MS	N/A	10, 20, 30 (LP)	153 [b]	150 [b]
Li et al. (2021) [33]	Waste basalt powder	856.5	15, 30, 45	155	115
Ling et al. (2021) [34]	Iron ore tailing	750.0	10, 20, 30	121 [b]	119 [b]
Liu et al. (2021 a) [35]	Carbonated or non-carbonated converter steel slag powder	925.0	15, 30, 45, 60 vol.%	158 [b]	120, 107 [b]
Liu et al. (2021 b) [36]	LP, quartz powder and wollastonite powder	810.0	20	105	119
Mao et al. (2019) [37]	Recycled powder	1000.0	10, 20, 30, 40	129 [b]	115 [b]
Meng et al. (2017) [38]	GGBS or FA	712.0	30, 40, 50, 60 vol.%	135	120, 124
Qian et al (2020) [39]	Dehydrated cement paste from recycled construction waste cementitious material	400.0	12.5, 25, 37.5, 50	107 [b]	87 [b]
Randl et al. (2014) [40]	FA or two types GGBS	729.0	45%	166.1	124.7-163.5
Shi et al. (2019) [20]	GGBS	634.0	17, 34, 59, 67, 75, 84, 92 [d]	140 [b]	44 [b]
Soliman & Tagnit-Hamou (2016) [41]	Glass powder	807.0	10, 20, 30, 40, 50	170 [b]	145 [b]
Tahwia et al. (2021) [42]	FA or GGBS	1000.0	30, 50	163.4	160.9, 136.8
Wang et al. (2021) [43]	Expanded perlite powder	880.0	20, 40, 60	180.4	153.1
Wang et al. (2018) [44]	Lead-zinc tailings	750.0	10, 20, 30, 40	180 [b]	140 [b]
Wu et al. (2017) [45]	FA or GGBS	792.0	20, 40, 60	149.8	138.2, 144 [b]
Xu et al. (2021) [46]	Ceramic tile waste powder	N/A	15, 25, 35, 45, 55	127 [b]	117 [b]
Yang et al. (2020) [47]	Quarry stone powders (basalt and LP)	720.0	22, 44	122.4	116 [b], 118 [b]
Yu et al. (2017) [48]	FA, GGBS or LP	883.9	30	114 [b]	102-112 [b]
Yu et al. (2015) [49]	FA, GGBS or LP	883.9-896.3	30	113 [b]	97-110 [b]
Zhang & Zhao (2017) [50]	LP, rich husk ash or kaolin	875.0	30, 35, 45 [d]	114 [b]	87-114 [b]
Zhang et al. (2019) [51]	Steel slag	620.2	10, 20, 30	181 [b]	170 [b]

Authors (year)	Replacement material	CEM content in Ref. [kg]	% CEM replacement	σ_{cRef} [MPa]	$\sigma_{cMaxsub\%}$
Zhu et al. (2016) [52]	Powder from waste of clay bricks	N/A	9, 18, 27	80 [b]	75 [b]

σ_{cRef}: Average compressive strength for reference mix. $\sigma_{cMaxsub\%}$: Average compressive strength for mix with highest substitution percentage of cement. [a] 90 day strength. [b] Read off figure. [c] heat curing 90°C, tested after 28 days. [d] calculated from info given. CEM: Cement. MS: Microsilica. LP: Limestone powder. GGBS: Ground granulated blast-furnace slag. FA: Fly ash. N/A: Not Applicable/available.

A variety of materials are used for cement substitution, often reflecting what is available at each location. Most materials are considered to have binding properties – some to be near inert. All are described as by-products from other industries, thus, accommodating a circular economy. Microsilica is normally not considered an SCM in this aspect, as it is one of the essential constituents in UHPC. The average microsilica content identified through these papers is ca. 140 kg/m^3, in most cases kept constant through all replacement levels. The replacement level of cement is investigated from 10 to above 90%. The results of these studies are discussed in Sections 3.2 and 3.3 towards the results of the experimental investigation.

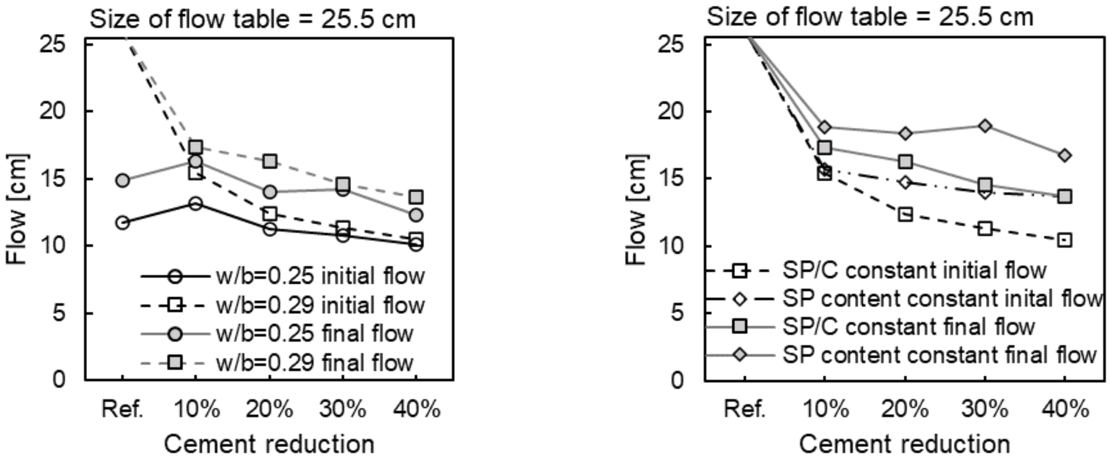
3.2 Experimental investigation

Flow

Ideally, in experimental investigations only one parameter should be varied at the same time, evaluating the impact of variations in just this parameter. However, variations in one parameter often induce changes in other aspects. In this case, reductions in cement content raise questions on how the two parameters *w*/*b*-ratio and SP content is kept constant - i.e., avoiding that also these parameters influence the results. To accommodate this intention, three groups of cement replacement investigations were designed; keeping *w*/*b*-ratio constant through two different levels (w/b = 0.25 in Group 1 and w/b = 0.29 in Group 2), and keeping SP constant through two different measurements (SP/C = constant in Group 2 and SP content constant in Group 3). All variations are expected to influence fresh consistency, thus, possibly also influencing the mechanical properties in hardened state. A decrease in workability might negatively influence the placing of the UHPC mortar in the moulds, possibly leading to more air voids and hence reduced strength in the hardened product.

Figure 5 a shows the initial and final flow (according to the *ASTM C1437*) at all substitution levels and two different *w*/*b*-ratios (Group 1 and 2).

The reference mixes show higher flow for Group 2 (exceeding the size of the flow table) than Group 1, having the higher *w*/*b*-ratio. However, already at 10% substitution level, this difference is nearly ruled out. For higher substitution levels, the flow is still stepwise reduced, but in small scale. The deviation from linear development might represent statistical variations related to the method. A corresponding loss of flow at increasing levels of cement substitution can be found in the literature, e.g. as described in [37]. Still, a discussion on causes and effects might be enlightening.



(a) *Variation between groups with different w/b-ratio (Groups 1 and 2).*

(b) *Variation between groups with different SP rules; SP/C constant and SP content constant (Groups 2 and 3).*

Figure 5 – Initial and final flow.

The PSD of the cement and filler is near identical (Figure 4). Thus, the substitution is probably not influencing the flow due to differences in PSD. However, the flow reduction might have at least two other causes. One is possible water absorption in the filler. The absorption potential of the filler is 10.7%, according to the product declaration sheet. To avoid problems with water absorption, the filler was pre-conditioned with 10.7% water and matured for at least 24 hours. The material might still not be Saturated Surface Dry (SSD) as intended, but at least the effect of water absorption is tentatively eliminated. Another explanation for the loss of flow is the “edgy” shape of the filler particles demonstrated in Figure 3. This shape increases the internal friction in the matrix and remains the most probable explanation for the loss of flow. However, the difference in flow between the two groups for all substitution levels (10-40%) remains small, near the scale of statistical variations caused by the measurement method. Hence, the between-group variations seem not to have the potential for explaining possible differences in mechanical properties between specimens from Groups 1 and 2.

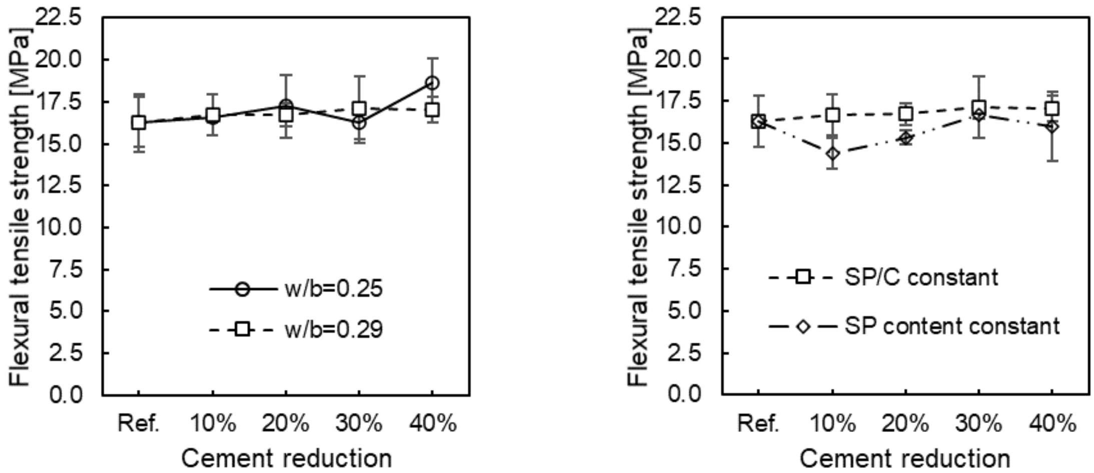
Figure 5 b shows the initial and final flow at all substitution levels with two different rules for keeping SP constant. The flow is far more influenced by the introduction of the filler (0 to 10% cement substitution), than by successive substitutions at higher levels (10-40%). There is a weak linear decrease in flow as the substitution level increases. However, the variations are scaled near the statistical variations of the measurement method. Overall, the differences remain small, probably not sufficient for explaining significant differences in mechanical properties of the hardened UHPC.

Flexural tensile strength in hardened state

Figure 6 shows the flexural tensile strength of the 40 mm × 40 mm × 160 mm prisms at increasing levels of cement substitution. In Figure 6 a, the development of flexural tensile strength at increasing substitution levels is compared for two different *w*/*b*-ratios (Group 1 vs Group 2). The development of flexural tensile strength seems not to be influenced by variations in the *w*/*b*-ratio at any substitution level. The graphs are nearly overlapping, and the small variations are within the statistical uncertainty of the measurement method.

Figure 6 b, where the development in flexural tensile strength is compared for two different regimes on SP content (Group 2 vs Group 3), reveals some larger deviations. However, the statistical variations are in the same range, and the fluctuations of the lower curve might rather be caused by statistical uncertainty than variations in actual physical properties. Thus, it is concluded that nor the two different rules for keeping SP constant causes differences in flow that might explain substantial variations in mechanical properties of UHPC in hardened state.

It is mentioned that in practice UHPC always contain large amounts of micro fibres. The fibres are the main contributor to the typical high tensile strength of UHPC. Though neither differences in *w/b*-ratio nor in SP content was found to cause differences in flexural tensile strength of the mortar in this investigation, both might cause differences in how fibres contribute to tensile strength when these are included in the UHPC.



(a) *Variation between groups with different w/b-ratio (Groups 1 and 2)*

(b) *Variation between groups with different SP rules; SP/C constant and SP content constant (Groups 2 and 3).*

Figure 6 – Flexural tensile strength (NS-EN 196-1) for all replacement percentages after heat treatment curing. Error bars show the SD values.

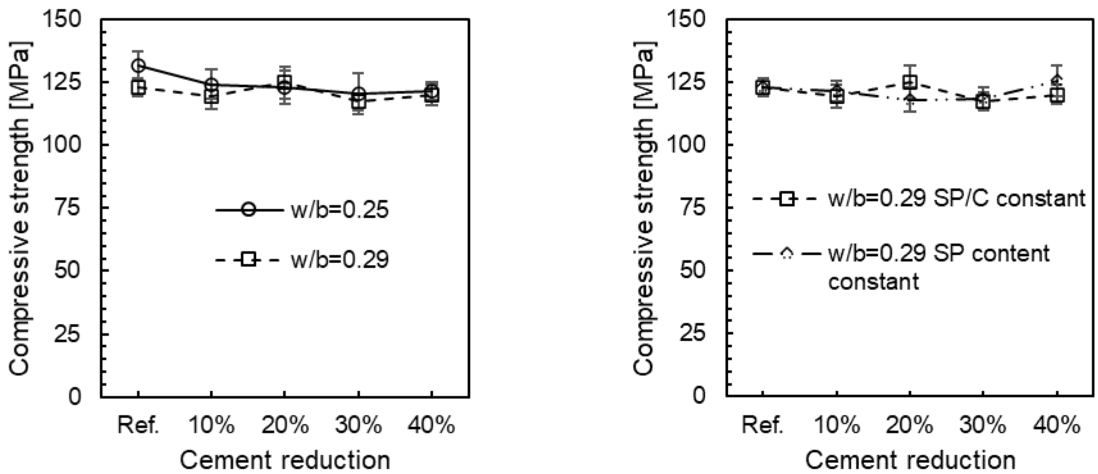
Compressive strength in hardened state

The compressive strength of all mixes in this investigation is in the lower range of what is normally defined as UHPC. Though, when cured at elevated temperature, the results are within the definition stated by [4]. The limited compressive strength was suspected to be influenced by the newly acquired aggregate being weak. Fracture through the aggregate particles post-testing was frequently observed, strengthening this theory. To evaluate this potential explanation, a test using natural aggregates with corresponding PSD curves to the original aggregates was tested in the same UHPC composition. The result from this test was a 16% increase in average compressive strength. This was considered a satisfactory indication of the potential in the UHPC composition.

Figure 7 shows the development of compressive strength for specimens cured at high temperature (*heat treatment*) and tested according to *NS-EN 196-1* at all substitution levels, compared for variations in *w/b*-ratio and SP regimes. Each data point is the average of 6 specimens tested in parallel. The reference mixes had a mean compressive strength of 122.9 to 131.8 MPa. The compressive strength shows only small variations within the parallel tests for all cement substitution levels up to 40%, all considered to be within the range of the statistical variations of the measuring method. Neither variations in *w*/*b*-ratio (Figure 7 a) nor in SP regime (Figure 7 b) influence these compressive strength results.

Normally in concrete technology, an increase in water content is expected to lead to an increase in porosity and hence reduced compressive strength. According to Figure 7 a, the reference mix with the lowest *w*/*b*-ratio (Group 1) has slightly higher compressive strength than the reference mix with a higher *w*/*b*-ratio (Group 2). The difference is small, and already at the first introduction of the filler (substitution level 10%), this difference is reduced. In cases where low *w*/*b*-ratios is limiting the amount of water available for cement hydration, it has formerly been shown that small increases in *w*/*b*-ratios have little influence on the strength of UHPC [49].

It is known that the pozzolanic effect that creates binder from microsilica increases at elevated temperature curing. The high amount of microsilica normally used in UHPC (in this case 25 mass-% of the cement in the reference), might also be part of the explanation why a change in *w*/*b*-ratio does not influence the compressive strength. If the amount of calcium hydroxide released from the (limited) cement hydration throughout all substitution levels remains sufficient for all the microsilica to react pozzolanicly, the relative influence of the cement hydration is reduced compared to what happens in ordinary concrete with low microsilica level and without the benefit of elevated temperature curing. This explanation might be strengthened if specimens cured at lower temperature reveals different results from variations in *w*/*b*-ratio.



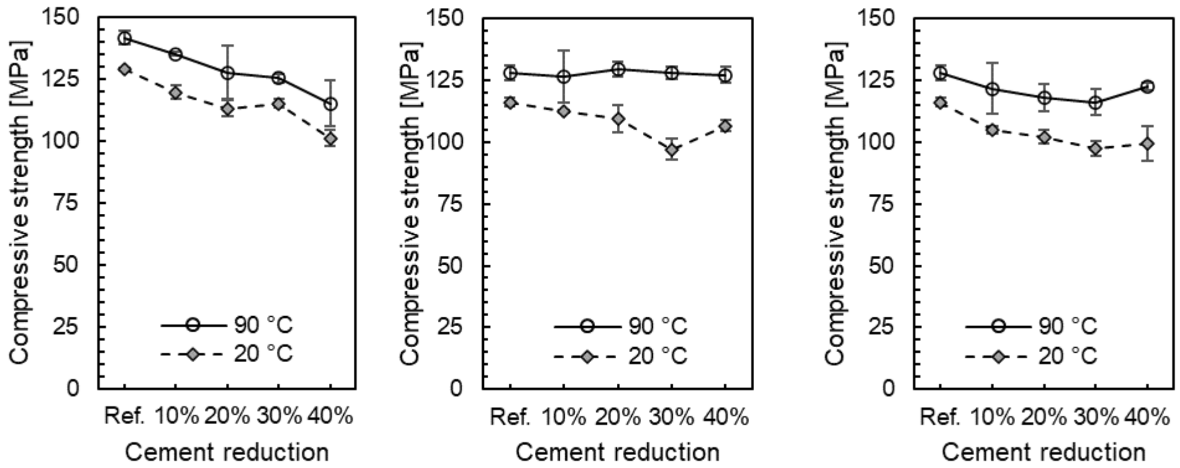
(a) *Variation between groups with different w/b-ratio (Groups 1 and 2)*

(b) *Variation between groups with different SP rules; SP/C constant and SP content constant (Groups 2 and 3)*

Figure 7 – Compressive strength (NS-EN 196-1) for all replacement percentages after heat treatment curing. Error bars show the SD values.

The effect of different curing regimes on compressive strength was investigated. The results are presented in Figure 8. For all Groups illustrated in Figure 8 (a through c), the compressive strength achieved at 20ºC is around 15% lower than those at 90ºC except for one single data point (Figure 8 b at 30% substitution level). This lack of correspondence in one point could be an outlier. The general increase in compressive strength achieved at elevated temperature is anticipated to be caused by the increased pozzolanic action at high-temperature curing, described above. However, since the relative differences between the two curves in each of the figure remains close to constant, it seems not relevant like indicated above, to relate the lack of reduction in compressive strength at high substitution levels to the increased pozzolanic action at elevated temperature.

A discrepancy between the results illustrated in Figures 8 a and b versus those in Figure 7 a, is that the compressive strength results seem to be influenced by the lower *w/b*-ratio in Figure 8 – while not in Figure 7. These are the results from two different tests; Figure 7 is presenting the results from tests according to *NS-EN 196-1*, while Figure 8 is according to *ASTM C109/C109M*. One clear difference is the geometry of the test specimens. *ASTM* uses 50 mm cubes, while *NS-EN* applies compressive load from square 40 mm surfaces towards approximately one half of a 40 mm × 40 mm × 160 mm prism. However, there might also be other differences between the two regimes. A paper, where inconsistencies between results from the standards for measuring the pozzolanic effect of cement substitution found in ASTM and EN is investigated [53], reveals that multiple factors e.g. the type of SP and the fineness of cement influence the test results in these two standards differently.

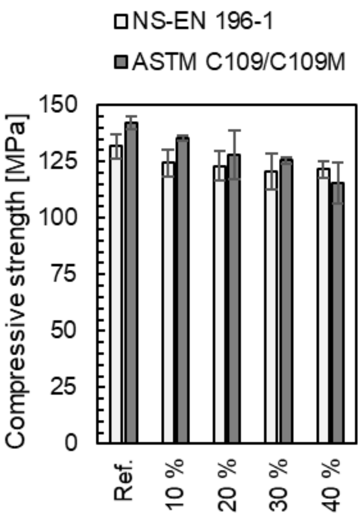


(a) w/b=0.25 with SP/C constant (Group 1)   *(b) w/b=0.29 with SP/C constant (Group 2)*   *(c) w/b=0.29 with SP content constant (Group 3)*

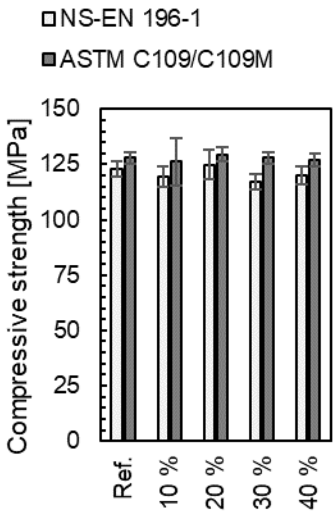
Figure 8 – Compressive strength (ASTM C109/C109M) following different curing regimes (heat treatment at 90°C for 48 hours or normal curing at 20°C for 28 days), for all replacement levels. Error bars show the SD values.

To evaluate whether there are systematic differences between the two testing regimes (*ASTM* vs *NS-EN*) in this investigation results from the compressive strength tests according to the two standards are compared in Figure 9. Though there are some differences, these seem to be within the range of the statistical variations of the methods. Hence, there does not seem to be any systematic differences between the results obtained from testing according to *ASTM* compared to those from *NS-EN*. The discrepancy discussed above between the results shown in Figures 8 a and b from those in Figure 7 a, remains unsolved.

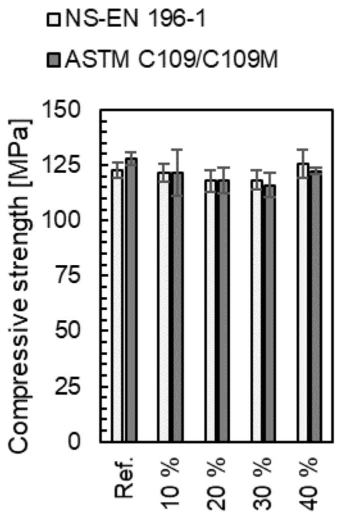
However, after a thorough discussion on substituting up to 40% of the cement in UHPC by an inert filler having PSD near identical to that of the substituted cement, the major conclusion is that the effect on strength is negligible. An explanation might be that the amount of cement that hydrates remain constant through all substitution levels. The cement particles that remain un-hydrated might be substituted with inert particles without compromising the strength of the UHPC.



(a) *w/b=0.25 with SP/C constant (Group 1)*



(b) *w/b=0.29 with SP/C constant (Group 2)*



(c) *w/b=0.29 with SP content constant (Group 3)*

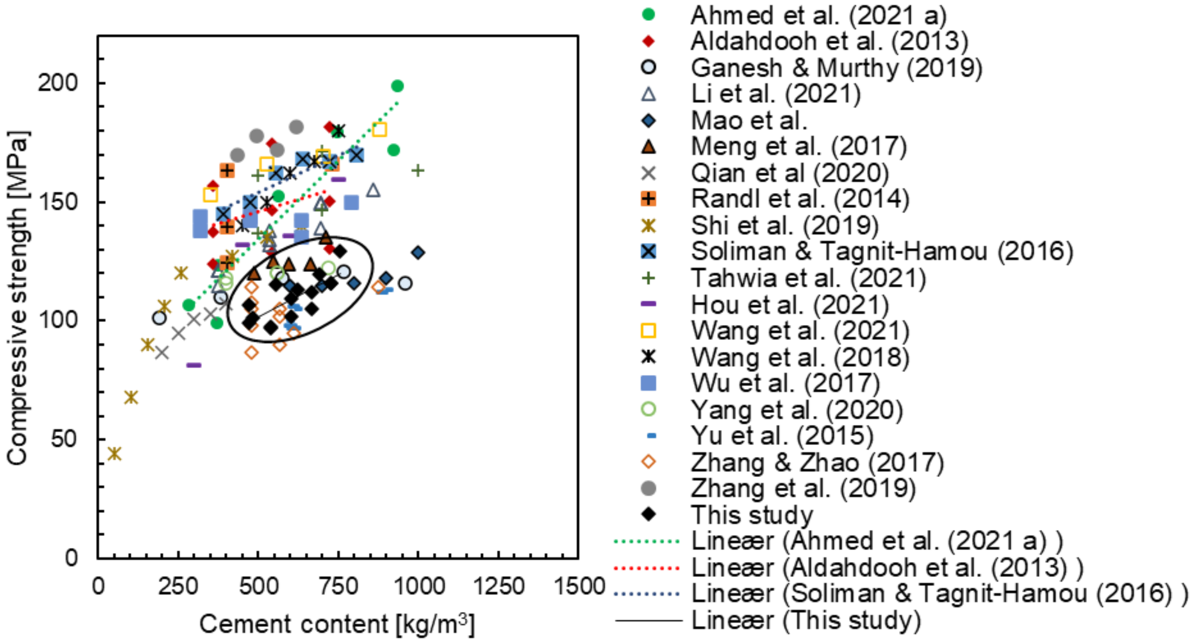
Figure 9 – Compressive strength following ASTM C109/C109M and NS-EN 196-1 for heat-treated test specimens.

