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 %	10.8

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	239.7	0.29
R2	10	689.7	76.7	1204.3	191.7	41,4	0.69	220.3	0.29
R3	20	613.0	153.3	1204.3	191.7	41,4	0.61	201.3	0.29
R4	30	536.3	230.0	1204.3	191.7	41,4	0.54	182.0	0.29
R5	40	436.0	306.7	1204.3	191.7	41,4	0.46	163.0	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, 18,5 % 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.

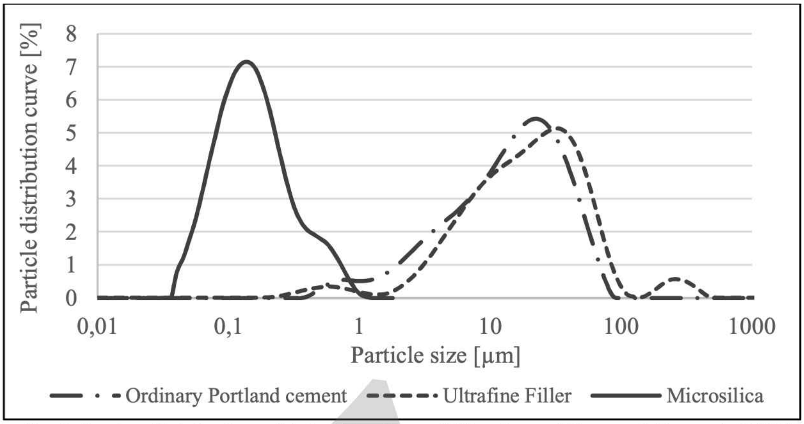

Fig. 1 Particle size distribution obtained by laser diffraction of the used Cement (OPC), Ultrafine inert filler (UF) used to substitute cement, and lastely the Microsilica (MS) (having the smallest particle size).

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.

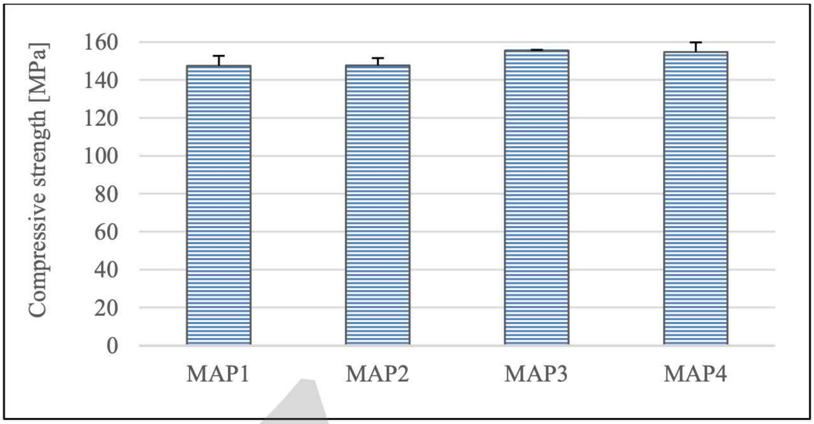

Fig. 2 Average results and in-series variability in compressive strength, for 50 mm x 50 mm x 50 mm cubes for the reference recipe using four different superplasticizers. In-series variability is characterized by standard deviation (SD), indicated on top of each column.

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).

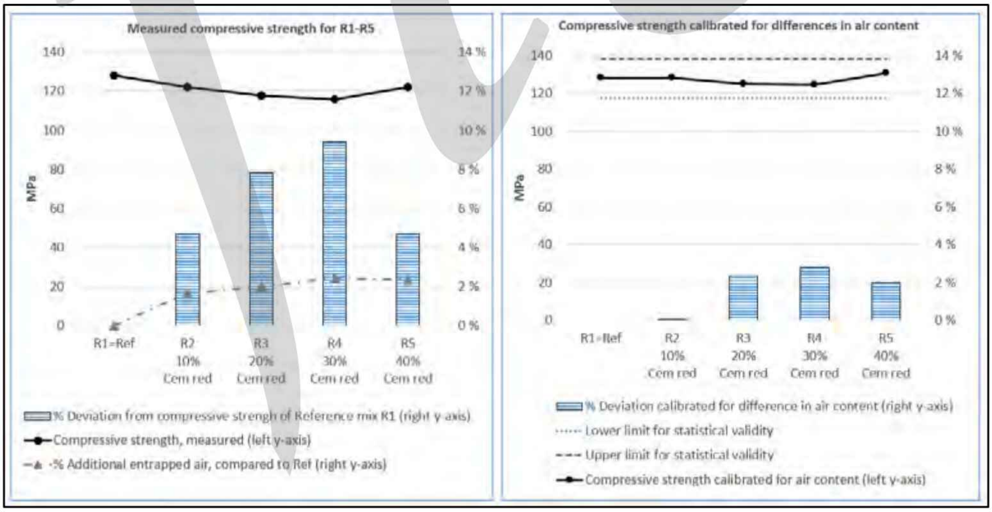

Fig. 4 Left: Measured values for compressive strength during up to 40% cement substitution. Right: Compressive strength calibrated for variations in air entrapped in specimens.

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 where 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.

Acknowledgement

This work was supported by two funding bodies: The Research Council of Norway (NFR) and Sørlandets Kompetansefond, through the project MEERC (More Efficient and Environmental friendly Road Construction).

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