Comparison with results from the literature review

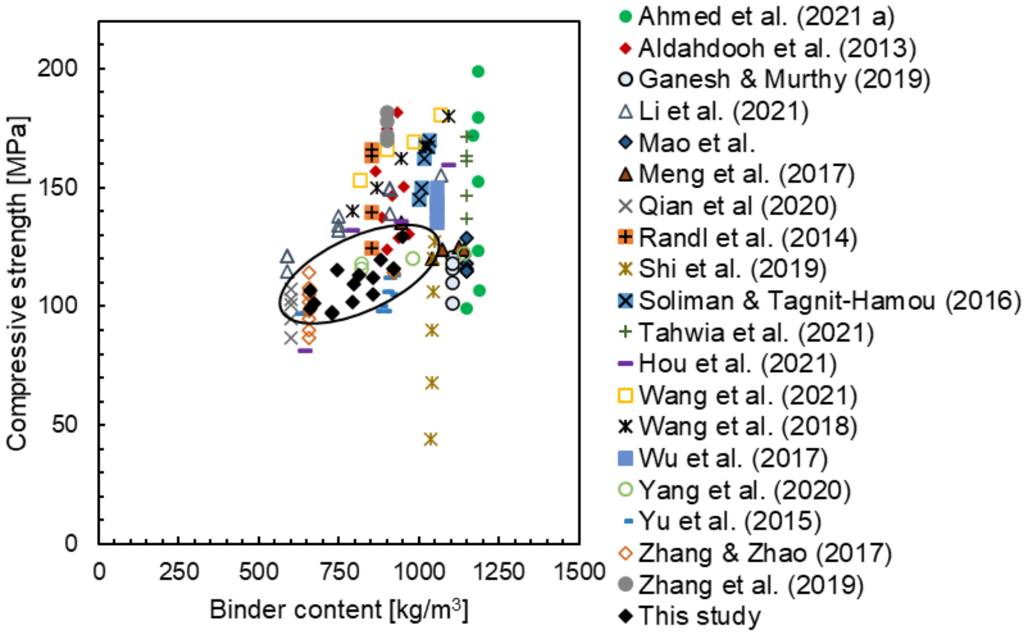
Figure 10 shows the compressive strength versus the total cement content (Figure 10 a) and total binder content (Figure 10 b) of the results from this study compared to results extracted from the literature review. All investigations shown in Figure 10, except two, use small cube specimens.

The compressive strength in this study is lower than the average compressive strength for the different UHPC mixes obtained from the literature review (after 28 days standard curing at 20°C). This is partly explained above with low-quality aggregate. And it is not central to the focus of this paper. However, what is interesting is the inclination of a linear regression line between the data points, shown for some of the investigations in Figure 10 a. This line represents the continuous effect on compressive strength, caused by the cement substitution. The inclination represents the average strength loss per unit of cement, during the stepwise substitution. Comparing the inclination of these lines between investigations reveals that the results on compressive strength during cement substitution found in the present investigation corresponds closely to the results from most of the papers identified in the literature review. The low inclinations of some of the lines (including the present investigation) show only limited strength loss from cement reduction of about 40% starting from an average level of around 750 kg cement per m^3. It is, however, also worth noticing that there seems to be a threshold under which the cement content should not be reduced. This is visible from Figure 10 a, where the results from Shi et al. (2019) [20] seem to have a breaking point around 250 kg/m^3.

What differs the present investigation from most other investigations identified in the literature review, is the properties of the material used for cement substitution. This becomes observable from Figure 10 b, showing compression strength versus total binder content. The inclination of the linear regression lines (not depicted) from many investigations becomes vertical. The reason is that most investigations use materials with binding properties for cement substitution. Thus, the binder content is not reduced. The investigation presented in this paper utilises an inert (waste) material for cement substitution, yet achieves corresponding strength results as the others. Only a few other investigations have tried this approach.



(a) Compressive strength vs cement content

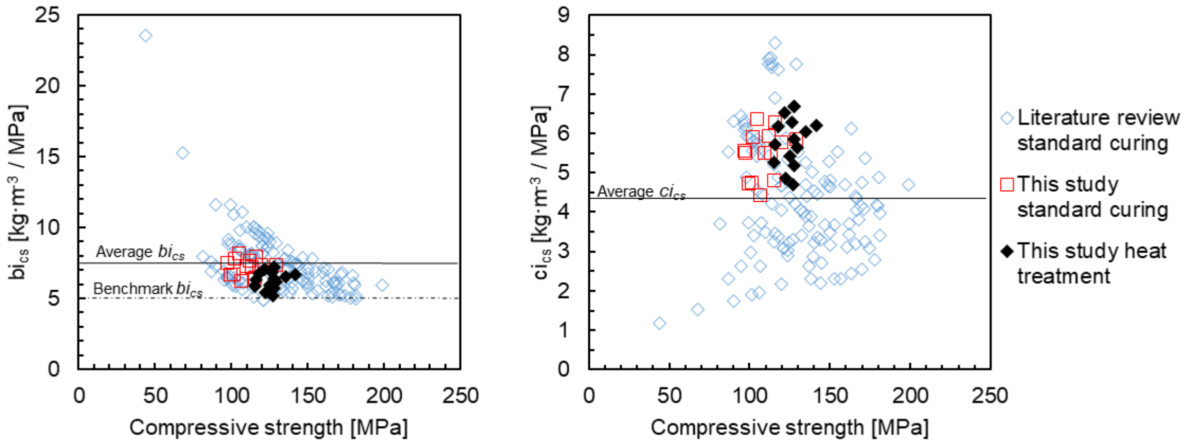


(b) Compressive strength vs total binder content

Figure 10 –Compressive strength vs cement/binder content, for specimens cured at 20°C in 28 days found in the literature compared to the results in this study (highlighted with a circle).

3.3 Cement efficiency evaluation

Figure 11 shows the calculated binder intensity (bi_{cs}) and CO_2 intensity (ci_{cs}) of this study compared to the results from the literature. The method of calculating the two indices is explained in Section 2.3. The compressive strength results used in the calculations for both indices in the present investigation are those identified from testing according to *ASTM C109/C109M*.



(a) binder intensity (bi_{cs}) according to Eq. 2 *(b) CO_2 intensity (ci_{cs}) according to Eq. 3*

Figure 11 – Compressive strength versus binder intensity/CO_2 intensity for results from this investigation, compared to results from other investigations identified in the literature review

The binder intensity (Figure 11 a) is intended for evaluating the cost perspective. In the present investigation, the index is calibrated to represent the amount of binder necessary to achieve 1 MPa compressive strength. Hence, it is favourable to achieve as low binder intensity index (bi_{cs}) as possible. The solid line in the figure represents the average binder intensity (*Average* bi_{cs}) of the results in the included papers. Also, the line representing a purposed future international benchmark of bi_{cs} for normal concrete according to [18], is depicted. This benchmark is 5.0 kg binder per m^3 normal concrete per 1 MPa compressive strength.

A general trend observable from all the data in Figure 11 a, is that the binder intensity decreases (favourable) as the compressive strength increases. The binder intensity (kg/m^3 per MPa) of 981 collected international data presented by Damineli et al. (2010) [18] showed similar results. Damineli et al. also observed that for normal concrete with compressive strength above 60 MPa, the binder intensity was normally between 5 and 10 kg/m^3 per MPa. A minimum binder intensity was observed to reach a plateau of around 5.0 kg/m^3 per MPa. Results of the present literature review confirm that the tendency Damineli et al. found for high strength standard concrete is also a tendency for UHPC, which is illustrated in Figure 11 a.

The results for the UHPC material with cement substitution up to 40% found in the present investigation, performs correspondingly to the average of the results identified from the literature review. It is observable from Figure 11 that high temperature (*heat treatment*) curing seems favourable for the binder efficiency index. However, this index does not caretake the extra cost and other expenses related to this special curing regime. Increasing compressive strength through other measures like improving the particle packing and selecting high-quality aggregate would benefit the binder intensity index. The potential for both is demonstrated in this paper.

For most UHPC compositions identified in the present literature review, the binder intensity is not below the future benchmark bi_{cs} (5.0 kg/m^3 per MPa). For UHPC, a bi_{cs} below 5 seems so far rarely to have been achieved, even for high replacement levels of cement. However, most investigations seem to focus on substituting cement with alternative binders, which would not benefit this index. The approach that is tested in the present investigation, reveals that cement can be successfully substituted with inert materials, which benefits the binder intensity index. This is visualised in Figure 11 a, where the highest markers for the present investigation represent the reference mixes, while the lower represents the stepwise cement substitution.

One method for further reducing the total binder content might be to reduce the high consumption of microsilica. The microsilica content is kept constant at 25 mass-% of the cement in the reference mix, through all replacement levels. A reduction of the microsilica would contribute to lower binder intensity if the compressive strength were maintained. However, the D_{50} of the microsilica particles used in this investigation are on average 1/100 of the cement particles. Thus, microsilica is anticipated to contribute significantly to the dense particle packing, and consequently to the compressive strength. Microsilica contributes more to the cost of UHPC than cement [7], and optimization would benefit the cost perspective, vaguely illustrated through the binder intensity index. Optimisation of the microsilica content of UHPC regarding the cost perspective remains to be investigated. An improvement of the binder intensity index might be to weigh the cost of each binding material.

Figure 11 b presents the estimated CO_2 intensity of the included UHPC mixes identified in the literature review, compared to the results obtained in the present experimental investigation. The CO_2 intensity index measures the CO_2 emission per 1 MPa compressive strength. Thus, again it is favourable to perform as low on the y-axis as possible (low ci_{cs}-index). The CO_2 intensity of the collected international studies presented by Damineli et al. (2010) [18], claimed that the minimum CO_2 intensity is 1.5 kg/m^3 per MPa for all ranges of concrete strength. The corresponding results from the investigations identified from the present literature review are illustrated in Figure 11 b. With few exceptions, all results are far higher than what was claimed possible by Damineli et al. It seems that achieving both required strength values for UHPC (> 120 MPa) and low CO_2 intensity, is difficult.

The ci_{cs} index achieved in the present investigation is above the average of the results from the literature review. But more important (since the overall score is manipulable by other measures like increasing the aggregate quality); the results show that the cement substitution reduces the Global Warming Potential (GWP) given by the CO_2 intensity index. In the present investigation, the index was improved from around 7 (reference mix) to around 4.5 (40% substitution level). The further reduction would be obtainable by substituting cement with high-quality SCMs since these materials are often industrial by-products (temporarily) considered to be without CO_2 load. However, these kinds of measures would harm the cost efficiency, illustrated through the binder intensity index. It is, of course, beneficial to reduce the environmental impact of any material and activity at all levels. Consequently, measures like the one presented in this investigation prove it environmentally beneficial to substitute cement with inert materials. Thus, comparing material development efforts through e.g., the CO_2 intensity index is meaningful. However, to understand the full environmental implications potentially related to the use of UHPC, it is necessary to compare full LCAs of alternative solutions. The main contribution from the use of UHPC is expected to stem from the possibility to construct more slender structures, consequently reducing the overall material consumption while also improving durability. This might be a powerful approach to reduce the CO_2 emissions from the concrete industry, in line with Mehta's tool number 1 [3].

5. CONCLUSION

The following conclusions are suggested based on the discussion above:

1) It was shown possible to substitute up to 40% of the cement in a typical locally produced UHPC mix, without significantly reducing the compressive strength or the flexural tensile strength. This is well corresponding with a variety of reports from other investigations on cement substitution, identified from a structured literature review which is also performed in the present work.
2) The measure that separates the present investigation from most other reported results, is that the cement was substituted with an inert material. Most investigations utilise materials with binding properties, often pozzolans. However, the effect on compressive strength from cement substitution found in this investigation is fully corresponding to those reported through the literature. Neither the flexural tensile strength was found to be reduced through the cement substitution. However, in practical use, UHPC is given flexural strength mainly through the inclusion of fibres. Whether the cement substitution would influence the flexural strength through manipulating the distribution or orientation of the fibres, has not been evaluated in this approach. Both the inert material used in the present investigation and most other materials used correspondingly in other investigations are industrial by-products considered to benefit circular economy and have low CO_2 emissions.
3) Investigations on cement substitution always raise questions on related issues, like whether to keep *w*/*c*-ratio or *w*/*b*-ratio constant, and how to keep SP constant (constant SP content, or SP/C constant). Also, the effect of the curing regime at elevated temperature and the use of different standards are in question. All of these were evaluated through the present investigation and found not to have a considerable impact on the results.
4) Two indices reported in the literature for measuring respectively "binder intensity" (cost perspective) and "CO_2 intensity" (Global Warming Potential perspective) have been identified and utilised to evaluate the present results towards those already reported in the research community. Substitution of cement by an inert material is found to improve significantly on the score of both indices and benchmark the performance towards corresponding results identified from the literature. The scores on both indexes are also found to be manipulable through other measures than cement (or binder) substitution.
5) Two commonly used indices are utilised in this paper; the binder intensity index (bi_{cs}) and CO_2 intensity index (ci_{cs}). Shortcomings regarding both are discussed: i) The binder intensity index is intended for evaluating the cost perspective. Still, all binder materials are treated equally, disregarding that some are low-cost waste materials while others have cost several times that of Portland cement. An improvement of the binder efficiency index might be to weigh the different binder materials according to the cost level. ii) The CO_2 intensity index includes only the emissions from cement. In the special case of UHPC, near 50% of the CO_2 emissions stems from micro steel fibres. Thus, it is suggested that the CO_2 intensity index is expanded to also comprise the CO_2 emissions from the fibres.

   The scores on both indices are found to be manipulable through other measures than cement (or binder) substitution. However, this is considered not to be a shortcoming, rather an opportunity that should be investigated through further research.

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Paper IV

The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review

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Review article

The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review

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HIGHLIGHTS

- Effects of fibres on compressive and tensile strength of UHPC are reviewed.
- A variety of specimen geometries, sizes and procedures are applied.
- Fibres have potential to improve the tensile strength of UHPC.
- Effects on tensile strength depend on fibre content, type and hybrid combination.
- The influence of fibres on compressive strength is questionable.

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ABSTRACT

This review paper presents the effects of steel fibre reinforcement regarding the compressive and tensile strength of UHPC. The intention is to give an overview of the research field and supply guidance for future research. Relevant papers were identified through a systematic literature search. An accumulation of the results shows that fibres have potential for improving the tensile strength of UHPC. The effect depends on fibre content, type and hybrid combinations. The effect of fibres on compressive strength seems to be questionable. Variations in test specimen geometry and other factors might also influence the results.
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Contents

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1. Introduction

Ultra High Performance Concrete (UHPC) is an advanced cement-based composite material with improved mechanical and durability properties compared to conventional concrete [1]. There is an increasing interest for research and commercial use of UHPC. Although applications of UHPC has been successfully demonstrated in several countries, widespread use is still limited. Several obstacles are known, including lack of understanding of the structural behaviour, procedures for material characterisation and generally accepted design codes. One driving force for increased use is the potential to design low-weight and slender structures [2]. Others are reduced cost and environmental footprint and low maintenance requirements.

The existing codes for production and structural use of conventional concrete are not fully applicable for UHPC. Design guidelines or recommendations for UHPC are currently emerging in several countries, including Germany [3], Switzerland [4], Australia [5], Canada [6], Spain [7] and Japan [8]. Each of these nationally emerging design guidelines has different requirements for material characterisation, and each approaches the design process differently. The Association Française de Génie Civil (AFGC) published design recommendations for UHPC already in 2002 [9]. In 2016, a development of this was adopted in France as a national appendix [10] to the design code for conventional concrete (Eurocode 2).

An essential constituent in UHPC is discontinuous fibre reinforcement. The inclusion of fibres is necessary to impose the ductility in compression, required for structural safety. Fibres prevent a brittle behaviour and might also improve several other material properties, e.g. provide exploitable tensile strength and increase the energy absorption capacity. Multiple types of fibres are used, varying in size, shape and material. Numerous factors cause variations in the distribution and orientation of the fibres, including the rheological properties of the fresh UHPC, the placement methods and the geometrical conditions shaped by the formwork. Variations in fibre content, geometry, combination, distribution and orientation are all central contributors to making the structural design of UHPC complex. Fibres are also one of the main reasons for the high unit cost and carbon footprint of UHPC. Consequently, increasing the knowledge on the effects of fibre reinforcement is an essential step towards the development of commonly accepted design codes and widespread use of UHPC.

Some review papers cover the mechanical properties of UHPC [2,11–13], but none focus specifically on the effects of steel fibre reinforcement on compressive and tensile strength. This study aims at contributing by presenting the state-of-the-art in research, based on a literature review. A preliminary version of this paper was presented and discussed on the 5th International Federation of Structural Concrete (fib) Congress in Melbourne 2018 [14]. The preliminary paper demonstrated that the research conclusions diverge considering the effects of fibres on the mechanical properties of UHPC. Enriched by the discussion at the fib Congress, this paper presents the results from a comprehensive literature review on the impact of steel fibre reinforcement on the compressive and tensile strength of UHPC.

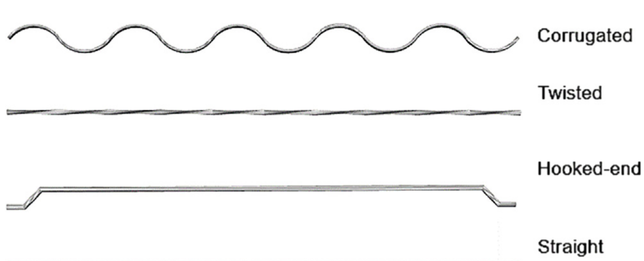


Fig. 1. Some frequently used steel fibres.

2. Fibre reinforcement in concrete

More than 60 years have passed since fibre reinforced concrete (FRC) were introduced in modern times [15]. However, the concept of strengthening brittle materials with fibres (e.g. straws and horsehair) was developed for more than a thousand years ago [16]. Multiple types of fibre reinforced concretes are now used for various applications in the construction industry [17]. One of them is fibre reinforced UHPC, often denoted UHPFRC.

One aim of using fibres is to reduce the brittleness of the cementitious matrix. Fibres can influence cracking behaviour, control the brittle fracture process and provide post-cracking strength and toughness [15]. The fibre reinforcement can be characterised by differences in material (steel, mineral or synthetic fibres), geometry, aspect ratio (fibre length divided by fibre diameter) and mechanical properties [18]. A variety of geometrical forms and lengths exists, from different sizes of straight fibres to various deformed fibres (Fig. 1), including hooked-end, corrugated and twisted fibres. The fibre content is normally stated as the volume fraction or percentage (vol.-%). Smaller fibre geometry will give a higher number of fibres than larger geometry, for the same volume fraction. The high number of smaller fibres are more densely distributed in the cementitious matrix and can efficiently control the development of microcracks, while longer fibres can improve the ultimate strength by being able to control the propagation of macrocracks [16]. The fibre volume fraction in conventional FRC often ranges from 0.25 up to 2 vol-% [19], while commercially available UHPC-mixes have been reported to contain between 2 and 6 vol-% of fibres [1]. Both geometrical differences (shape, length, aspect ratio) and the fibre content are expected to affect the mechanical properties, as discussed later in this review paper.

3. Review methodology

The objective of this literature review was to identify the effects of steel fibre reinforcement on compressive and tensile strength of UHPC. The review focused on the following questions:

- What experimental methods are used to find the impact of fibre reinforcement on compressive and tensile strengths?
- What are the effects of different fibre contents, types and hybrid combinations on the compressive and tensile strength?

3.1. Search terms and search strategies

Relevant research papers were found through a systematic literature search in Scopus and Web of Science (WoS). Both databases are widely used in engineering. Three main search categories were

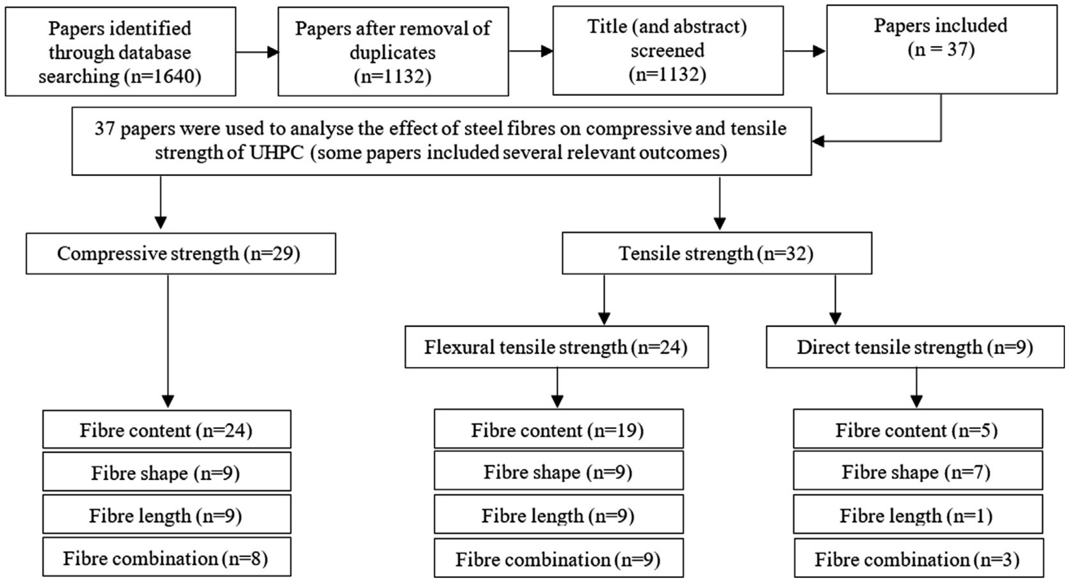


Fig. 2. Flow chart of the search process and results.

Table 1
Exclusion and inclusion criteria.

Exclusion criteria	Inclusion criteria
- Non-English language - Other document types than research papers (e.g. books, book-sections, reviews) - Numerical or analytical studies - Structural members (e.g. slabs, beams) - Other loadings than compressive and tensile strength (e.g. impact, blast, shear, fatigue) - Non-steel fibre reinforcement - Investigations of extreme conditions or curing conditions or autoclave curing	- English language - Journal or conference papers - Experimental research paper - Tensile strength or compressive strength - Investigations on the effect of fibre content, fibre shape, fibre length or hybrid fibre combinations

identified: i) Ultra High Performance Concrete, ii) steel fibre reinforcement and, iii) compressive and tensile strength. A block of keywords represented each of these search categories. The different search terms within each search block were combined with the Boolean operator "OR". The keywords (including synonyms) were refined by finding indexed keywords or author keywords in Scopus and WoS. Each search block was searched separately, and in the end, the search blocks were combined with the Boolean operator "AND". The search was done in Title, Abstract and Keywords (referred to as "Topic" in WoS). The search was updated in November 2019. Fig. 2 shows the flow chart of the search process and results.

After removal of duplicates (using EndNote) and studies in other languages than English, 1132 papers were identified (conference and journal papers). The titles and/or abstracts of these papers were assessed against the inclusion and exclusion criteria (Table 1). Only papers fulfilling the inclusion criteria were included for further analysis.

3.2. Data extraction and analyses

Thirty-seven papers were finally included. Relevant information from the included research papers was extracted and divided into different categories (Fig. 2). The two main categories were: "Compressive strength" and "Tensile strength", the latter covering both "Flexural tensile strength" and "Direct tensile strength". Each of those categories was then divided into four sub-categories: i) "Fibre content", ii) "Fibre length", iii) "Fibre shape" and iv) "Fibre combination". Fibre combination refers to the use of hybrid fibre reinforcement. Relevant strength values were also extracted and analysed. Some papers had only presented the results in diagrams, not including exact values. In these cases, values were recorded as readouts from the diagrams. In cases where different test ages were presented, 28 days-strength results were extracted. For the papers investigating various parameters (e.g. w/b-ratios, type of binders, amount of superplasticiser), one parameter was chosen and kept constant.

4. Results

4.1. Properties of fibre reinforcement

Table 2 list all included papers with information about the fibre reinforcement and the measured properties (compressive strength, flexural tensile strength and direct tensile strength).

Several investigations examined the effect of fibre content by increasing the content from 0 up to 2–3 vol-% (Table 2). The effect of fibres above 4 vol-% was studied in only five of the investigations [20,28,33,38,41]. Most of the papers have reported steel fibre tensile strengths above 2000 MPa [20,23,27,29,31,33–37,39,40,42,43,45–56]. Many have investigated the effect of fibre shape [27,29,34,36–38,40,46–48,50,52–54,56], using straight micro fibres as a reference and compared it to different types of deformed fibres (hooked-end, corrugated, twisted and spiral) – all in different lengths and diameters. Amongst the deformed fibres, hooked-end with a length of 30 mm and a diameter 0.3–0.6 mm were frequently studied [26,27,29,32,34,36,38,40,43,46,47,52–55]. In some studies, micro hooked-end and corrugated fibres were investigated [23,36,37,48,50]. The most frequently studied fibre type were straight micro fibres with a length of 12–13 mm and a diameter of around 0.2 mm [20–22,24,27,30,31,33–56]. Hybrid combinations were reported in eleven of the included papers [27,34,37,38,40,43,44,49,52,55,56], while the effect of single fibre combination was reported in twenty-six [20–26,28–33,35,36,39,4

Table 2
Fibre characteristics of the included research papers.

Author(s) (year)	Relevant properties	Fibre volumes	Fibre combination	Fibre shape	Aspect ratio (l/d)*	Fibre tensile strength [MPa]	Ref.
Abbas et al. (2015)	Compressive strength, flexural tensile strength	0%, 1%, 3%, 6%	Single	Straight	8/0.2	2850	[20]
					12/0.2	2850	
					16/0.2	2850	
Allena et al. (2012)	Compressive strength, flexural tensile strength	0%, 1.5%	Single	Straight	13/**	**	[21]
Alsalman et al. (2017)	Compressive strength	0%, 3%	Single	Straight	12.7/0.2	**	[22]
Arel (2016)	Compressive strength	1.9%	Single	Hooked-end	8/0.2	2500	[23]
					13/0.2	2500	
					16/0.2	2500	
Arora et al. (2019)	Compressive strength, flexural tensile strength	0%, 1%, 3%	Single	Straight	13/0.2	1900	[24]
Bae et al. (2016)	Compressive strength	0%, 0.5%, 1%, 2%	Single	**	**	**	[25]
Chkheiwer & Kadim (2019)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%, 1.5%, 2%, 2.5%	Single	Hooked-end	30/0.5	850	[26]
Chun & Yoo (2019)	Direct tensile strength	2%	Single + Hybrid	Straight	13/0.2	2788	[27]
					30/0.3	2580	
				Hooked-end	30/0.375	2900	
				Twisted	30/0.3	2428	
Erdoğdu et al. (2019)	Compressive strength, flexural tensile strength	0%, 3%, 4%	Single	Straight	6/0.15	1100	[28]
Gesoglu et al. (2016)	Compressive strength, flexural tensile strength	0%, 0.25%, 0.5%, 0.75% 1%, 1.5%, 2%	Single	Straight	6/0.16	2250	[29]
				Hooked-end	30/0.55	1345	
Hassan et al. (2012)	Compressive strength, direct tensile strength	0%, 2%	Single	Straight	13/0.2	**	[30]
Ibrahim et al. (2017)	Compressive strength, flexural tensile strength	0%, 0.65%, 1.4%, 2%	Single	Straight	13/0.2	2160	[31]
Jin et al. (2018)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Hooked-end	30/0.6	1100	[32]
Kazemi & Lubell (2012)	Compressive strength	0%, 2%, 3%, 4%, 5%	Single	Straight	13/0.2	2500	[33]
Kim et al. (2011)	Flexural tensile strength	1%, 1.5%, 2%, 2.5%	Single + Hybrid	Straight	13/0.2	2788	[34]
					30/0.3	2580	
				Hooked-end	30/0.375	2311	
					62/0.775	1891	
				Twisted	30/0.3	2428	
Le Hoang & Fehling (2017)	Compressive strength, direct tensile strength	0%, 1.5%, 3%	Single	Straight	9/0.15	2500	[35]
					13/0.175	2500	
					20/0.25	2500	
Liu et al. (2016)	Compressive strength, direct tensile strength	0%, 1%, 1.75%, 2.5%	Single	Straight	13/0.2	2940	[36]
				Spiral	13/0.2	2860	
				Hooked-end	13/0.2	2940	
					30/0.6	1890	
Ma et al. (2019)	Compressive strength, flexural tensile strength	2.5%	Single + Hybrid	Straight	13/0.2	2850	[37]
				Hooked-end	13/0.2	2850	
Meng & Khayat (2018)	Compressive strength, flexural tensile strength, direct tensile strength	0%, 1%, 2%, 3%, 4%, 5%	Single + Hybrid	Straight	13/0.2	1900	[38]
				Hooked-end	30/0.5	1900	
Park et al. (2017)	Compressive strength, flexural tensile strength	0.5%, 1%, 1.5%, 2%	Single	Straight	13/0.2	2788	[39]
					19.5/0.2	2500	
					30/0.3	2580	
Park et al. (2012)	Direct tensile strength	1%,1.5%, 2%, 2.5%	Single + Hybrid	Straight	13/0.2	2788	[40]
					30/0.3	2580	
				Hooked-end	30/0.375	2311	
					62/0.775	1891	
				Twisted	30/0.3	2428	
Pourbaba et al. (2018)	Compressive strength	0%, 1%, 2%, 3%, 4%, 5%, 6%	Single	Straight	13/0.16	**	[41]
Prem et al. (2015)	Compressive strength, flexural tensile strength	0%, 2%, 2.5%	Single	Straight	6/0.16	2000	[42]
					13/0.16	2000	
Ryu et al. (2012)	Compressive strength, flexural tensile strength	2%	Hybrid	Straight	13/0.2	2700	[43]
					16.3/0.2	2700	
					19.5/0.2	2700	
				Hooked-end	30/0.375	2311	

Table 2 (*continued*)

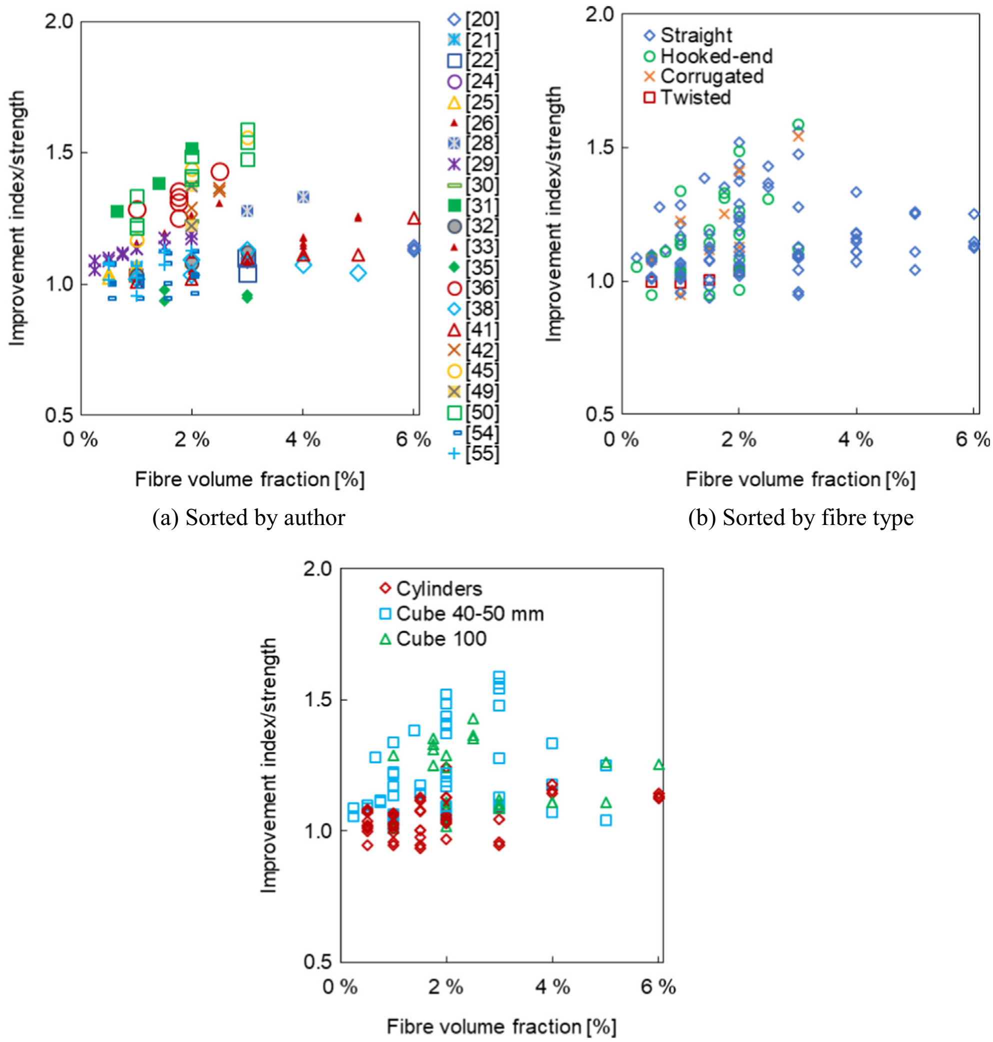
Author(s) (year)	Relevant properties	Fibre volumes	Fibre combination	Fibre shape	Aspect ratio (l/d)*	Fibre tensile strength [MPa]	Ref.
Ryu et al. (2011)	Compressive strength, flexural tensile strength	1.5%, 2%	Hybrid	Straight	13/0.2	**	[44]
					16.3/0.2	**	
					19.5/0.2	**	
Wang & Gao (2016)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Straight	13/0.2	2850	[45]
Wille et al. (2014)	Direct tensile strength	1.5%, 2%, 2.5%, 3%	Single	Straight	13/0.2	2600	[46]
				Hooked-end	30/0.38	2900	
				Twisted	18/0.3	2100	
Wille et al. (2011)	Direct tensile strength	1.5%, 2%, 2.5%	Single	Straight	13/0.2	2600	[47]
				Hooked-end	30/0.38	2900	
				Twisted	30/0.3	2100	
					30/0.3	3100	
Wu et al. (2018)	Flexural tensile strength	0%, 2%	Single	Straight	13/0.2	2800	[48]
				Hooked-end	13/0.2	2800	
				Corrugated	13/0.2	2800	
Wu et al. (2017)	Compressive strength, flexural tensile strength	0%, 2%	Single + Hybrid	Straight	6/0.2	2800	[49]
					13/0.2	2800	
Wu et al. (2016)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Straight	13/0.2	2800	[50]
				Hooked-end	13/0.2	2800	
				Corrugated	13/0.2	2800	
Yoo et al. (2016)	Flexural tensile strength	2%	Single	Straight	13/0.2	2500	[51]
					16.3/0.2	2500	
					19.5/0.2	2500	
Yoo et al. (2017 a)	Compressive strength, flexural tensile strength	2%	Single + Hybrid	Straight	13/0.2	2788	[52]
					19.5/0.2	2500	
				Hooked-end	30/0.38	2500	
				Twisted	30/0.3	2428	
Yoo et al. (2019)	Direct tensile strength	2%	Single	Straight	13/0.2	2788	[53]
				Hooked-end	30/0.375	2900	
					25/0.375	2900	
				Twisted	30/0.3	2428	
Yoo et al. (2017b)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%, 1.5%, 2%	Single	Straight	13/0.2	2788	[54]
					19.5/0.2	2500	
					30/0.3	2580	
				Hooked-end	30/0.38	2500	
				Twisted	30/0.3	2428	
Yoo et al. (2017c)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%,1.5%, 2%	Single + Hybrid	Straight	13/0.2	2788	[55]
					19.5/0.2	2500	
					30/0.3	2580	
Zhang et al. (2018)	Compressive strength, flexural tensile strength	2%	Single + Hybrid	Straight	13/0.2	2940	[56]
				Hooked-end	20/0.25	2860	
					20/0.35	2810	

*Length/diameter in mm **not stated

Table 3
Standards and test specimen geometry used for compressive strength tests.

Author(s) (year)	Standard	Specimen size	Ref.
Abbas et al. (2015)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International)	75 mm × 150 mm cylinders	[20]
Allena et al. (2012)	BS 1881-116, Testing concrete. Method for determination of compressive strength of concrete cubes	50 mm cubes and 100 mm cubes	[21]
Alsalman et al. (2017)	ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm cubes 75 mm × 150 mm cylinders	[22]
Arel (2016)	EN 12390-3:2009-7, Testing hardened concrete. Compressive strength of test specimens [59] (European standard)	150 mm cubes	[23]
Arora et al. (2019)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [60] (ASTM International)	75 mm × 150 mm cylinders	[24]
Bae et al. (2016)	KS F 2405, Standard Test Method for Compressive Strength of Concrete [62] (Korean standard)	100 mm × 200 mm cylinders	[25]
Chkheiwer & Kadim (2019)	**	Cube (size not stated)	[26]
Erdoğdu et al. (2019)	EN 196-1:2016, Methods of testing cement - Part 1: Determination of strength [70] (European standard)	40 mm cubes*	[28]
Gesoglu et al. (2016)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International)	50 mm cubes	[29]
Hassan et al. (2012)	Purposed method	50 mm × 100 mm cylinders	[30]
Ibrahim et al. (2017)	** Loading rate given	50 mm cubes	[31]
Jin et al. (2018)	CECS 13:2009, Standard test methods for fiber reinforced concrete [65] (Chinese standard)	100 mm cubes	[32]
Kazemi & Lubell (2012)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International) ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm, 75 mm and 100 mm cylinders 50 mm and 100 mm cubes	[33]
Le Hoang & Fehling (2017)	EN 12390-3:2009-7, Testing hardened concrete. Compressive strength of test specimens [59] (European standard)	150 mm × 300 mm cylinders	[35]
Liu et al. (2016)	GB/T 31387-2015, Reactive powder concrete [66] (Chinese standard)	100 mm cubes	[36]
Ma et al. (2019)	EN 196-1, Methods of testing cement—Part 1: Determination of strength [71] (European standard)	40 mm cubes*	[37]
Meng & Khayat (2018)	ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm cubes	[38]
Park et al. (2017)	** Loading rate given	100 mm × 200 mm cylinders	[39]
Pourbaba et al. (2018)	**	100 mm cubes	[41]
Prem et al. (2015)	ASTM C1609, States that this standard is used: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	100 mm cubes	[42]
Ryu et al. (2012)	KS F 2405, Standard Test Method for Compressive Strength of Concrete [62] (Korean standard)	100 mm × 200 mm cylinders	[43]
Ryu et al. (2011)	**	**	[44]
Wang & Gao (2016)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	40 mm cubes*	[45]
Wu et al. (2017)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	40 mm cubes*	[49]
Wu et al. (2016)	** Loading rate given	40 mm cubes*	[50]
Yoo et al. (2017 a)	**	**	[52]
Yoo et al. (2017b)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [60] (ASTM International)	100 mm × 200 mm cylinders	[54]
Yoo et al. (2017c)	** Loading rate given	100 mm × 200 mm cylinders	[55]
Zhang et al. (2018)	GB/T 31387-2015, Reactive powder concrete [66] (Chinese standard)	100 mm cubes	[56]

*Specimens are the remaining parts of prisms, after splitting through flexural tensile strength test **Not stated.



(a) Sorted by author (b) Sorted by fibre type

(c) Sorted by specimen geometry

Fig. 3. Improvement index for compressive strength of fibre reinforced UHPC as a function of fibre content. The improvement index is calculated following Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete relative to that of the unreinforced concrete sample. The data is obtained from all relevant research papers in Table 2.

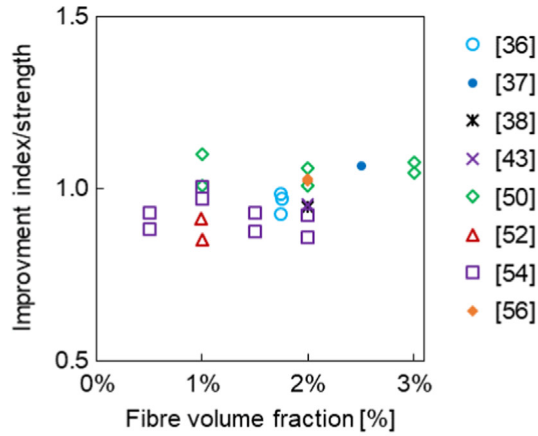
1,42,45–48,50,51,53,54]. The results from all those are summarised and discussed in the following.

4.2. Compressive strength

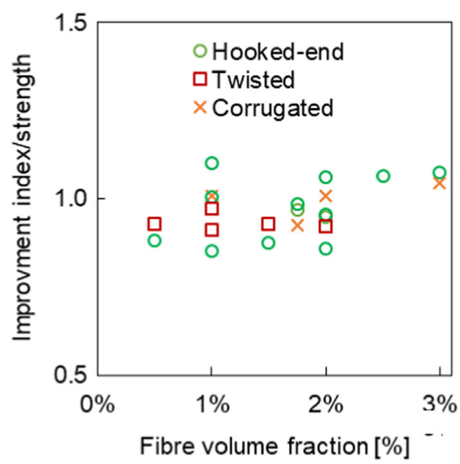
4.2.1. Test setup

For compressive strength measurements, cylinders or cubes are exposed to increasing compressive load until failure. Various standards regulate the size of the test specimens and the loading rates for conventional concrete. These procedures are often appropriate for UHPC, sometimes with small modifications and requirements [1]. The size of cubes used for compressive testing varies between the included studies; from small cubes (40–50 mm) [21,22,28,29,31,33,37,38,45,49,50] to larger ones (100–150 mm) [21,23,32,33,36,41,42,56]. Also cylindrical specimens of different sizes were used to test compressive strength [20,22,24,25,30,33,35,36,39,43,54,55]. The size variations in the test specimens have been reported to influence the compressive strength results [57,58]. A study by Josef and Bílý [57] showed that size dependency decreases with increasing strength and varies for different mix composition, making the issue of size effect rather complicated. Whether differences in size and geometry influence the impact of fibre reinforcement is not fully answered in the included papers. Only three of the studies have investigated the effect of using different size of cubic samples (50 mm and 100 mm cubes) [21] and cylinders [22,33].

Table 3 shows the different test standards and test specimen geometry used to measure compressive strength. In most investigations, the measurements of the compressive strength were done according to a standardised procedure. This might be the Eurocode (EN 12390–3:2009–7) [59], the ASTM standard C39 [60,61], the Korean standard (KS F 2405) [62] or the Chinese standard (GB/T 17671-1999) [63]. In other studies, standards for fibre reinforced concrete was used; the ASTM standard C1609 [64] or the Chinese standard CECS 13:2009 [65]. Two studies have used a Chinese standard for Reactive Powder Concrete (GB/T 31387-2015) [66]. None of the studies used a standard developed explicitly for compressive strength measurements of UHPC. The French standard for the production of UHPFRC [67] and Swiss recommendation for UHPFRC [4] are both referring to the European standard for conventional concrete, EN 12390-3 [59]. ASTM has published a standard for practice on production and testing of UHPC [68]. Also, this standard refers to a test method for conventional concrete, ASTM C39/C39M *Standard Test Method for Compressive Strength of Cylindrical Concrete*



(a) Sorted by author



(b) Sorted by fibre type

Fig. 4. Improvement index for deformed fibres on compressive strength as a function of fibre content. The improvement index is calculated for different deformed fibres relative to 13 mm straight fibres for corresponding volume fractions. The data is obtained from all relevant research papers presented in Table 2.

Specimens [60]. Other standards for UHPC might also be referring to standards for conventional concrete. However, this remains unknown to the authors of the present paper.

4.2.2. Effects of steel fibres on compressive strength

Compressive strength is one of the most important and frequently measured properties of UHPC [1], as it is for conventional concrete. Inclusion of fibres is essential to avoid explosive behaviour at failure [22,25,30,35,55]. The compressive behaviour of UHPC with fibres is not substantially different compared to conventional concrete. The main difference is the improved compressive strength and stiffness. The compressive strength is dependent on the constituent materials, mix proportions, curing conditions [1] and fibre content (Fig. 3).

Twenty-nine of the included research papers reported the effect of steel fibres on compressive strength (Fig. 2). Fig. 3 shows a comparison of improvement of compressive strength as a function of fibre content, relative to UHPC without fibre reinforcement. All data points are collected from the included papers and are sorted by author (Fig. 3(a)), fibre type (Fig. 3(b)) and specimen geometry (Fig. 3(c)). The influence of fibre content on compressive strength varies between the different studies. Some studies found that inclusion of fibres yielded relatively low levels of influence on compressive strength (<10%) [21,22,35,39]. Arora et al. [24] stated that the compressive strength is highly dependent on the volume of hydration products and the packing density of aggregates. Other investigations found more substantial effects; >50% increase in compressive strength as a result of the inclusion of fibres [31,45,50]. Such an increase might be explained by the ability of the fibres to delay the formation and propagation of cracks [31,45]. By increasing the fibre content, the compressive strength increased accordingly [31,33,41,45,50]. However, at some point, increasing the fibre content could have an adverse effect on the compressive strength. Meng and Khayat [38] reported this effect when the fibre content exceeded 3 vol-%. The negative impact on the compressive strength was explained by fibre agglomeration and entrapped air. Le Hoang and Fehling [35] also experienced fibre agglomeration for the mixes with 3 vol-% of fibres.

The results are also presented sorted by specimen type, to accommodate the aforementioned influence that test specimen geometry might have (Fig. 3(c)). According to this, cylindrical test specimens show little effect on compressive strength, from the inclusion of any volume fraction of fibres. For large cubes (100 mm), a slight increase in compressive strength seems to be the result of the inclusion of fibres. However, this effect seems only to differentiate fibre reinforced from not reinforced UHPC – it does not seem to be a function of fibre fraction. Only small cubes (40–50 mm) seem to benefit from an increase in the volume fraction of fibres up to 3 vol-%. For higher levels, the compressive strength seems to decrease towards the level of the UHPC without fibres. This reduction in compressive strength might be explained by fibre agglomerations and reduced workability, leading to entrapped air. However, a major concern remains on whether some of the demonstrated variations in results can be explained through discussions on test specimen geometry rather than actual fibre effects. Cylinders are generally accepted to represent a more uniaxial stress distribution than cubes. A compressive failure in cubes is more influenced by internal shear stress, both because of the presence of corners and the lower height/cross-section dimension ratio. The most influential objection towards drawing strict conclusions from the comparison between test specimen geometries presented in Fig. 3(c) is, however, all the information that is not included. Differences in factors like constituent materials, mix proportion, and curing regimes might explain more of the differences in test results, than test specimen geometry. The authors of this review article settle with a conclusion that there are indications that the test specimen geometry might influence the results from investigations.

Deformed fibres have higher pullout strength than straight, giving them the ability to bridge cracks more effectively [38,56]. Fig. 4 shows the effect of using different shaped fibres relative to using 13 mm straight micro steel fibres. The improved pullout strength is not evident on the compressive strength of UHPC; all papers concluded that the influence of using deformed fibres was within ± 15% (Fig. 4). Liu et al. [36] investigated macro (l = 30 mm) and micro (l = 13 mm) hooked-end fibres and found little difference in compressive strength. Yoo et al. [52] observed a slight increase in compressive strength for straight fibres compared to macro deformed fibres. This effect was explained by the increased number of fibres available to bridge and delay the propagation of microcracks compared to that of deformed macro fibres. In addition to this, a poorer fibre distribution was observed for the deformed fibre types. Low level of influence (±15%) was also shown for differences in fibre length [20,23,35,39,42,49,54,55].

4.3. Tensile strength

4.3.1. Test setups

Three or four-point bending tests are often used to determine the tensile properties of UHPC. These tests are easier to execute than testing direct tensile strength. Due to the fibre reinforcement,

Table 4
Standards and test specimen geometry used for flexural tensile strength tests.

Author(s) (year)	Standard	Specimen size [mm^3]	Ref.
Abbas et al. (2015)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[20]
Allena et al. (2012)	ASTM C78, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) [75] (ASTM International)	Prisms 75 × 100 × 400	[21]
Arora et al. (2019)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 457 Prisms 50 × 65 × 380	[24]
Chkheiwer & Kadim (2019)	**	Prism **	[26]
Erdoğdu et al. (2019)	EN 196-1:2016, Methods of testing cement – Part 1: Determination of strength [70] (European standard)	Prisms 40 × 40 × 160	[28]
Gesoglu et al. (2016)	RILEM 50-FMC/198, Determination of fracture energy of mortar and concrete using three-point bend tests on notched beams [76]	Prisms 70 × 70 × 280 (notched)	[29]
Ibrahim et al. (2017)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 50 × 50 × 300	[31]
Jin et al. (2018)	CECS 13:2009, Standard test methods for fiber reinforced concrete [65] (Chinese standard)	Prisms 100 × 100 × 400	[32]
Kim et al. (2011)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[34]
Ma et al. (2019)	EN 196-1, Methods of testing cement—Part 1: Determination of strength [71] (European standard)	Prisms 40 × 40 × 160	[37]
Meng & Khayat (2018)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	Prisms 76.2 × 76.2 × 304.8	[38]
Park et al. (2017)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[39]
Prem et al. (2015)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	Prisms 70 × 70 × 350 (notched)	[42]
Ryu et al. (2012)	** Loading rate given	**	[43]
Ryu et al. (2011)	** Loading rate given	**	[44]
Wang & Gao (2016)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	Prisms 40 × 40 × 160	[45]
Wu et al. (2018)	** Loading rate given	Prisms 40 × 40 × 160	[48]
Wu et al. (2017)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	Prisms 40 × 40 × 160	[49]
Wu et al. (2016)	**Loading rate given	Prisms 40 × 40 × 160	[50]
Yoo et al. (2016)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[51]
Yoo et al. (2017 a)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[52]
Yoo et al. (2017b)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[54]
Yoo et al. (2017c)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[55]
Zhang et al. (2018)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[56]

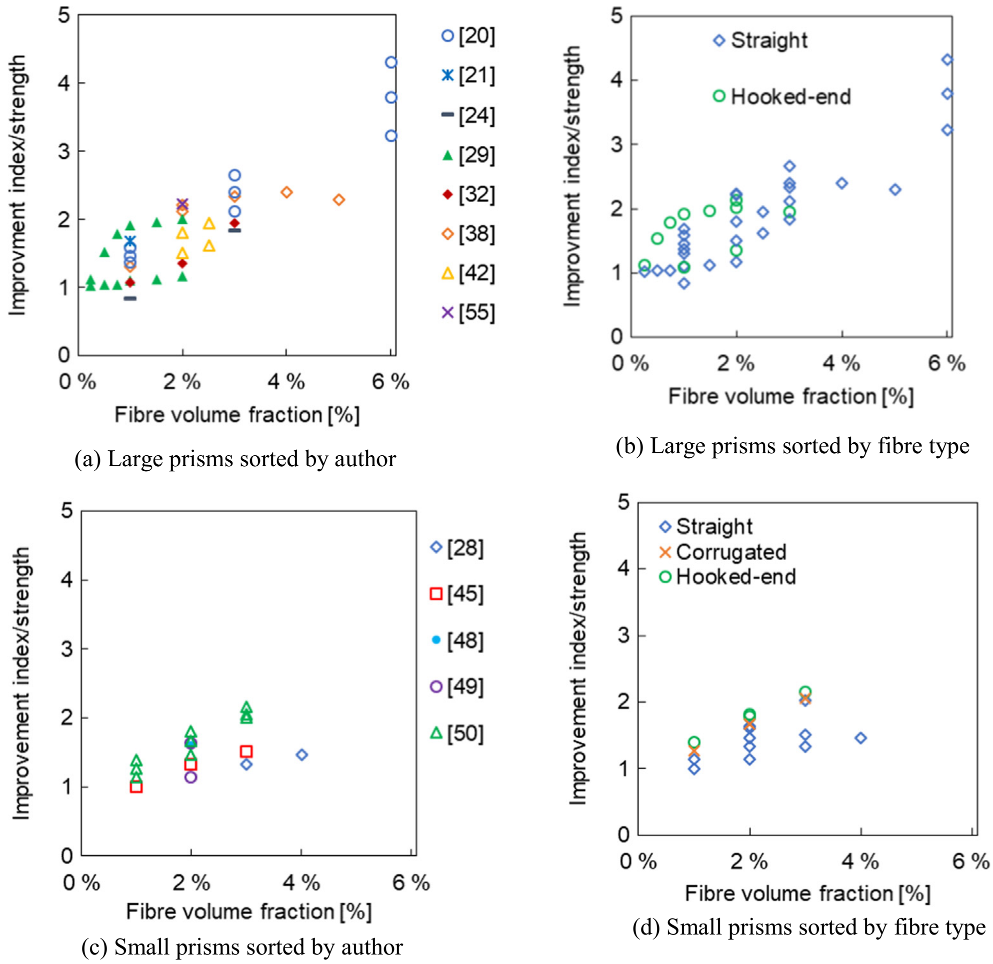
*Span length **Not stated.

Table 5
Standards and test specimen geometry used for direct tensile strength tests.

Author(s) (year)	Standard	Specimen size* [mm^2]	Ref.
Chun & Yoo (2019)	According to recommendations from JSCE [77]	Dog-bone 30 × 13	[27]
Hassan et al. (2012)	No standard, test setup described	Dog-bone 50 × 26	[30]
Le Hoang & Fehling (2017)	No standard, Leutbecher (2008) [78]	Prisms 40 × 40 (notched)	[35]
Liu et al. (2016)	No standard, Park et al. (2012) [40]	Dog-bone 100 × 50	[36]
Meng & Khayat (2018)	No standard, Meng & Khayat (2016) [79]	Dog-bone 50 × 25	[38]
Park et al. (2012)	No standard, loading rate and test setup described	Dog-bone 100 × 50	[40]
Wille et al. (2014)	AASHTO T 132–87 Standard Method of Test for Tensile Strength of Hydraulic Cement Mortars [80] and Sujivorakul (2002) [81]	Dog-bone 25 × 25	[46]
Wille et al. (2011)	According to Sujivorakul and Naaman [82]	Dog-bone 50.8 × 25.4	[47]
Yoo et al. (2019)	According to recommendations from JSCE [77]	Dog-bone 30 × 13	[53]

*Cross-sectional testing area.

UHPC can exhibit considerable tensile strength compared to conventional concrete, even after first-cracking. The capacity of both pre- and post-cracking strength are central properties to measure. Hence, standards for conventional concrete are less applicable for measuring the tensile strength of UHPC, as these standards usually only provide a first-cracking strength value. This shortcoming is, however, expected to change through revisions, e.g. the coming revision of the Eurocode 2 aims at including regulations for structural use of fibres in conventional concrete. The new addition entails values for post-cracking strength. The included papers report the use of different standards to determine the flexural tensile strength (Table 4). ASTM C1609 [64] is the most frequently applied standard for testing the effects of fibres on flexural tensile strength of UHPC (Table 4). This is a standard for fibre reinforced



(a) Large prisms sorted by author

(b) Large prisms sorted by fibre type

(c) Small prisms sorted by author

(d) Small prisms sorted by fibre type

Fig. 5. Improvement index for peak flexural tensile strength of fibre reinforced UHPC as a function of fibre content. The figure differentiates between large test prisms (length ≥ 280 mm) and small test prisms (length ≤ 160 mm). Both are sorted by author and fibre type. The improvement index is calculated in accordance with Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete with respect to that of the unreinforced concrete sample. The data is obtained from the relevant research papers in Table 2.

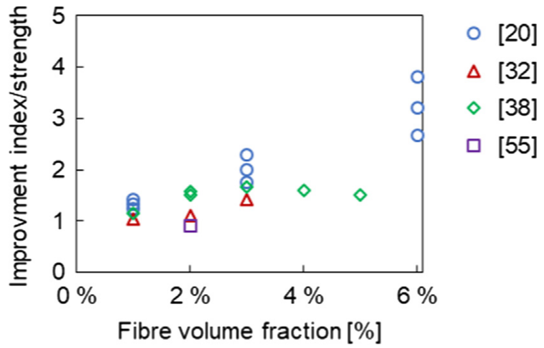
concrete, using large prisms (length > 350 mm). Some studies used standards for testing cement; the Chinese standard, *Method of testing cements – Determination of strength* [63] and the European standard *Methods of testing cement - Part 1: Determination of strength* [70]. Both standards use small prisms of 40 × 40 × 160 mm^3. The use of such small test specimens excludes the use of macro fibres, as there is no room for free orientation of those fibres. In ASTM C1609 [64], the requirement for test specimen size is that both the depth and width should be at least three times the maximum fibre length. Differences in specimen size have been reported to influence the results [57,74]. One main reason is that differences in the specimen geometry might induce differences in fibre distribution [74]. Josef and Bílý [57] collected data in former studies, reporting a clear size dependency for flexural strength. In the following analysis, the results from testing the flexural tensile strength are presented in two separate figures: one for the small prisms and another one for the larger prisms.

Only nine of the research papers investigated the effect of fibre reinforcement using direct tensile strength tests. One reason might be that the test setup is more complicated than the three or four-point bending tests. Table 5 provides information about the test setups for direct tensile strength. The applied test setups are often based on earlier studies, and standards are rarely referenced. Only one investigation applied a standard as the basis for the test setup [46], while two referred to a recommendation [27,53]. The specimen geometry varies between investigations, from one study using prisms to others using differently sized and shaped dog-bones. All variations in geometry are expected to influence the results.

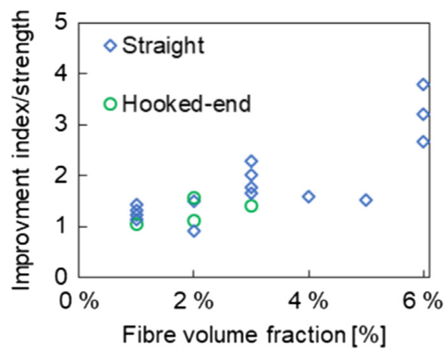
4.3.2. Effects of steel fibres on flexural tensile strength

In structural design codes for conventional concrete, the tensile strength is often considered to be zero. Concrete can resist tensile loads. However, this capacity is low. Fibres enable the concrete to sustain structural integrity towards tensile load after first cracking by bridging cracks and transferring the load across the cracks. Fig. 5 presents the improvement of flexural tensile strength as a function of fibre content, relative to the same UHPC without fibre reinforcement. Due to the expected size dependency on flexural strength [57], the figure differentiates between large test prisms (length ≥ 280 mm) and small test prisms (length ≤ 160 mm). However, the figures do not separate on other differences between investigations, like constituting materials, mix proportions, curing regimes, etc.

Most studies report an improvement in flexural tensile strength corresponding to an increase in fibre content (Fig. 5). An explanation might be that at higher fibre contents, the fibres are more closely spaced [20]. Consequently, more fibres are spanning each crack [54]. This gives a higher bonding area between the matrix and the fibres [54] and more effective control of crack propagation [20]. Park et al. [39] observed 3 times higher peak strength for

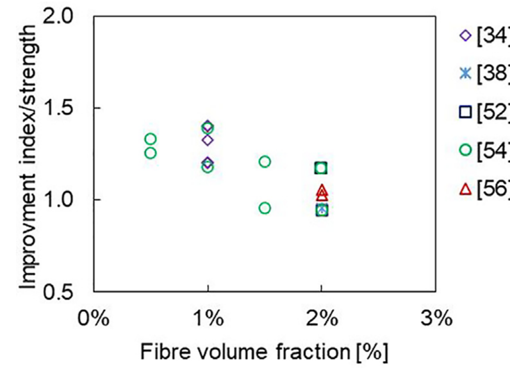


(a) Large prisms sorted by author

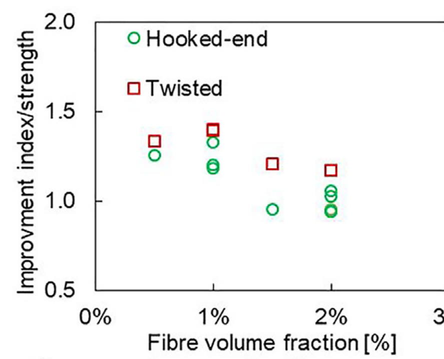


(b) Large prisms sorted by fibre type

Fig. 6. Improvement index for first-cracking flexural tensile strength of fibre reinforced UHPC large prisms (length ≥ 280 mm) as a function of fibre content. The improvement index is calculated in accordance with Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete with respect to that of the unreinforced concrete sample. The data is obtained from the relevant research papers in Table 2.



(a) Large prisms sorted by author



(b) Large prisms sorted by fibre type

Fig. 7. Improvement index for using deformed fibres on flexural tensile strength of large prisms (≥280 mm) as a function of fibre content. The improvement index is calculated by deformed fibres relative to that of 13 mm straight fibres for corresponding volume fractions. The data is obtained from the relevant research papers presented in Table 2.

prisms with 2 vol-% of fibres compared to the ones with 0.5 vol-%. For some studies, the flexural tensile strength did not continuously improve with fibre content [29,38]. Meng and Khayat [38] observed fibre agglomeration for high fibre contents (>3 vol-%), giving an adverse effect on flexural tensile strength. Abbas et al. [20] observed only slightly reduced flowability even for high contents of fibres (up to 6 vol-%) and reported a considerable increase in peak load for high dosages of fibres. This supports the idea that the effects of fibres are influenced by additional factors, like the constituent materials and mix proportion, affecting the rheological properties of the UHPC material. Extended curing time might provide a denser microstructure and a higher degree of hydration around the fibre, creating better bond strength between the fibres and matrix [83]. Greater bond properties can also be achieved by increasing the amount of silica fume [48,84]. The inclusion of silica fume contributes to creating more hydration products, which may reduce the weakness of the Interfacial Transition Zone (ITZ) around the fibres, and hence enhance the bond strength to the fibres [83]. Using more coarse aggregates can give defects in the microstructure, thus lower the bond strength between the fibres and the matrix [36]. Additionally, the use of coarse aggregates may impair the fibre dispersion, giving lower flexural strength.

Fig. 6 shows the improvement of first-cracking flexural tensile strength as a function of fibre content, relative to UHPC without fibre reinforcement. Park et al. [39], Wu et al. [50] and Yoo et al. [55] observed that the first-cracking strength was not influenced by an increase in fibre content or variations in fibre type. According to Yoo et al. [55], the first-cracking strength is strongly dependent on the tensile cracking strength of the cementitious matrix. The fibres are mainly activated after the first-cracking strength is reached [42]. Meng and Khayat [38] found an increase in first-cracking strength as a function of fibre content, but a plateau was identified for volume fractions above 3 vol-%. Some reported improvement in first-cracking strength with fibre content [20,32], even up to 6 vol-% [20]. Abbas et al. [20] explained this effect by the formation of multiple microcracks that delay the growth of macrocracks, leading to higher first-cracking strength.

Fig. 7 compares the effect of using different deformed fibres relative to 13 mm straight micro fibres. Based on the results in Fig. 7, the influence of using deformed fibres varies from 5% decrease [52,54] up to 40% increase [34,52]. However, the effect of using deformed fibres seems to decline after reaching 1 vol-%. As discussed earlier, deformed fibres have higher pullout strength, making them able to bridge cracks more efficiently [38,56]. Kim et al. [34] observed an increase of 20 to 40% for 1 vol-% of three different deformed fibres in comparison to using only micro straight steel fibres. Gesoglu et al. [29] reported flexural tensile strength of notched prisms using 6 mm micro fibres as reference. The study showed that using macro hooked-end fibres (l = 30 mm), improved the flexural tensile strength more efficiently than using the micro straight fibres. However, regardless of the higher pullout strength, some investigations observed reduced capacity or little effect of using 2 vol-% of hooked-end fibres [52,56]. Yoo et al. [52] found that 2 vol-% of twisted fibres (l = 30 mm) increased the flexural tensile strength, while hooked-end (l = 30 mm) fibres gave similar results as using micro straight steel fibres (l = 13 mm). They also observed that using long straight fibres (l = 30 mm) gave even higher flexural tensile strength, although resistance to fibre pullout was lower than for the deformed fibres. Another study by Yoo et al. [54] found that at lower fibre content (≤1 vol-%), deformed fibres showed the highest strength, while at higher fibre dosages

(≥1.5 vol-%) the straight fibres (l = 19.5 mm) performed better. According to Yoo et al. [54], this might be caused by the formation of split cracks in the cementitious matrix. As the fibres are pulled out of the matrix, the high bond strength of the deformed fibres leads to the formation of split cracks in the surrounding matrix. For higher fibre contents, a higher number of split cracks are formed which will weaken the pullout capacity of the nearby fibres, and consequently reduce the capacity.

Wu et al. [48,50] and Ma et al. [37] investigated the effect of variations in fibre shape using small prisms and deformed micro fibres (l = 13 mm). Wu et al. [48,50] observed a noticeable increase for two types of deformed fibres compared to using only straight fibres up to 2 vol-%, while the results from Ma et al. [37] showed a slight decrease of strength for 2.5 vol-% of fibres.

Nine of the included papers reported results on the effect of fibre length on the flexural tensile strength of UHPC [20,34,39,42,49,51,52,54,55]. Several found that the flexural tensile strength can be increased by >20% when using longer straight fibres [39,42,49,51,52,54,55]. Yoo et al. [51] explained this effect with the improved fibre bridging capacity of longer fibres, as the bonding area between the fibre and the matrix is increased. They also reported a higher number of microcracks and lower average cracks spacing for the test beams with longer fibres. Abbas et al. [20] experienced the highest flexural capacity when using the smallest fibres (8 mm). The increased strength can be explained by the increased number of short fibres present to bridge the cracks compared to the number of the longer fibres.

4.3.3. Effects of steel fibres on direct tensile strength

Nine papers presented direct tensile strength results [27,30,35,36,38,40,46,47,53]. Only one investigation reported on the effect of fibre content relative to UHPC without fibres [30]. Hassan et al. [30] observed that the strength was nearly doubled compared to unreinforced UHPC. Four of the studies investigated the effect of fibre content without having unreinforced UHPC as a reference [35,36,46,47]. All investigations found that the peak flexural tensile strength improved with higher fibre content.

Wille et al. [47] reported a considerable improvement in the direct tensile strength by using deformed fibres compared to straight fibres. Park et al. [40] found minor differences for 1 vol-% of two types of hooked-end fibres (l = 30 mm and l = 62 mm) compared to using long straight ones (l = 30 mm), but considerable improvements in tensile strength for the twisted fibres. Liu et al. [36] reported that macro hooked-end fibres (l = 30 mm) gave lower tensile strength than micro hooked-end fibres (l = 13 mm). The decreased capacity was explained with the reduced frictional bonding and the low number of fibres at the same fibre volume fraction. Despite the higher pullout strength for deformed fibres, the results from some investigations showed minor effects (≤15%) of using deformed fibres compared to straight ones [36,38,46]. Yoo et al. [53] observed a considerable decrease in tensile strength for two types of macro hooked-end fibres (>40%) and macro twisted fibres (15%) compared to the straight micro fibres (l = 13 mm). Chun and Yoo [28] reported similar results. This could be explained by fibre congestion and high bond strength causing matrix damage [53].

Only Le Hoang and Fehling [35] reported on the effects of fibre length on direct tensile strength. They achieved the highest tensile strength for the 13 mm fibres compared to 9 mm and 20 mm fibres.

4.4. Hybrid combinations of fibres

Hybrid fibre combinations include both short and long fibres, aiming at synergetic effects benefitting from all the included fibre types. Short fibres bridge microcracks more efficiently, as they are small and numerous for the same fibre volume, whereas the longer fibres have better pullout properties and can more efficiently prevent the propagation of macrocracks [85]. This might minimise the fibre content while maintaining performance.

The method of combining longer and hooked-end fibres with micro fibres was investigated in several of the included research papers [27,34,37,38,40,43,52,56]. Some investigated the hybrid combination of different straight fibres [44,49,55]. Fig. 8 shows the effect of using hybrid combinations of fibres on compressive strength and flexural tensile strength of larger prisms. Several hybrid combinations were found to efficiently improve the flexural tensile strength of UHPC compared to using only one type of fibres (Fig. 8). Meng and Khayat [38] reported that hybrid fibre combinations were more effective in improving the compressive strength than increasing the fibre content. Similar results were shown for flexural tensile strength. In many studies, it was found that although some hybrid combinations improved the flexural tensile strength, others gave similar or lower results [34,43,44,49,52,55]. Disadvantages of deformed macro fibres are the creation of damaging split cracks in the matrix, while straight micro fibres have limited pullout strength [52]. Yoo et al. [52] found an optimal ratio of macro twisted and straight micro fibres to be 1:1. This combination effectively compensated the weakness of both types of fibres. The optimal combination of fibres differs between the studies. Only a few hybrid combinations were found to provide improved flexural tensile strength while also giving increased compressive strength (Fig. 8). Ma et al. [37] observed that only the compressive strength was enhanced for the hybrid combinations. However, most of the included papers showed a relatively low influence (<15%) on compressive strength compared to using 13 mm fibres [38,43,44,49,52,56].

Three papers reported on the effect of using hybrid combinations on direct tensile strength [27,38,40]. Chun and Yoo [27] compared the use of hybrid fibre combination with different macro fibres. They observed that the tensile strength was improved with the increasing replacement ratio of macro hooked-end and twisted fibres by micro straight fibres. However, using only straight macro fibres showed better or similar tensile strength results compared to the various hybrid combinations. Park et al. [40] performed similar experiments, also reporting on the benefits of increasing the content of micro fibres in hybrid systems.

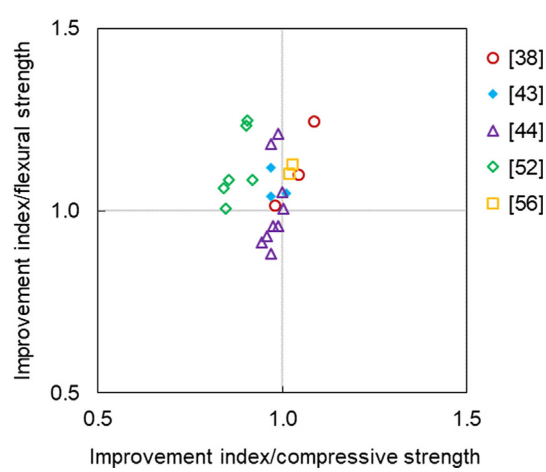


Fig. 8. Improvement index for flexural tensile strength for larger prisms (y-axis) and compressive strength (x-axis) of hybrid fibre reinforced UHPC. The improvement index is calculated by using hybrid fibre combinations relative to only 13 mm straight fibres. The data is obtained from all relevant research papers presented in Table 2. The fibre content is 2–2.5 vol-%.for all datapoints.

5. Conclusions

Through a structured literature search, thirty-seven research papers were analysed considering the influence of fibre content, type and combination on the compressive and tensile strength of UHPC. The results of this review paper show that:

- ASTM C1609 is the most frequently applied standard for testing the effects of fibres on flexural tensile strength of UHPC. This is a standard for fibre reinforced concrete. Standardised procedures for conventional or fibre reinforced concrete is often applied, in spite of the emergence of dedicated UHPC standards. For some tests, e.g. compressive strength, even the dedicated UHPC standards are referring to standards for conventional concrete.
- Different test specimen geometries have been used to measure the effects of fibre reinforcement on compressive and tensile strength of UHPC. This is often a consequence of applying different standards. Differences in geometry are often claimed to influence the test results. From the analysis of the accumulated results from all the included papers in this review, it seems clear that the geometry plays a role both for compressive and tensile strength. However, few of the papers have investigated into this, and the effects of variations in other factors like constituting materials, mix proportion and curing regime seems not to be focused.
- Variations in fibre types have been investigated, spanning from micro to macro fibres, straight or deformed (hooked-end, twisted or corrugated). For all fibre geometries, high strength steel fibres (tensile strength > 2000 MPa) were mostly used. For compressive strength, the accumulated results show little effect of using deformed fibres rather than straight. It seems that deformed fibres can improve the flexural tensile strength for low fibre volumes. In contrast, at higher fibre volumes, straight fibres perform better. Hence, the optimum fibre type seems to be dependent on the fibre volume fraction.
- Fibre reinforcement is necessary in UHPC to avoid explosive behaviour at failure. Several investigations reported that the compressive strength was affected by the inclusion of fibre reinforcement, giving UHPC higher strength. However, the influence of variations in test specimen geometry and other variable factors were hardly discussed. When the accumulated results are differentiated, it seems that inclusion of fibres has little effect on compressive strength when tested on cylinders, though some higher effects on large cubes (100 mm). For small cubes (40–50 mm) there seems to be an increase in compressive strength as a function of fibre content up to 3 vol-%.
- The inclusion of fibre reinforcement profoundly influences the flexural tensile strength of UHPC. In most cases, the flexural tensile strength is improved as a function of increased fibre content. This seems to be valid for both small (l = 160 mm) and large (l > 280 mm) test specimen. At high content, fibres may have the opposite effect by reducing the tensile strength. This might partly be explained by fibre agglomeration and entrapped air.
- Combining different types of fibres might benefit from exploiting the synergetic effect of each type. This is often denoted hybrid fibre combinations. The use of hybrid fibre combinations has the potential to increase the tensile strength of UHPC. Some hybrid combinations seem to improve especially the flexural tensile strength, while others have little effect.

Recommendations for future research

To approach a better accumulated understanding from the collective efforts of the research society, we recommend that future investigations support repeatability and reliability by reporting enough information on all variables and have enough parallel tests to the number of variables tested. Future research should also focus on replication of already reported studies to strengthen the statistical basis of any conclusions.

We believe that it is not advantageous for researchers from different cultural background to agree on the use of only one single set amongst the existing plurality of standards. However, following the emergence of new standards for testing and reporting of UHPC, comparisons of the effects of differences between standards when all other factors are kept constant would benefit the scientific discussions on relating new research towards existing knowledge.

Declaration of Competing Interest

No conflict of interest has been identified.

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Paper V

Locally Produced UHPC: The Influence of Type and Content of Steel Fibres

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Locally Produced UHPC: The Influence of Type and Content of Steel Fibres

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ABSTRACT
Ultra-high performance concrete might be a competitive alternative to normal concrete for some purposes. But despite research efforts during decades, utilisation is still not widespread. Reasons include limited competence and material availability. This paper presents one step of a research initiative aimed at facilitating the use of UHPC in Norway. The step presented here comprises the accumulated results from investigations on the influence steel fibres (content, type, and hybrid combination) have on material strength and deformation behaviour of locally produced UHPC, made with constituents found in southern Norway. 231 specimens were tested, spanning nine UHPC mixes. Digital Image Correlation (DIC) was successfully used to study crack propagation. Compressive strength of 166 MPa and E-modulus of 46 GPa were obtained, not being influenced by fibre content. The flexural tensile strength was found to be strongly dependent on variations in

steel fibre properties and mix design. The highest flexural tensile strength was obtained for prisms with micro straight steel fibres alone, or in 50% combination with macro hooked-end fibres. The experimental results are considered in a theory-informed discussion. Suggestions are made on the use of steel fibres in locally produced UHPC, potentially lowering the cost by 30%.

Keywords: Ultra-High Performance Concrete (UHPC), Local materials, Material properties, Steel fibres, Digital Image Correlation (DIC)

1. INTRODUCTION

Though the term Ultra-High Performance Concrete (UHPC) has been used for decades, a unified definition of required material properties to merit this notation has not yet been accepted. In a novel paper by five leading researchers within the field, the following suggestion is made for defining UHPC class materials [1]: "*(1) a compressive strength greater than 120 MPa; (2) a disconnected pore structure that significantly reduces permeability and thus enhances durability; and (3) sufficient fiber reinforcement to allow for sustained postcracking tensile resistance that exceeds a minimum cracking strength of 5 MPa"*. Research work over at least 50 years [2] has been manifested through various applications worldwide both within the bridge sector and the construction industry in general. Some countries (e.g., Switzerland, France, Germany, South Korea, Malaysia, Canada, and the US) have successfully implemented UHPC in different bridge projects as field-cast connections between prefabricated concrete bridge elements, on-site rehabilitation overlays or as the primary material in new road or pedestrian bridges [1]. In most of these countries, the implementation has been motivated through government agencies [3]. The US Federal Highway Administration (FHWA) has been at the forefront of both the research work and pilot applications. A series of reports by FHWA, e.g. a state-of-the-art report [4], has created a foundation for the implementation of UHPC in the bridge sector.

Proprietary UHPC materials are utilised in the majority of the existing UHPC structures. These commercially available products are offered from a limited number of producers worldwide, leading to an oligopolistic market situation with high costs compared to expectations in a competitive market. The price of the proprietary UHPC products is found to be 20 times higher than conventional concrete materials [5, 6]. The actual production cost of UHPC using local materials in the US is about half of this [6]. Most of the cost is attributed to the extensive use of micro straight steel fibres. The high cost and low local availability are two aspects that have limited wider use of UHPC. Smart use of UHPC is frequently claimed to have the potential for reducing CO_2 emission [7] and the life cycle cost of concrete structures. A reduction in material cost might be an important driving force towards more widespread implementation. The potential for producing high-quality UHPC with local materials has been proven over and over by a variety of researchers, e.g., [8-12]. Scandinavian experiences have been reported since the 1980s (e.g. [13]), also regarding an industrial mock-up test [14] and commercial applications (e.g., [15, 16]). In a not yet scientifically reported industrial-academic cooperation ("New applications of UHPC", financially supported by the Research Council of Norway), high-quality UHPC was successfully produced from local constituents in the full-scale production facilities of an ordinary concrete supplier in Norway. Subsequently, UHPC with corresponding properties was reproduced in laboratory scale, utilising local constituents from other sources and through only minor adjustments in the mix proportioning [17]. However, Scandinavian participation in the development towards widespread utilisation of UHPC seems scarce.

High contents of high strength straight micro steel fibres (often 13 mm in length and 0.2 mm in diameter) is the main cost contributor in UHPC, responsible for half of the price [6]. It is also one of the main attributes of high CO_2 emissions. Large parts of these emissions stem from the process of wet wire drawing of the fibres into small diameters (around 0.2 mm) [18]. To reduce this impact, Stengel and Schießl [18] recommended using fibres with larger diameters. Several studies (e.g., [19-24]) have focused on more efficient use of steel fibres in UHPC through utilising various fibre types. Some have focused on increasing the pull-out strength by either increasing the fibre length or by using deformed fibres (e.g., [19, 20, 23]). Another concept is utilising hybrid fibre configuration (e.g., in [21, 22, 24]). The principle is to combine different fibres, often micro straight fibres and macro deformed fibres, utilising the synergy of their individual properties [25]. Prior research on hybrid fibre reinforcement used macro fibres with length up to 30 mm [26], while limited investigations have focused on the effects of larger macro hooked-end fibres with fibre length above 50 mm. These are frequently used in normal fibre reinforced concrete and are easily available at a low cost. It would be beneficial for local production of UHPC if these fibres could at least partially substitute micro fibres, while retaining UHPC properties. Utilising fibres made for normal concrete in a high strength UHPC matrix introduces a risk of fibre rupture, due to the lower tensile strength of the fibres (around 1000 MPa) combined with the high mechanical anchorage at the fibre ends.

This paper presents one step of a research initiative on understanding the material properties and behaviour of UHPC made from local materials, with the long-term goal of facilitating the use of UHPC in Norway. The work presented in this paper was focused on experimental investigations on UHPC made from local constituents found in southern Norway. The aim was twofold:

- Developing high-quality non-proprietary UHPC mixes using locally available materials.
- Investigating the influence of steel fibres (content, type, and combination) on material properties and deformation behaviour of local UHPC mixes.

The key material properties investigated in this study was compressive strength, modulus of elasticity (E-modulus) and flexural tensile strength and behaviour. A Digital Image Correlation system (DIC) was used to monitor and analyse the deformation behaviour of prisms in flexure. The experiments included variations in mix composition, fibre configuration, test specimen geometry and curing regime, comprising 231 tested specimens.

2. LITTERATURE REVIEW OF COMPOSITION AND PROPERTIES

UHPC has developed through several stages, spanning from laboratory materials utilising high pressure (autoclaving) and elevated temperatures (250 to 400°C) to create extremely high compressive strength (above 490 MPa) and flexural tensile strength (above 45 MPa) [27], to a material suitable for structural applications, producible from locally available constituents and by using traditional production equipment. In the following, a brief literature review is given of existing data on constituents, mix design and relevant properties identified through the research papers on both proprietary brands and locally produced UHPC materials.

2.1 UHPC constituents and mix design

The constituents used in UHPC is similar to those used in conventional concrete, such as aggregates, cement, microsilica, superplasticiser (SP) and water. However, the paste phase (cement, microsilica, fillers, water, SP) usually stands for about 2/3 of the volume in UHPC materials, while the particle phase is only 1/3 and consists of fine particles only with maximum grain size (D_{max}) often lower than 1 mm [2]. In the state-of-the-art report by FHWA [4], recommendations on D_{max} are 0.8 mm. The paste phase consists of large contents of cement and microsilica. Normally 700 to 1100 kg per cubic meter of cement is applied with a microsilica ratio of around 0.25 to the mass of cement. In some mixes, other types of cementitious binders (e.g., fly ash, ground granulated blast-furnace slag or limestone powder) are used in addition or to reduce the cement or microsilica content [22, 28]. Usually, water/binder-ratio (*w*/*b*-ratio) around 0.2 is applied, made possible through a high content of SP. In contrary to conventional concrete, fibres are a necessary component in UHPC to reduce brittleness in compression and tension and give exploitable tensile strength. In proprietary UHPC products, straight micro steel fibres with a length (l_f) around 10-20 mm and diameter (d_f) of 0.2-0.4 mm is applied with fibre content between 2 and 6 vol.% [12]. Recommendations on mix proportions of UHPC class materials can be found e.g. in [6, 29] and reads as follows:

- Microsilica content and other cementitious binders both 25% of the mass of cement.
- Aggregate to cement ratio between 1 and 2.
- Water/cement (*w/c*-ratio) between 0.2 and 0.3.
- Fibre content between 1 and 2 vol.%.

Mix proportions of both proprietary UHPC products and UHPC mixes found in research, are summarised in Table 1.

Table 1 – Mix composition of proprietary UHPC products and UHPC mixes in research.

	Proprietary UHPC [a]	Yoo et al.	Meng & Khayat	Yu et al.	Le Hoang & Fehling	Gesoglu et al.
Materials	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³
Cement	712-1114	789	641-675	582-896	772-795	960
Microsilica	169-275	197	41-43	24 [b]	164-169	240
Other binders	N/A	N/A	367-422	0-275	N/A	N/A
Fine sand	730-1325	1104	943-992	1256-1337	1134-1169	706-794
SP	31-40	53	23-113	43-46	23-24	45-57
Water	109-211	160	228	153-179	182-188	234
Steel fibres	156-470	39-156	0-390	N/A	0-236	0-157
w/b	0.14-0.16 [c]	0.2	0.2	0.165-0.2	0.21	0.195
D_{max} [mm]	0.5-6	0.3	4.8	2	0.5	2.5
Reference	[3, 4, 12]	[21, 30]	[22]	[28]	[31]	[20]

[a] Ductal®, CEMTEC multiscale®, BSI®, CRC®. [b] Nano-silica. [c] Calculated from given *w/c*-ratio.
N/A - Not available.

High particle packing density is important to obtain the special material properties of UHPC. Different approaches have been applied [32]. One method used in several studies (e.g. in [12, 28, 29]), is the modified version [33] of the Andreasen and Andersen model for granular materials [34]. The particle distribution curve reads as follows (Eq. 1):

$$\mathrm{CPFT} = \left(\frac{D - D_{\min}}{D_{\max} - D_{\min}}\right)^q \quad (1)$$

where CPFT is the cumulative per cent finer than size D, D is the varying particle size, D_{min} and D_{max} represent the smallest and largest particle size of the distribution, respectively. The q-value represents the distribution coefficient and determine the curvature of the cumulative PSD. The curve acts as a target for the densest possible particle composition.

2.2 UHPC strength properties

Table 2 lists some material properties of UHPC found in the literature. Compressive strength exceeding 120 MPa is found in the research literature as well as for proprietary UHPC. E-modulus values are ranging from 39 to 70 GPa.

Table 2 – Material properties of proprietary UHPC product and UHPC mixes in research.

Material properties	Proprietary UHPC [a]	Yoo et al.	Meng & Khayat	Yu et al.	Le Hoang & Fehling	Gesoglu et al.	SOA by FHWA
Compressive strength [MPa]	180-225	185-220	140-166	100-117[b]	199-219	137-162[b]	140-200
E-modulus [GPa]	55-59	N/A	N/A	N/A	52-55	39-45[b]	40-70
Flexural tensile strength [MPa]	40-50	34-49	10-27	12-19[b]	N/A	7-14[b,c]	N/A
Density [kg/m^3]	2440-2550	N/A	N/A	N/A	N/A	N/A	N/A
Reference	[35]	[21, 30]	[22]	[28]	[31]	[20]	[4]

SOA – State-of-the-art report. [a] Ductal®. [b] Read-off from figures. [c] Notched prism. N/A – Not applicable.

The inclusion of discrete steel fibres has shown to give high tensile properties, often characterised by a multiple cracking phase after first cracking. At high dosages, it also creates deflection-hardening behaviour. Table 2 shows that flexural strength up to 50 MPa is achieved under three- or four-point bending tests. These flexural tests are often used to characterise the tensile capacity properties, probably due to the easiness of execution. Sometimes also direct tensile strength tests are performed, often showing tensile cracking strength values from 6 to 10 MPa [4].

An increase in material properties can be achieved through curing at elevated temperatures, usually at 90°C for 48 hours (95% relative humidity and without high pressure). Studies have shown improved compressive strength, tensile cracking strength and E-modulus, as well as the resistance against chloride ions diffusion through the application of high temperature curing treatment [4]. Another advantage is that the final properties are achieved as soon as the high-temperature curing is completed. The drawback is the cost and practical issues if applied at a construction site. Even higher properties can be achieved using high pressure (autoclaving) and temperatures over 150°C [4], but this is not discussed here.

3. MATERIALS AND EXPERIMENTAL METHODOLOGY

The experimental program aimed at developing and investigating non-proprietary UHPC mixes utilising locally available materials in combination with varying content, types, and a hybrid combination of steel fibres. Two types of aggregate were used in two different UHPC mixes to investigate the influence of variations in the effect of steel fibres in synergy with different aggregates. In the following, a description of the development and production of the local UHPC mixes is given (Section 3.1), along with the experimental program (Section 3.2).

3.1 Development and production of local UHPC

Materials

The materials used for the UHPC mixes consisted of cement, microsilica, fine aggregates, SP, water and two types of steel fibres (micro straight fibres and macro hooked-end fibres). Besides the fine aggregate types and small micro steel fibres, all materials were the same as used in the laboratory to produce conventional concrete. Two aggregate types were applied, both received from suppliers in Norway and being by-products from the production process of crushed gravel. The aggregates were chosen due to their fineness and availability, as well as following the intention of contributing to increasing circular economy through utilisation of by-products. One of the aggregates were filtered harvested dust with D_{max} of 0.6 mm, while the other one was surplus sand with D_{max} of 6 mm. Further information on the constituents is stated in Table 3. The filler aggregate (A1) was pre-treated to ensure a saturated surface dry (SSD) condition, while adjustments in the applied water content during material mixing was applied to account for water adsorption in the crushed sand (A2).

Table 3 – Characteristics of used constituents.

Material	Characteristics	Density [kg/m^3]
Cement (CEM)	CEM I 52.5 N	3100
Microsilica (MS)	Undensified microsilica	2200
Filler sand (A1)	Filter harvest dust from production of gravel (D_{max} = 0.6 mm)	2610
Crushed Sand (A2)	Surplus sand from production of machined gravel (D_{max} = 6 mm)	2770[a]
Superplasticiser (SP)	Modified acrylic polymers, 18% dry content	1060

[a] Obtained from 0-8 mm fraction of the same origin.

The two types of steel fibres, straight micro fibres (SS) and macro hooked-end fibres (HE), are shown in Figure 1 and Table 4 provides some properties given by the manufacturer. The straight micro steel fibres represent the fibre type commonly applied in UHPC, while the macro hooked-end fibre is frequently used in ordinary concrete. The macro hooked-end fibre is introduced due to its lower cost, environmental footprint, and higher availability. Straight micro steel fibres are not used in the traditional concrete industry and had to be imported.

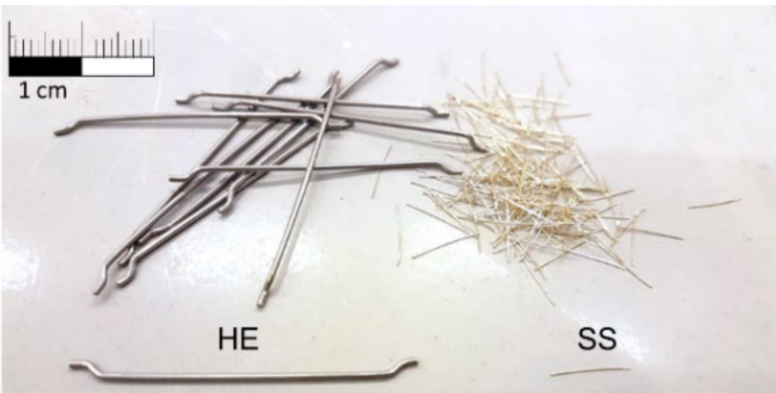


Figure 1 – The two types of steel fibres.

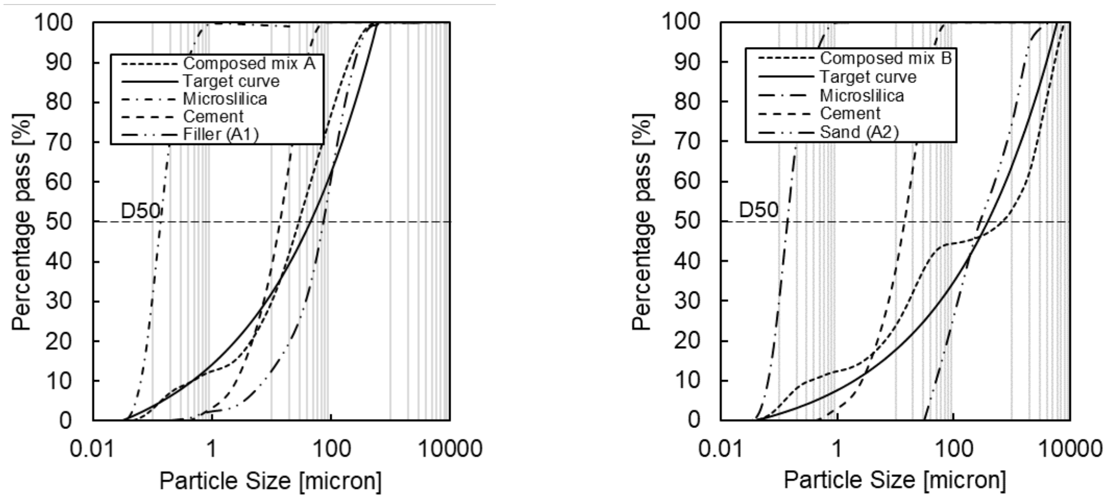
Table 4 – Properties of the steel fibres reported by the manufacturer.

Notation	Shape	l_f [mm]	d_f [mm]	l_f/d_f	Tensile strength [MPa]	E-modulus [GPa]
SS	Straight	13	0.2	65	2600	200
HE	Hooked-end	50	1	50	1100	200

l_f – Fibre length. d_f – Fibre diameter. l_f/d_f – Aspect ratio.

UHPC mix composition
Inspired by the literature review shown in Section 2.1, the following mix proportions were pursued: (i) cement content around 700-800 kg/m^3, (ii) microsilica content of 25% of the mass of cement, (iii) a *w*/*c*-ratio between 0.2 and 0.3, and (iv) an aggregate to cement ratio between 1 and 2. Recommendations on fibre content between 1 and 2 vol.% [6, 29] and D_{max} of 0.8 mm [4] were exceeded in the presented study by including UHPC mixes with lower fibre content and by applying an aggregate type with higher D_{max} in one of the mixes (Mix B).

The particle packing was simulated using the modified Andreasen and Andersen model [33] following (Eq. 1). A q-value of 0.23 was applied, based on recommendations by Yu et al. [28] for materials with high amounts of fines, like UHPC. The software EMMA (Elkem Materials Mix Analyzer) (version 3.5.2) which operates the mathematical model, were used to design the mixes. Both the cumulative PSD curve of the combined dry materials and the target curve is calculated (Eq. 1) in EMMA, and shown in the same diagram, thus illustrating the match of the composed curve towards the target. Figure 2 shows the final PSD of the composed mixes compared to the target curve and the individual PSDs for all dry materials.



(a) Mix A *(b) Mix B*

Figure 2 – PSDs of the dry constituents, the target curve (modified Andreasen and Andersen curve) and curve of the composed mixes represented in a single-logarithmic plot.

Each constituent was included "as is", without manipulating the fractioning to fit the target curve. Obtaining the best fit to the target curve in EMMA was strived for by adjusting the relative amount of each constituent while maintaining the above-mentioned requirements for mix proportions. The PSDs of the dry materials with D_{max} less than 1 mm were determined through laser diffraction, while sieve analysis was used for larger materials (A2). Assembling measurements from indirect methods like laser diffraction and direct methods like sieving has weaknesses. However, given that no available method, direct or indirect, has the potential for measuring the present span in particle size from 1 nanometre to 10 mm, this procedure has been applied in Figure 2. Table 5 shows the composed UHPC mixes.

Table 5 – Mix composition of the UHPC mixes.

kg/m^3 Mix	CEM	MS	A1	A2	W[a]	SP[b]	SS	HE	*w/c*	*w/b*	v_f, %	Fresh properties Air[c] %	Flow[d] mm
NF-A	728	182	1237	-	204	13.1	0	-	0.28	0.22	0	5.0	163.7
SS05-A	724	181	1231	-	203	13.0	39	-	0.28	0.22	0.5	4.2	188.7
SS1-A	720	180	1225	-	202	13.0	78	-	0.28	0.22	1	4.2	177.2
SS2-A	713	178	1212	-	200	12.8	156	-	0.28	0.22	2	4.6	192.8
HE2-A	713	178	1212	-	200	12.8	-	156	0.28	0.22	2	3.8	186.3
HY2-A	713	178	1212	-	200	12.8	78	78	0.28	0.22	2	4.0	202.7
SS2-B	756	189	-	1188	170	9.5	156	-	0.22	0.18	2	3.5	142.5
HE2-B	756	189	-	1188	170	9.5	-	156	0.22	0.18	2	3.3	137.5
HY2-B	756	189	-	1188	170	9.5	78	78	0.22	0.18	2	3.5	126.7

CEM – Cement. MS – Microsilica. A1 – Filler sand. A2 – Crushed Sand. W – Water. SP – Superplasticiser. SS – Straight micro steel fibres. HE – Hooked-end fibres. v_f – Volume fraction of steel fibres. [a] Including water from SP. [b] Solid content. [c] EN 12350-7: 2009. [d] Final flow, ASTM C230/C230M.

Mixing and specimen fabrication

The UHPCs were mixed at standard laboratory conditions in a laboratory rotating pan-mixer for conventional concrete. The total volume of each batch varied based on the desired number and type of test specimens. The mixing procedure is stated in Table 6 and is similar to the one used by Graybeal [35]. Prior to casting, the rheological properties were measured using a flow table test with a small slump cone (ASTM C230/C230M [36]) often applied for UHPC. The air content was measured according to EN 12350-7:2009 [37]. The average results of the final flow (after jolting the flow table) and air content are shown in Table 5. All specimens were cast in one layer before they were compacted on a vibration table using the procedure given by Graybeal [35], screeded and covered with plastic sheets until demoulding 24 to 48 hours after casting. The casting of the prismatic specimens was done by placing the UHPC in one end of the prism moulds, allowing it to flow to the other end [35].

Table 6 – Mixing procedure.

Process	Time [min]
Mixing of dry materials	10
Adding water and half of the SP while mixing	2
Continue mixing for 1 min before adding the remaining SP over 30 seconds	1.5
Mixing (from powder to thick paste)	10
Adding steel fibres while mixing	2-5
Final mixing	5

Curing at 90°C is an often seen manufacturer-recommended treatment for UHPC [35], which can be challenging to apply in practical construction. In this study three different curing regimes were applied:

1) Submerged in water at 20°C until testing, representing the standard procedure for normal concrete.
2) Moderate heat treatment in water at 45°C for 5 days, then submerged in water at 20°C until testing.
3) Heat treatment in water at 90°C for 48-72 hours (including a gradual increase and decrease of temperature), subsequently submerged in water at 20°C until testing.

3.2 Test program

231 specimens were tested, spanning nine different mixes with two different mix composition and varying steel fibre content, type, and hybrid combination. The two different UHPC mix compositions are denoted Mix A and B in the following. Table 7 gives information about the conducted tests, number and type of test specimen and curing regimes. The flexural test specimens were tested seven to eight days after casting. A Digital Image Correlation (DIC) system was used for observing the behaviour during some of the flexural tests. One series of Mix A was produced to investigate the influence of fibre content by increasing the fibre volume of straight micro steel fibres from 0 to 2%. Another series of Mix A and B was produced to investigate the effects of different fibre types and hybrid combinations when the content was kept constant at 2 vol.%: 100% straight micro fibres (SS), 100% hooked-end fibres (HE) and 50/50 hybrid combination of those (HY).

Table 7 – Test program.

Mix	v_f, %	Mix ID	No. of batches	Tests	Specimens cast	Curing [b]
A	0	NF-A	3	Compressive strength	6 cu, 3 cyl	3
				E-modulus	3 cyl	3
	0.5	SS05-A	3	Compressive strength	6 cu, 3 cyl	3
				E-modulus	3 cyl	3
	1	SS1-A	4	Compressive strength	6 cu, 3 cyl	3
				E-modulus	3 cy	3
	2	SS2-A	4	Compressive strength	36 cu, 12 cyl	1, 3
				Flexural tensile behaviour (DIC)	6 prisms	1
	2	HE2-A	3	Compressive strength	35 cu	1, 3
				Flexural tensile behaviour (DIC)	9 prisms	1
	2	HY2-A	3	Compressive strength	34 cu	1, 3
				Flexural tensile behaviour (DIC)	9 prisms	1
B	2	SS2-B	2	Compressive strength	12 cu	2, 3
				Flexural tensile behaviour	3 prisms	2
	2	HE2-B	2	Compressive strength	12 cu	2, 3
				Flexural tensile behaviour	3 prisms	2
	2	HY2-B	3	Compressive strength	18 cu	2, 3
				Flexural tensile behaviour	6 prisms	2

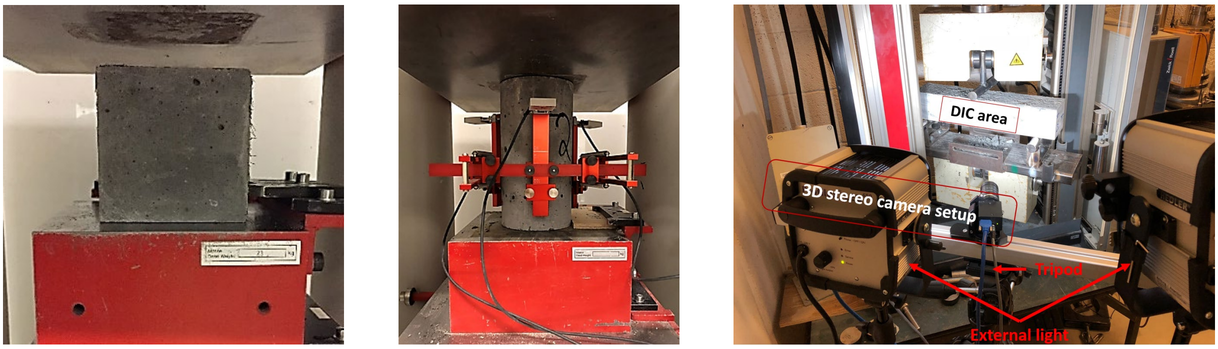
cu – 100 mm cube. cyl – 100 mm × 200 mm cylinder. prisms – 100 mm × 100 mm × 500 mm prism. [b] 1 – 20°C standard curing. 2 – 45°C moderate heat treatment. 3 – 90°C heat treatment.

Test setups

Figure 3 shows the different test setups. 100 mm cubes were used to measure compressive strength following NS-EN 12390-3:2009 [38]. Cylinders with a diameter of 100 mm and a height of 200 mm were used to measure compressive strength (NS-EN 12390-3:2009 [38]) and E-modulus (NS-EN 12390-13:2013 [39]). The flexural tensile strength was determined using centre-point loading (three-point bending) on prisms of 100 mm × 100 mm × 500 mm at a constant load increment rate of (0.1-0.3 kN/sec). A similar test setup was used in a previous study on the development of local UHPC recipes [12]. The test setup was inspired by ASTM C293 and the flexural strength at peak load was calculated accordingly [40] (Eq. 2):

$$f_t = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot d^2} \quad (2)$$

where P is the peak load, L is the span length, b is the width of the prism, and d is the height. The DIC system was used to monitor the deformation during the flexural tensile tests for the various fibre combinations of Mix A. The force from the hydraulic machine was matched with the DIC recordings.



(a) (b) (c)

Figure 3 – Test setups (a) compressive strength, (b) E-modulus and (c) flexural tensile strength with the DIC setup.

Statistical treatment of data
Statistical outliers amongst the results were excluded from the experimental data, before calculating average values. This is implemented as a standard procedure, to secure that the average value from repeated experiments has the best available representativity for the situation. Results were considered to be outliers if it differed more than one and a half time the interquartile range (IQR) below the first quartile (25 percentile, Q1), or above the third quartile (75 percentile, Q3), a procedure described e.g. in [41]. IQR is the difference between Q3 and Q1.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Strength and behaviour in compression

Influence of content of fibres on compressive strength and E-modulus
Figure 4 (a) shows the average compressive strength and E-modulus of heat-treated UHPC cylinders when varying the content of straight micro steel fibres. All strength results are well above the requirements for UHPC (120 MPa). Both the compressive strength and the E-modulus are minorly influenced by inclusion and variations in fibre content. Similar results have been found in other studies (e.g., in [8, 31]). Yet researchers have found considerable contribution from the fibre reinforcement (e.g., in [23, 24]), making it unclear whether the compressive strength of UHPC is influenced by fibre content. An explanation for positive effects from the fibre reinforcement on compressive strength might be the confining effect of the fibres. However, the addition of fibres might also make the concrete more difficult to cast and in turn give reduced compressive strength. In a recent literature review [26], it is suggested that the seemingly contradictory conclusions might be caused by the shape of the test specimen rather than the actual effects of the fibres. Through the review, it was found that substantial positive influence of the presence of fibres was mainly concluded in investigations using small cubical shaped specimens (40-50 mm), while those using larger cube specimens (100 mm) found some effect, and little influence was found on cylindrical specimens. Figure 4 (b) shows that the cubic samples (cu) in our investigation achieved an increase of 6% for 0.5 vol.% fibres, and about a 10% increase for 2 vol.%, compared to non-fibre reinforced UHPC. No strength increase was observed when using cylindrical specimens. Theoretically, it can be argued that the geometry of test specimens influences stress distribution. The cylindrical shape is often considered to represent the desired

uniaxial stress distribution better than the cubical shape, where the failure is claimed to be more heavily influenced by shear. The results from our investigation strengthen this suggestion, but further investigations with a larger sample size are required to verify this to be the main reason for the contradictions in conclusions on the influence of fibre reinforcement on compressive strength.

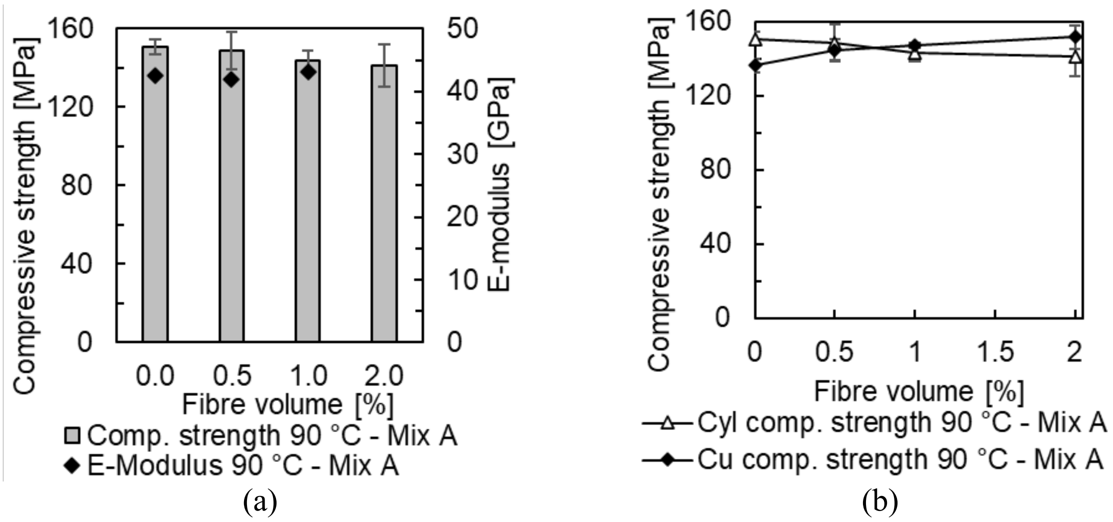


Figure 4 – Average (a) compressive strength and E-modulus of heat-treated cylinders and (b) compressive strength of heat-treated cubes and cylinders. The error bars show the S.D values.

Influence of type and combination of fibres on compressive strength

Figure 5 shows the average cube compressive strength of differently cured specimens with 2 vol.% of either straight steel fibres (SS), hooked-end fibres (HE) or a combination of those two fibres (HY). Little or no impact on the compressive strength was found from variations in fibre type and hybrid combination, whether the curing regime or the UHPC mix composition was altered. Both mixes respond positively to heat curing, as the strength development correlates with curing temperature for all applied levels (20, 45 and 90°C).

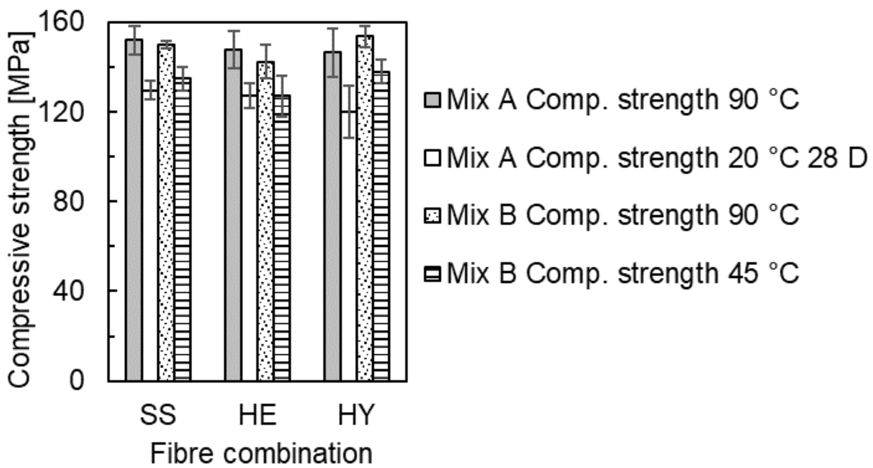


Figure 5 – Average cube compressive strength with 2 vol.% of different fibre types and combination. The error bars show the S.D values.

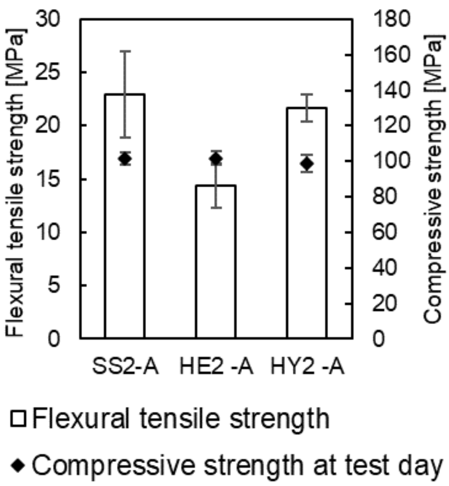
4.2 Flexural tensile strength and behaviour

Flexural tensile strength

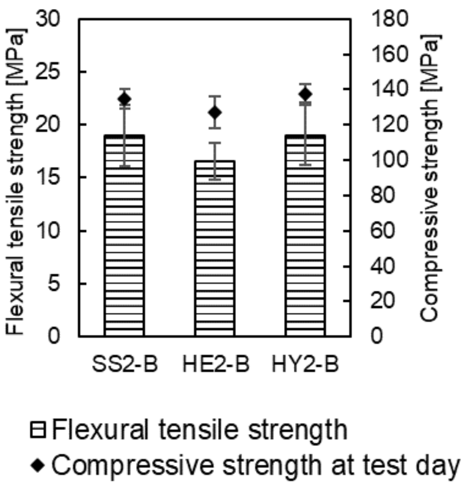
Figure 6 shows the average flexural tensile strength and the corresponding compressive strength at the test day for different types and hybrid combination of steel fibres. The Mix A prisms were exposed to standard curing conditions (20°C), while the Mix B prisms were moderate heat-treated at 45°C. Both test sets were tested seven to eight days after casting. Hence, the Mix B matrix was close to fully matured, while Mix A was still "young". Generally, higher variations in test results can be seen for flexural strength compared to compression and E-modulus results (Figures 4 and 5). This can be explained by the flexural tensile strength being more sensitive than the compressive strength to the presence of fibres, including variations in dispersion and orientation.

Prisms with only macro hooked-end fibres (HE) exhibited the lowest flexural tensile strength. For Mix A prisms, the prisms with straight micro fibres (SS) and hybrid combination (HY) achieved about 60% higher capacity compared to the prisms with only hooked-end fibres. One explanation might be the higher number of fibres in the prisms with straight micro fibres (SS and HY prisms), at constant vol.%. Volume differences of the different fibre types cause the number of straight micro fibres to be 100 times that of hooked-end fibres at fixed vol.%. Hence, the possibility of initiated cracks to be bridged by fibres is much higher for prisms with straight micro fibres. Figure 7 visualises the differences in the number of fibres in cross-sections of the different beam types.

The SS prisms exhibit slightly increased average-strength (5.6%) compared to the HY prisms. From several investigations reported in the literature (e.g., [21, 22, 24]), it is known that hybrid fibre combinations have the potential to increase the tensile properties of UHPC. This is often explained as the synergetic effect from combining fibres with different properties [25], but the effect depends on the applied combination [21, 22].



(a)



(b)

Figure 6 – Average flexural tensile strength of (a) Mix A and (b) Mix B at peak load and cube compressive strength at test day. The error bars show S.D values.

Although hooked-end fibres are generally proven to have considerably higher pull-out capacity than straight fibres [22], this property is not always fully exploitable in UHPC. The explanation is the creation of localised micro-cracks (split cracks) in the cementitious matrix when several fibres with high mechanical anchoring are bundled up in a small volume of matrix [42], also experienced and reported in [21, 30]. This problem where closely located fibres are prone to reduced anchoring is often denoted "fibre group effect" [42]. The risk of this negative effect is greater at high fibre volume fraction, as the fibre bundles is created and consequently matrix confinement (enveloping) decrease [42]. Figure 7 shows that the HE prisms have several fibre bundles and poor fibre distribution. A better distribution with fewer bundles can be seen for the HY prism with lower content of hooked-end fibres.

(a) (b) (c)

Figure 7 – Sawn cross-sections with 2 vol.% of (a) straight fibres, (b) hybrid combination of fibres and (c) hooked-end fibres. The cut was made near the critical crack.

The same relative variations in effect between different fibre types were observed for prisms made from Mix B, as for Mix A: SS and HY prisms achieved higher flexural strength than the HE prisms (Figure 6 b). But the positive impact was lower; around 15%. Mix B included a coarser aggregate type than Mix A. Using a coarser aggregate can result in better distribution of macro hooked-end fibres than when introduced to a fine-grained mix [21]. However, the distribution of micro fibres is negatively impacted by the use of coarser aggregate, and also the fibre-matrix bonding of micro fibres have been found weakened [43].

Despite the higher maturity of Mix B than of Mix A at testing day for the prisms (caused by the moderate-heat curing of Mix B), higher capacity was observed for prisms made from Mix A with straight micro fibres (SS and HY prisms). All other variables were kept constant between the two series: the content and types of fibres, specimen geometry and test setup. This supports the idea that the effect of fibre is influenced by other factors than just the fibre type and hybrid combinations. Several differences can be observed that possibly have affected the effectiveness of the fibres. Firstly, the flow values for Mix B were lower than that of Mix A (Table 5). Consequently, it was more difficult to cast, which might have given an adverse effect on the flexural performance by influencing the homogeneity and compactability of the matrix, and the fibre distribution. Secondly, the size of the aggregate differed (Figure 2) which might have caused more defects and pores, poorer distribution of micro fibres and weakened the bonding between the micro fibres and the matrix [43]. Thirdly, the particle packing of the aggregate also differs between the mixes. Figure 2 demonstrates larger deviations between the PSD of the composed Mix B and the target curve than for Mix A. The physical interpretation of these differences is that the particle packing is denser in Mix A than in Mix B. This denser particle packing might affect the bonding between fibres and matrix, emphasising the need for competence and knowledge for utilisation of locally produced UHPC.

The ratio between fibre length and prism cross-section size is known to affect the orientation of fibres, through what is recognised as the wall effect [44]. The wall effect is more profound as the width of the prism tends towards the fibre length [45]. To reduce the influence of the wall effect on the fibre orientation during lab investigations, requirements on the size of the specimen is given in standards for testing normal fibre reinforced concrete (e.g., ASTM C1609 and EN 14651). Due to practical reasons, a cross-section of 100 mm × 100 mm was chosen for this experimental investigation. Thus, the low fibre length to prism cross-section ratio was probably influencing the orientation of the macro fibres more profoundly than when only using micro fibres. The orientation of fibres is also influenced by other factors, like the flow of the matrix during the casting procedure. Both the fibre length to prism cross-section ratio and the casting process have increased the probability of fibres to orient along the beam axis – yielding higher flexural tensile strength compared to prisms with random fibre orientation. While the influence of the casting procedure concerns both micro and macro fibres, the fibre length to prism cross-section ratio is more influential for the larger hooked-end fibres.

Deformation behaviour
Figure 8 presents the load-displacement curves for selected prisms of Mix A obtained from the DIC system. Three parallel tests for each variable are shown in the figure, along with the average peak load (Av. P_{max}). Mid-point displacement at failure was around 1.5 mm for HE prisms, while for HY and SS prisms the displacement was higher at failure, around 2 to 2.5 mm and 2.5 to 3 mm, respectively. A difference in ductility can be seen in Figure 8 between the beam sets. The prisms with straight micro fibres achieved a more gradual failure. This can be partly explained by a more uniform distribution of fibres and a higher number of fibres crossing the cracks compared to prisms with only hooked-end fibres. Little difference in ductility was observed between the SS and HY prisms. For all beam types, the fibres were pulled out of the matrix and fibre rupture was not observed. Differences in post-peak behaviour could not be registered due to the load-controlled test setup.

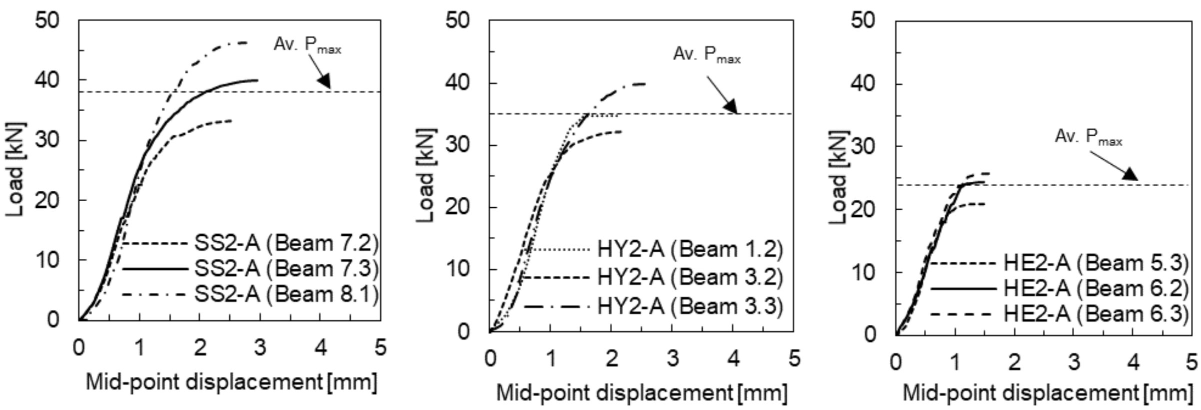


Figure 8 – Load-displacement curves from the DIC measurement for selected UHPC prisms with (a) straight micro fibres (SS), (b) hybrid fibres (HY) and (c) hooked-end fibres (HE). The dotted horizontal line represents the average peak load of the various beam types.

The DIC measurements were used to obtain strain contour plots and crack widths. The cracks were detected by visually identifying high strain gradients from the strain contour plots. Figure 9 shows typical examples of crack patterns at different load stages (15 kN, 20 kN, 30 kN and failure), for the prisms made from Mix A with varying fibre configuration at constant fibre vol.%. The first cracks appeared early in the loading process (first line in Figure 9) in the lower part of the prisms and near the region of the highest bending moment, for all variations of fibre configuration. The prisms including straight micro fibres (SS and HY prisms) developed numerous micro cracks, constantly adding on new cracks as the load increased. For SS prisms, it was not possible to identify at low load levels, which crack would develop into the critical one. However, the prisms with only macro hooked-end fibres (HE prisms) developed a small number of cracks. Later in the loading process, new cracks were only sparsely formed. Rather, the cracks formed at low load levels widened until one crack developed into the critical one. Hence, which crack developing to become the critical one, was observable already at low load levels. The HY prisms behaved something in between; developing a high number of small cracks, still indicating which crack would develop into the critical one at a lower load level than for the SS prisms.

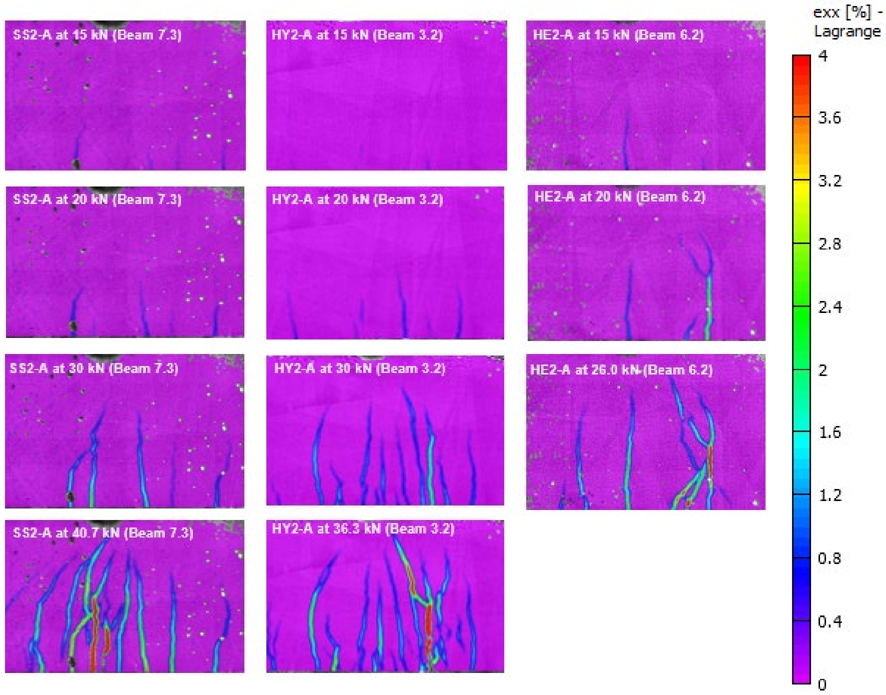


Figure 9 – Selected crack pattern in the area under the load at increasing load levels from DIC strain contour plots (Lagrange strain in the longitudinal direction).

It was possible to track the propagation of the critical crack in each prism by utilising virtual extensometers during the post-processing of the DIC recordings. The result is shown in Figure 10, as a visualisation of propagation of the critical crack for two typical prisms from each beam set.

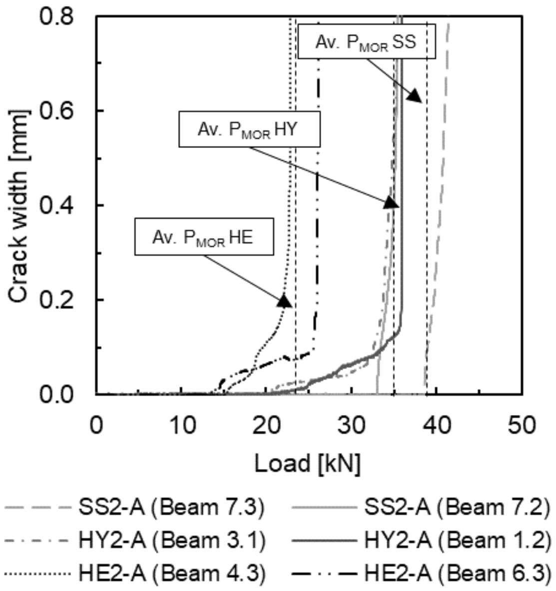


Figure 10 – Selected crack width–load curves of critical cracks. The dotted lines represent the average peak load (Av. P_{MOR}) for each beam type.

The critical crack in the prisms with straight micro fibres (SS) can be seen to form at a later stage of loading than for the other prisms, then propagating steeper. This is consistent with a high number of fibres contributing to a longer multiple cracking phase. The pull-out resistance of each straight micro fibre is low, depending only on the physiochemical bond [46]. When the pull-out of fibres finally occur in what becomes the critical crack, the low remaining capacity allows for the accelerated growth of that crack. Although a steep slope can be observed, the collapse appeared non-brittle (Figure 8). The high number of fibres at the crack surface limited the crack opening at failure. A various number of cracks were formed beside the one that developed to become critical. The average size of these cracks was similar for all beam types and limited to a maximum of 0.3 mm at failure, according to DIC measurements.

The hooked-end fibres have better pull-out properties than the straight micro fibres, due to the longer fibre length and the high mechanical bonding at the end, where the hooks anchor towards the matrix. Thus, the hooked-end fibres bridging the critical crack were capable of delay crack growth and hence having remaining capacity during propagation of the critical crack. This can be seen in Figure 10, as the curve for HE prisms is less steep than for the prisms with only straight micro fibres.

As mentioned in the introduction, there is a risk of rupture of the applied macro fibres. This is due to the relatively low tensile strength (1100 MPa) of these fibres, in combination with a high mechanical anchorage and a high strength matrix. Fibre rupture would have a negative influence on performance and ductility. However, in these experimental investigations (Mix A and B), fibre rupture was not observed. One reason might be the appearance of localised cracks (split cracks) causing premature fibre pullout, as discussed in Section 4.2 *Flexural tensile strength*.

The hooked-end fibres were pulled out of the matrix maintaining the original shape, without straightening of the end-hooks. A visual investigation of the failure zones revealed that cracks appeared near the ends of the fibres (Figure 11). This was also observed by Markovic et al. [47] for dog-bone specimens in direct tension. Straightening of hooked-end fibres leads to an increased pull-out capacity [46], but as the fibre maintained its deformed shape, severe crushing of the surrounding concrete was observed at failure. This fracturing of the matrix phase being the consequence of pull-out of un-deformed hooked-end fibres is visible in the close-up photo in Figure 11. A similar observation of non-straightened hooked-end fibres was also observed and reported in [21, 30].

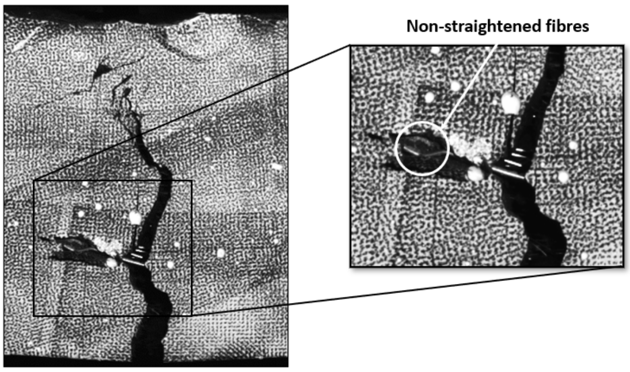


Figure 11 – Non-straightened fibre in one HE prism (Beam 4.1).

The prisms with hybrid fibre combination seemed to benefit from the synergetic effects of the two fibre types. Although the number of fibres was lower for HY prisms than SS prisms, the average number of cracks at failure was near identical. This might indicate the existence of a critical number of micro fibres, necessary to obtain the multiple-crack development. Unlike SS prisms with the critical crack being identifiable only close to failure load, the critical crack of the HY prisms appeared earlier in the loading process (Figure 10), at a load level around 20 to 25 kN. However, due to the high anchoring properties of the hooked-end fibres, the fibres crossing the critical crack was able to delay further crack propagation. The likelihood of fibre bundling and consequently impaired pull-out capacity for the hooked-end fibres, due to the formation of split cracks, should be reduced compared to the HE prisms, as fewer hooked-end fibres were present in the hybrid fibre combination. This expectation was confirmed by the empirical observation (Figure 7), with fewer fibre bundles observed.

As mentioned above, the synergetic effect of hybrid fibre combination has been found in some investigations to increase the overall performance, compared to single fibre configuration at constant vol.%. The level of gaining from the synergy is, however, depending on specifics in each situation. In our investigations, the synergetic performance of the hybrid fibre combination (HY) was not found to outperform that of single-use of straight micro fibres (SS). However, it was nearly as good. As hooked-end fibres have considerably lower cost and environmental footprint per kg than micro straight steel fibres, this is still a positive effect.

4.3 Comparison to other research and further discussion

Close to 80 UHPC mixes were identified through the papers included in the literature review (Section 2) [12, 20-22, 28, 30, 31]. In addition, four proprietary and commercially available UHPC products were included, with data from [12, 15, 35]. In Figure 12, the average compressive strength of our locally produced UHPC is compared to the strength of both the proprietary and the 80 mixes mentioned above. To compensate for the use of test specimens with different geometry, results using other specimen geometries were converted into equivalent 100 mm cube compressive strength using equations from Wille et al. [9] (Eq. 3 and 4):

$$f_c[\text{cylinder}100 \times 200]/f_c[\text{cube}100] = 0.98 \quad (3)$$

$$f_c[\text{cube}50]/f_c[\text{cube}100] = 1.04 \quad (4)$$

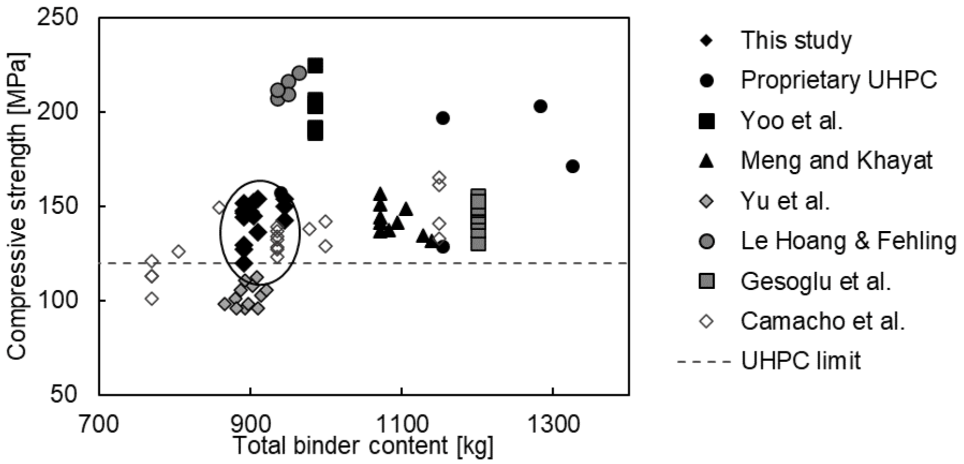


Figure 12 – Comparison between compressive strength (cube 100 mm) in this study (highlighted with a circle) using local materials to proprietary UHPC and UHPC mixes found in research.

Through careful composition, it has been shown easy to prepare UHPC from locally available constituents, performing as good or even better than the proprietary products that are commercially available. Making UHPC with available materials without manipulating PSDs might lead to reduced properties compared to the use of well-composed aggregates or proprietary UHPC products. For industrial purposes, the use of available materials without cost-rising manipulations is often crucial. UHPC class materials might be beneficial for some purposes, even if not fully complying with the UHPC requirements stated in [1] (dotted line in Figure 12). Other qualities than compressive strength might be more important in some applications. One example might be to benefit from the extended durability compared to ordinary concrete, e.g., in the renovation of bridge decks where water tightness is required to delay corrosion of reinforcement in the underlying original structure. Also, UHPC mixes that need curing at elevated temperature to perform better than the requirements stated in [1], might prove to be a better option in terms of cost when utilised without this special curing regime [16].

The flexural strength empirically achieved in this investigation with capacities 18-25 MPa (SS and HY prisms) after only 7 days of curing, was found in line with results found in most of the papers included in Table 2. Higher capacity can be achieved, like those of the proprietary UHPC product presented (Table 2) and the mixes presented by Yoo et al. [21, 30]. Improved flexural capacity could be a result of longer curing or application of heat treatment [4] in line with instructions given by Yoo et al. [21, 30]. However, tensile strength is primarily believed to be influenced by the fibre content. So is the cost and environmental footprint. The price of high strength straight micro fibres is substantially higher than that of ordinary hooked-end macro fibres. Correspondingly is the CO_2 emission, as the micro straight fibres are made from high tensile strength steel through a highly emitting production process (wet wire drawing into small diamters) [18]. Thus, even if the content of micro fibres exceeding 6 vol.% is seen in proprietary UHPC products, it seems wise to adjust the fibre content to meet the requirements for classes of applications. Further benefits might come from investigating potentials indicatively presented in this paper, through partially substituting the straight micro fibres with macro hooked-end fibres, and through optimising the matrix for fibre bonding and distribution.

The opportunity to benefit from adjusting the fibre content to what is strictly needed, from synergies in hybrid fibre configuration and to optimise the matrix for fibre bonding and distribution, seems all to be in favour of UHPC made from locally produced constituents. Correspondingly the potential in using UHPC mixes is made low-cost without manipulating PSDs for optimisation when only certain properties of the UHPC are needed. However, to gain from these opportunities, knowledge and competence on how to produce and manipulate the UHPC is needed.

5. CONCLUSIONS

The work presented in this paper has shown that it is possible to develop UHPC materials using available constituents by applying simple recommendations on mix proportions and the modified Andreasen and Andersen curve. Compressive strength above 120 MPa was achieved, without applying heat-curing. Even higher compressive strength up to 166 MPa was achieved by applying heat treatment for 48 hours at 90°C. High flexural capacity was demonstrated for prisms, and the deformation behaviour was investigated using a Digital Image Correlation (DIC) camera system. The influence of steel fibre content, type, and hybrid combination in two UHPC mixes can be summarised as follows:

- Neither the compressive strength nor E-modulus of cylinder specimens was found to be influenced by the inclusion or content (vol.%) of steel fibres. A tendency towards a small increase in compressive strength correlating with fibre content was visual for cube specimens. It is suggested that cylindrical specimens simulate the uniaxial conditions better than the cubes and that the appearing strength gains in cubes are attributed to specimen geometry rather than being a material property. The compressive capacity was not found to be affected by variations in fibre type.
- Variations of 60% in flexural strength was found in the fine-grained UHPC mix (Mix A) at a constant level of fibres (2 vol.%) when varying the fibre type from hooked-end macro fibres (HE) to micro fibres (SS). For the coarser mix (Mix B), the corresponding variations were only 15%. Thus, the matrix composition is found to influence the effect of fibres.
- Other factors than just the type and combination of fibres are found to influence the flexural tensile strength of the UHPC, such as flowability, constituent materials and mix design of the matrix. Denser particle packing and smaller aggregate size were found to increase the effect of the straight micro fibres. Consequently, to successfully predict the effect of fibres, also the matrix composition must be considered.
- The hybrid combination (HY) of 50% micro straight steel fibres and 50% hooked-end fibres (2 vol.%) was found to induce similar flexural strength as the exclusive use of straight micro fibres (SS), consistent for both types of UHPC mixes. UHPC with hybrid fibre combination seems to draw synergies by benefiting from the best of each fibre type. Hooked-end fibres are beneficial for reducing CO_2 emissions and cost. Hence, hybrid combinations of fibres demonstrate a potential for gaining the environmental footprint of locally produced UHPC, and to lower the unit price by 30%. There is a risk that especially the macro fibres have an increased tendency to orient along the beam axis due to the wall effect. The consequence would be overestimating the tensile capacity, compared to a situation where the fibres are randomly oriented.
- The opportunity to benefit from four mechanisms seems to be in favour of the development and application of UHPC made from local constituents, compared to the use of proprietary products: i) Adjusting the fibre content to what is strictly needed, ii) synergies from hybrid fibre configuration, iii) optimised matrix composition for fibre bonding and distribution and iv) producing low-cost UHPC mixes without manipulating PSDs for optimisation, when only certain properties of the UHPC are needed. However, to gain from these opportunities, knowledge and competence on how to produce and manipulate the UHPC is needed.

ACKNOWLEDGEMENTS

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Paper VI

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

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

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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 five-tool strategy for more sustainable use of UHPC. The strategy 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*.

Keywords:

- Ultra-high Performance Concrete (UHPC)
- Ultra-high Performance Fibre Reinforced Concrete (UHPFRC)
- Environmental impact
- CO_2 emissions
- Sustainability
- Sustainable concrete

1. Introduction

1.1. 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 [1].

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" [2], 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 [3], with their embodied CO_2 and energy consumption lower than steel [4]. However, massive greenhouse gas emissions and the demand for resources are associated with the concrete industry [5, 6]. 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 [5, 6]. According to a recent report by Scrivener et al. [7], 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 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.

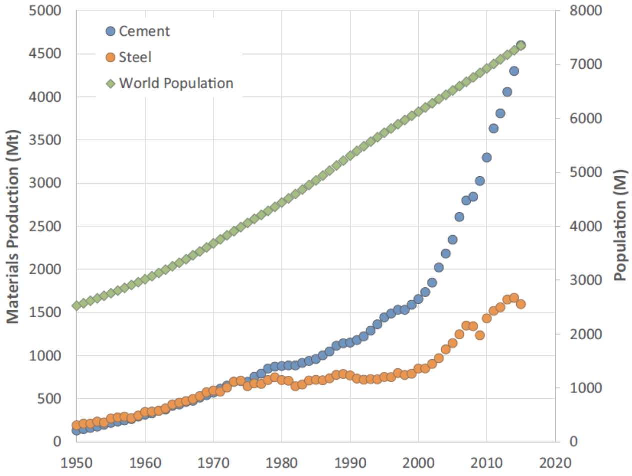

Fig 1: Comparison of cement and crude steel production growth towards world population, according to Scrivener et al. [7]. Reprinted with permission from Elsevier [8].

Conclusions from the 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 [9]. However, a possible sustainable approach to utilise UHPC has not been sufficiently investigated.

1.2. 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.

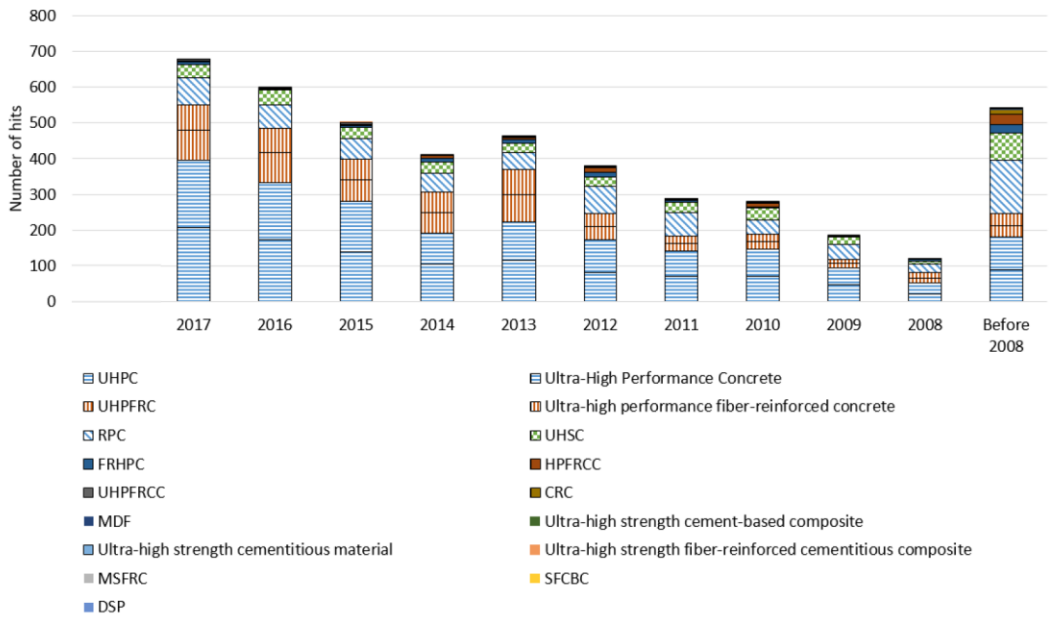

Fig 2: Development in publication rates on papers regarding UHPC (including alternative notations), according to Larsen et al. [10].

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 [11]. 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 [4, 12-14]. However, the high content of cement (700–1400 kg/m^3) [15-17] and high-strength steel fibres (2–9 vol. %) [11, 16, 17] indicates that the CO_2 emission per volume unit of UHPC is higher than that of conventional concrete [17, 18].

Wang et al. [19] 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 [20-24]. Others applied other local industrial by-products or construction and demolition (C&D) waste to reduce the cement content, such as red mud [25], basalt powder [26], lead-zinc tailings [27], waste from clay bricks and cement solids [28], concrete demolition waste [29] and glass powder [30]. Methods replacing costly micro-silica have also been investigated [31]. Other sustainable approaches found in research include applying fibre types other than micro straight steel fibres [32-35], hybrid configurations of different fibre types [36-39], or attempts to control and improve the distribution and orientation of the fibres [24, 40, 41]. Alternative approaches have focused on applying aggregates other than the typical quartz sand used in UHPC [42-45].

Some studies have focused on the structural level through life cycle assessments (LCA) of UHPC solutions compared to traditional methods [17, 18, 46, 47].

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.

2. 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.

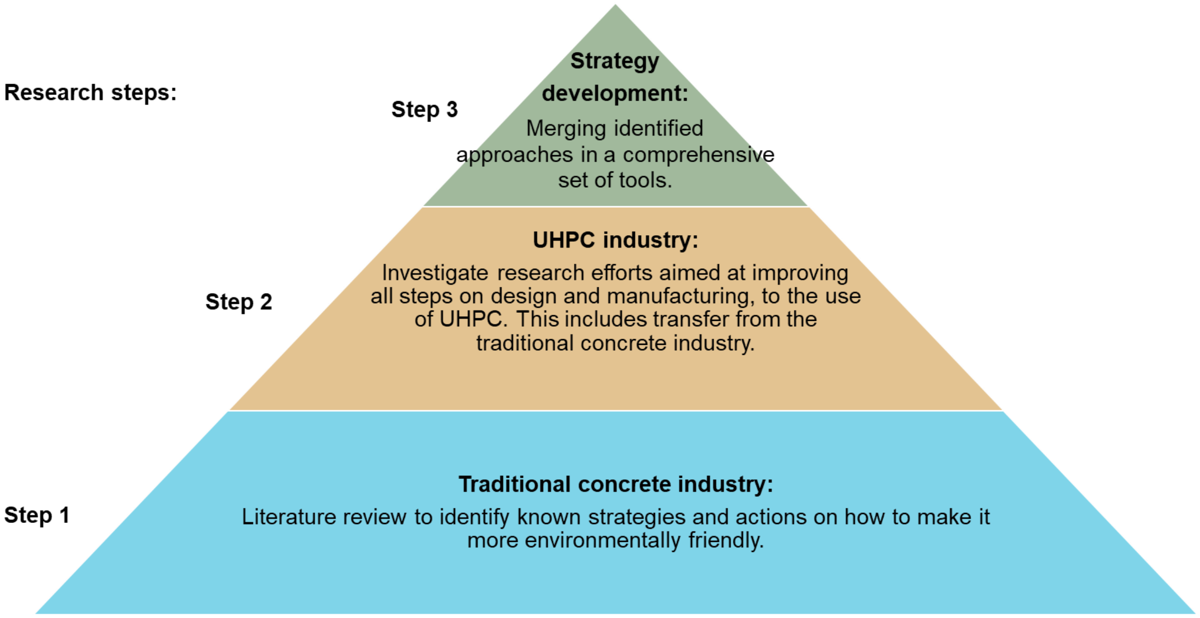

Fig 3: Stepwise descriptions of the procedure followed to identify strategies to improve the sustainability of UHPC.

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.

3. Results and discussion

3.1. 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 [48] 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 [49].
- *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 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).

3.2. An existing strategy to expand

Mehta [50] 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*.

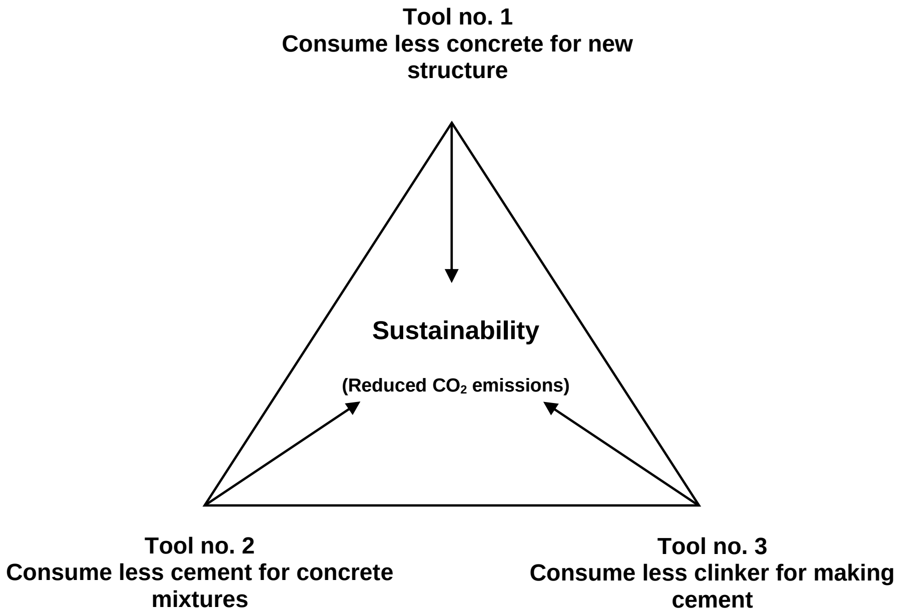

Fig 4: Mehta's strategy for a more sustainable concrete industry in terms of reduced CO_2 emissions. Redrawn according to Mehta [50].

Mehta’s first tool, *Consume less concrete for new structures* [50], has been suggested by other researchers, such as Scrivener et al. [7], Miller et al. [51] and Habert et al. [6]. Reducing CO_2 within this tool can be achieved by innovative designs to limit concrete consumption [6, 7, 50] using concrete with high durability that extends the time before a structure needs to be demolished and rebuilt [6, 7, 50] and using reusable prefabricated elements [50]. One example involves using high-strength concrete for new bridge designs to reduce concrete volume and environmental impact [52]. The other is using UHPC for bridge rehabilitation (example in [17, 46]). However, Scrivener et al. [7] highlighted that although measures within the structural design can contribute to a significant reduction in CO_2 emissions, considerable efforts must be invested 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 [7] 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 [7, 50]. 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 [6, 7]. John et al. [53] showed that by applying this measure 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. Thus, the measures originally presented by Mehta have until recently been repeated and elaborated upon by others, for example, Scrivener et al. [7] and Habert et al. [6].

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 [4, 7, 50], as well as limestone powder [6, 7]. These may be added during concrete mixing or manufactured by the cement producer in blended cement. Adding SCMs is a well-established measure in the concrete industry [7, 54]. Currently, the majority of cements sold in Europe are blended types [54]. The most sold cement in Europe is Portland composite cement (CEM II-A), where up to 20% of Portland clinker is substituted with limestone [54]. Fly ash and blast furnace slag are the widely used SCMs [6]. Owing to decreased availability in the future, it is vital to find other materials to substitute cement [6, 7]. Adding various types of SCMs in UHPC mixes to substitute cement has also been reported by several researchers [20, 22, 23, 55].

According to Mehta [50], a reduction of 50% in cement clinker consumption may be possible when these three tools are combined. Active research [4, 6, 7, 51, 54, 56, 57] 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. [58], 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.

3.3. 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 3.2). Another example is the paper "Reducing the Environmental Impact of Concrete" [2], which focuses on consuming and conversing 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 3.1) and whether they primarily contribute to reducing CO_2 emissions or conserving natural resources through reuse or recycling, using the notation *circularity*.

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):*				[50]
Design efficiency: innovative structures and designs to reduce the use of concrete	➡	➡	➡	[6, 7, 48, 50, 51]

Reuse elements/structures	➡↻	➡↻	➡↻	[6, 48, 50, 51]
Prefabrication	➡	➡↻	➡↻	[6, 51]
Building flexibility		➡↻	➡↻	[48]
Apply durable concrete materials for longer service life with limited maintenance		➡	➡	[7, 48, 50]
Repair existing structures with HPC/UHPC	➡	➡	➡	[6, 17, 46, 47]
*Consume less cement for making concrete (*Mehta's *Tool no.*2*):*				[50]
Apply 56- or 90-day compressive strength (especially relevant for alternative binders)	➡	➡	➡	[50]
Utilise superplasticisers instead of water (and cement) to adjust workability or reduce the water content	➡	➡	➡	[4, 7, 50]
Utilise other chemical admixtures	➡	➡	➡	[4, 7]
Utilise fillers (inert materials) in combination with admixtures	➡	➡	➡	[6, 7]
Optimize particle size and grading to limit the need for cement paste	➡	➡	➡	[6, 7, 50]
*Consume less clinker for making cement (*Mehta's *Tool no.3):*				[50]
SCMs added in concrete mix or blended cements	➡↻	➡↻	➡↻	[4, 6, 7, 48, 50, 51, 56]
Utilise locally available by-products from other industries to substitute cement	➡↻	➡↻	➡↻	[7]
Cement manufacturing:				
Efficiency of clinker production, e.g., use of alternative fuels, dry technologies	➡↻	➡↻	➡↻	[4, 6, 7, 48, 51]
Use of alternative cements (non-Portland clinkers) (e.g., geo-polymers)		➡	➡	[4, 6, 7, 51, 56]
CCS/CCU		➡	➡	[4, 6, 7, 51, 56]
Recycling:				
Recycle components	➡↻	➡↻	➡↻	[6, 48, 50, 51]
Recycle concrete aggregates	➡↻	➡↻	➡↻	[4, 7, 51, 56]

Recycle other materials (e.g., excavation materials, C&D waste) as aggregate in concrete	➡ ↻	➡ ↻	➡ ↻	[6, 51]
Facilitate CO_2 uptake at the end-of-life	➡ ↻	➡ ↻	➡ ↻	[6, 51]
Recycling of materials as a binder in concrete	➡ ↻	➡ ↻	➡ ↻	[6, 7, 51]

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.

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.
- 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.

3.4. UHPC composition, material properties, and environmental impact

3.4.1. 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) [59], low *water-to-cement* ratio (*w*/*c*-ratio) of approximately 0.14–0.3 [15, 60], extensive use of superplasticisers [15, 16], high binder content, and micro-steel fibres [11, 15, 16, 59] primarily in the range of 2–6 vol.% [11, 16]. The binder content is often composed of 700–1000 kg/m^3 Portland cement [15, 16, 61] and micro-silica content of approximately 25% of the mass of cement [15, 16, 60, 62]. A cement content of up to 1400 kg per m^3 [17] and micro-silica content of up to 50% were found [61]. Occasionally, additional cementitious binders, such as fly ash, blast furnace slag, or limestone powder [15, 60, 61], are used. Solid materials are densely packed, often through particle packing models, such as the modified Andreasen and Andersen model [39, 55, 63, 64]. Quartz sand in fractions with particle sizes ranging from 0.1 to 600 micrometres is often used for aggregates and as fillers to help densify the particle skeleton [15].

Few commercial producers of UHPC dominate the global market. The typical compositions of these products have been reported previously [16, 65-67]. A summary is presented in Table 2.

Table 2: Typical compositions of commercially available UHPC powder mixes from dominant producers [16, 65-67]

	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	981
Ground quartz	211	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

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

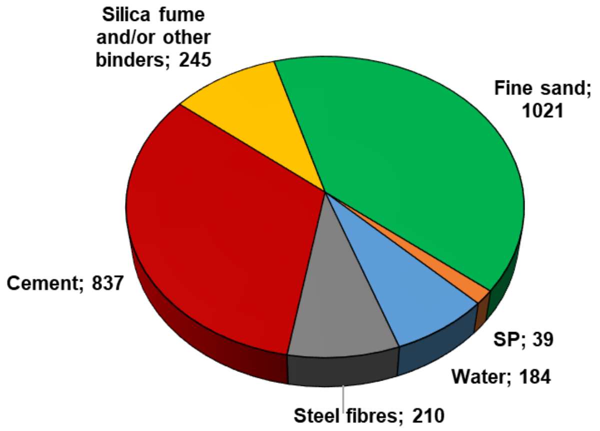

Fig 5: Typical composition of UHPC presented in [63] (based on data in [39]), each material stated in kg/m^3.

Steel fibres are usually included in UHPC, which is essential to avoid the brittle behaviour occurring in tension and compression [68]. The steel fibres used in UHPC are usually micro-steel fibres with high tensile strength [15, 68, 69]. The data for steel fibres typically used in commercially available UHPC products are listed in Table 3.

Table 3 Typical data for steel fibres in commercially available UHPCs [69]

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 of SS and HE.
[1] Laboratory developed. [2] Subsidiary of a multinational corporation.

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.

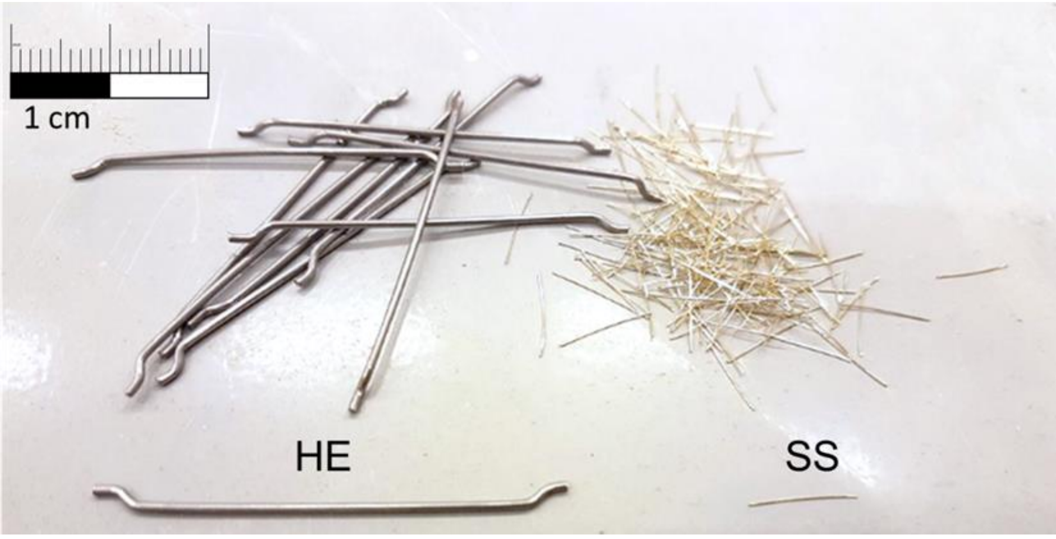

Fig 6: Steel fibres typically used in UHPC (SS) compared to fibres typically used in traditional concrete (HE) [70].

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).

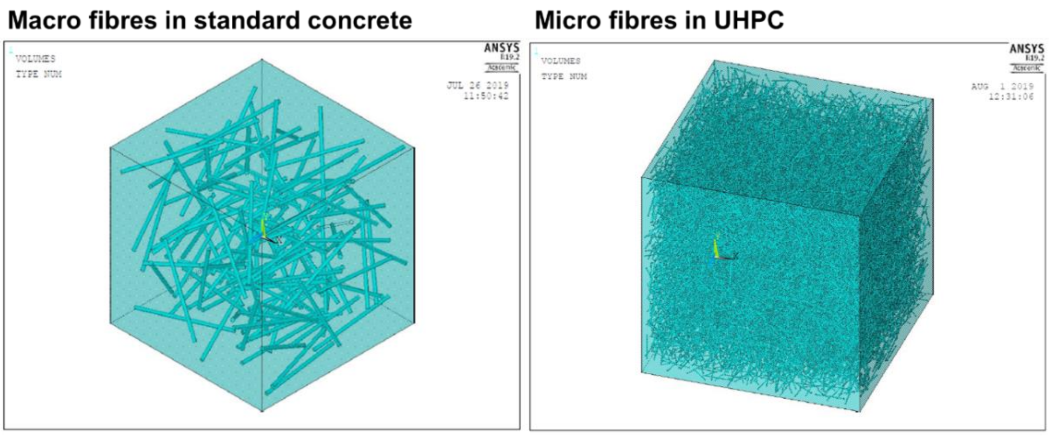

Fig 7: Typical distribution of fibres in a 10 cm cube in standard concrete (left) vs UHPC (right) (own simulations).

UHPC can be produced using conventional equipment [16, 71]. However, mixing time is usually longer [16, 71]. 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 [15]. Steam curing at 90 °C for 48 hours has been found to accelerate strength development and improve the final compressive and tensile cracking strength, E-modulus, and durability [16, 72]. 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 [71, 73].

3.4.2. 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 [69]. 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 [16].

The compressive strength of UHPC varies from around the strength limit for UHPC materials (120 MPa) [35, 55, 64, 72, 74] to above 180 MPa [33, 34, 37, 72] without using synthetic aggregate and pressure curing. The flexural strength of UHPC depends on the applied fibre type and content [33, 34, 37, 68, 75]. UHPC products can have flexural strengths above 40 MPa [37, 72] and uniaxial tensile strength from around 6 up to 13 MPa [16, 69].

The increased durability properties include considerably better resistance against chloride ingression and carbonation and improved frost resistance (freeze-thaw) compared to conventional concrete [16]. The higher resistance against these mechanisms is predicted to provide structures with at least twice the service life of conventional concrete structures [23].

3.4.3. Environmental impacts of UHPC materials

Calculations on how the different constituents contribute to the CO_2 emissions of UHPC have been reported previously [17, 18, 76]. 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 [17, 77]. 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.

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}	[17]
Micro-silica	3.1×10^{-4}	[17]
Limestone filler	2.6×10^{-2}	[17]
Blast furnace slag	1.9×10^{-2}	[77]
Fly ash	9.0×10^{-3}	[77]
Sand	2.4×10^{-3}	[17]
Quartz sand	1.0×10^{-2}	[77]
Superplasticiser	7.5×10^{-1}	[17]
Water	1.5×10^{-4}	[17]
Micro-steel fibres	2.68	[17]

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 3.5.1 and 3.5.2.

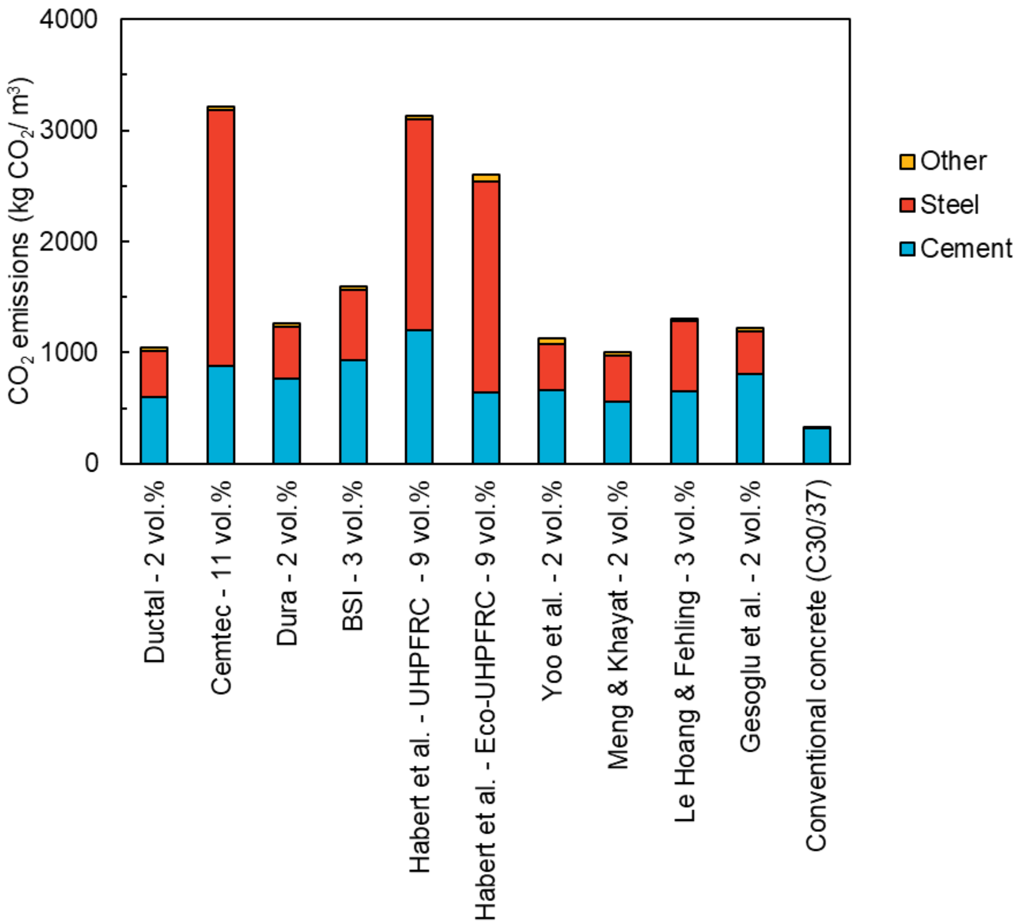

Fig. 8 Comparison of CO_2 emissions of UHPC material per cubic meter from different references, including proprietary recipes [16, 65-67] *and recipes found in research [17, 33, 34, 36, 37, 75]. Data for the conventional concrete was found in [17].*

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 [17, 76]), with the production of 1 kg of micro-steel fibres typically emitting around 2.7 kg of CO_2 equivalents [17, 76], while the production of steel fibres for conventional concrete emits between 0.77–1.5 [78, 79]. 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 [60] and [76]).

Curing at elevated temperatures increases CO_2 emissions. Shi et al. [77] found that the influence of steam curing was 125.7 kg of CO_2 emissions per m^3 of UHPC.

3.5. Constructing a strategy for the sustainable use of UHPC

According to Section 3.2 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 (Section 3.2).

A further reduction in the CO_2 emissions of UHPC can also be approached by extending the logic of Mehta [50] 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.

3.5.1. 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" [50] (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 cement consumption, identifying alternative binders and densifying the particle skeleton as the primary measures [6, 7].

As UHPC has a high cement content and a low *w*/*c* ratio (between 0.14–0.3) (Section 3.4.1), large portions of the cement will remain unhydrated [64, 80]. 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 [80]. 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 [24, 25, 55, 81]. 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 [22, 23, 55, 77, 82]. Additionally, various locally available C&D waste or industrial by-products are appropriate to reduce the cement content in UHPC [27, 29, 81]. This will be further discussed in Section 3.5.3. 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.

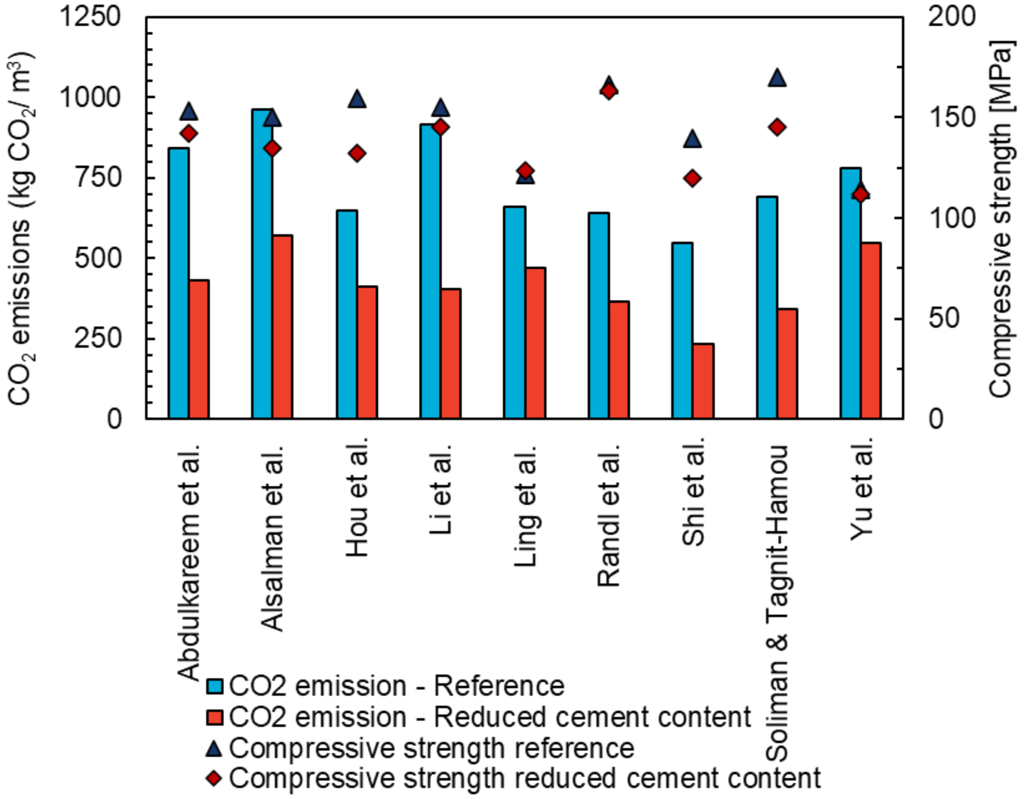

Fig. 9: Comparison of CO_2 emissions of UHPC material without steel fibres per cubic meter from different references. The compressive strength is also given on the secondary axis. The figure shows the reference UHPC recipe compared to a recipe with reduced cement content while limiting the reduction in compressive strength to 15%. The values are found in [22-25, 30, 77, 83-85] and calculated in accordance with Fig. 8.

Achieving a high reduction in the cement content of UHPC can reduce CO_2 emissions 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)*.

3.5.2. 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 [36-38, 86, 87] or applying various fibres with better pullout properties, such as longer or deformed steel fibres (e.g. twisted or hooked-end) [33, 35, 75, 88]. Several recent papers have attempted to utilise hybrid fibre configurations, combining the microfibres usually applied in UHPC with macro hooked-end fibres (e.g., [36, 37, 39]). Using the hybrid fibre configuration could potentially achieve synergetic effects that compensate for the reduced number of macrofibers compared to microfibres [39]. Other approaches for more efficient use of fibres are the improvement of fibre distribution and orientation by controlling the casting process [24, 40, 41, 89] and using synthetic fibres or other materials with lower CO_2 emissions [32].

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*).

3.5.3. 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 [2]. This measure can also be applied to UHPC, for example, by using industrial by-products to partly substitute cement in UHPC (Section 3.5.1). Various by-products can be utilised in UHPC to substitute cement, such as common SCMs (fly ash and blast furnace slag) [23, 55, 90], inert rock dust collected from rock crushing [44, 45, 63], recycled construction and demolition (C & D) waste [28, 29, 91] and locally available industrial by-products [25, 27, 85].

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, 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 [6, 7]. By-products or surplus materials have been used to replace high-quality quartz sand in UHPC [39, 42-45, 63], as the production of quartz sand to obtain the required aggregate size (150–600 μm) can be energy intensive and polluting [43, 44]. 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 over 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 [92].

3.5.4. 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 3.4.1), 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 [39, 60, 61, 73, 74, 93, 94], and in standard ready-mix facilities for conventional concrete [71, 93] using standard curing methods [71, 73]. 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 over 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.

3.5.5. 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 [71, 95-100]. The increased strength can reduce the material consumption of some structures, and the service life can be considerably extended [14, 23]. A promising area of research is the bridge sector. UHPC is especially applicable for rehabilitating deteriorated bridges [11, 59, 98-100]. In such cases, UHPC is often applied as an overlay on existing reinforced concrete structures, improving the structural capacity [101, 102] and durability [59] 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 [17, 46]. UHPC can also be applied to new structures as a primary construction material [11, 16, 59, 69]. The applications within the bridge sector are well documented, for example, by the US Federal Highway Administration in [16] and [103]. In Europe, Switzerland has taken the lead in applying UHPC within the bridge sector, winning projects in commercial terms and documenting projects effectively [59, 99, 100]. However, relatively few research initiatives [17, 18, 46, 47, 104] 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 in a short-time horizon, for example, when using UHPC for bridge rehabilitation [46]. 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 [17, 47, 76, 104]. 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 [17, 18, 47, 104] (*Focus 2050* and *Focus lifetime*).

3.5.6. 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 [96], France [97], and Switzerland [59] in Europe, in addition to the US and several others [16]).

4. Conclusions

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

- *Efficient use of cement* can be achieved by reducing the cement content in UHPC through a combination of dense particle packing and substituting part of the cement with materials having lower CO_2 emissions. Inert materials and SCMs common to conventional concrete (fly ash, blast furnace slag, and limestone powder) can be used, as well as locally available construction and demolition waste and industrial by-products.
- Opportunities within the *Efficient use of steel fibres* tool include using fibres with better pullout properties (e.g., longer or deformed steel fibres), using synthetic fibres with lower CO_2 emissions, utilisation of hybrid fibre configurations (combination of different fibre types), and enhancing the fibre orientation and distribution.
- The *Circularity: Utilisation of by-products* tool includes the possibility of utilising industrial by-products or construction and demolition waste to substitute cement, the special quartz sand that is often a constituent in UHPC, and the aggregate. Thus, locally available materials are preferable.
- *Local production* considers using available materials and local production to develop UHPC mixes rather than transporting UHPC premixes over long distances. In addition, it is expected that local production would contribute to raising awareness of the potential and competence of UHPC, which is necessary to promote its utilisation.
- *Efficient use of UHPC in structures* involves identifying favourable application areas for UHPC, where the environmental impact can be reduced, as well as competitive solutions compared to conventional concrete. Based on current research and applications, using

UHPC for bridges and bridge rehabilitation are potential application areas where the improved strength and durability properties of UHPC can be utilised.

Applying all five tools simultaneously is a promising approach for the sustainable application of UHPC. The application of each tool has the potential to contribute to reducing the environmental impact in either of the three-time foci addressed in the discussion above *Focus 2030*, *Focus 2050*, or *Focus lifetime*. 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.

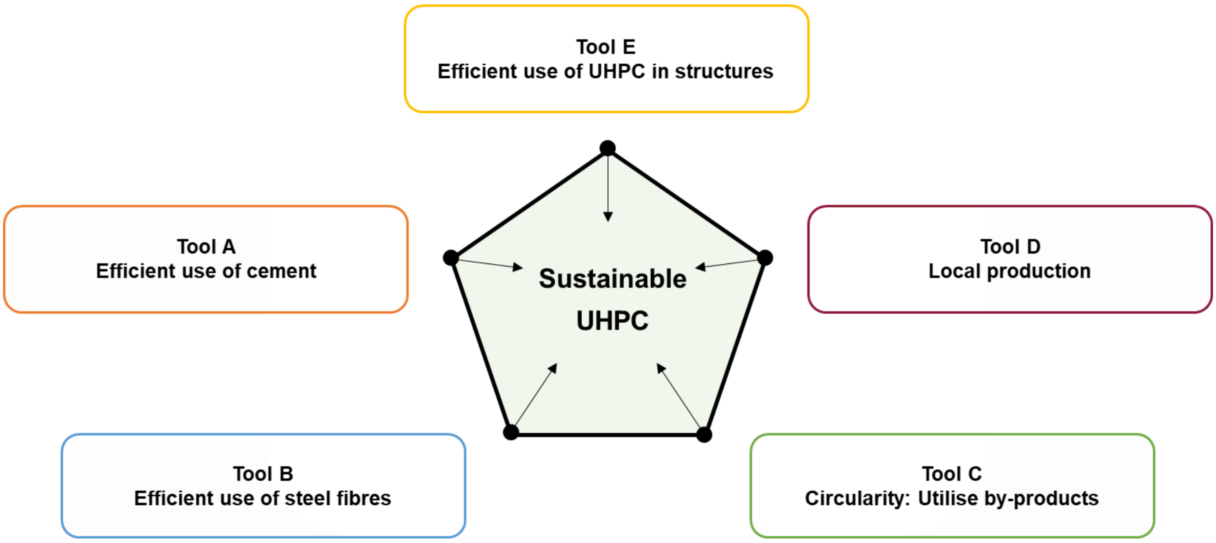

Fig 10: Strategy for making UHPC more sustainable.

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