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Material efficiency in the design of ultra-high performance concrete

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HIGHLIGHTS

- Material efficiency in ultra-high performance concrete design.
- Using spread value as quick indicator to fine-tune mix design.
- Combine workability, mechanical performance and costs to conclude efficiency.
- Provide UHPC mix designs using materials available in the US.
- Material costs are mainly influenced by fiber reinforcement.

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ABSTRACT

This research investigates the material efficiency in the design of ultra-high performance concrete. The material efficiency is influenced by the flowability, mechanical performance, durability and cost. Suitable material constituents have been pre-selected based on their properties and availability in the United States of America. The efficiency of the constituents is progressively investigated using the following three step approach emphasizing: (1) ultra-high performance paste, (2) ultra-high performance matrix, and (3) ultra-high performance fiber composite. Mix design recommendations for performance and cost effective ultra-high performance concretes are made and conclusions for further enhancements are drawn.

1. Introduction

Ultra-high performance concrete (UHPC) has the potential to address the poor condition of the ageing infrastructure in the United States of America, rated with a D+ by the American Society of Civil Engineers (ASCE) in 2013 [1]. ASCE estimated that an investment of $US 3.6 trillion is needed by 2020 to remedy the infrastructure. The two main reasons for the poor conditions are identified as corrosion of steel reinforcement and concrete deterioration through invasive ions. UHPC's durability and low permeability against chlorides, sulfates, carbon dioxide and other aggressors are the key properties to building structural elements of longer lifespan and reduced maintenance. UHPC conferences in Kassel, Germany in 2004, 2008, 2012 [2–4] and Marseille, France in 2009, 2013 [5,6] have demonstrated the material's mechanical and durability performance in this regard. In comparison to the cost of conventional concrete of about $US100/yd^3 ($US130 per m^3), commercially available UHPC is about 20 times more expensive. The proprietary nature, increased quality control and high material costs have hindered an accelerated and wide spread use of UHPC in the U.S. infrastructure. Addressing these concerns, this research provides methodical recommendations for material efficiency in the design of UHPC. The efficiency of selected material components will be shown and several UHPC mix proportions will be provided based on local available materials.

2. Definition and material selection

Based on information from Rossi [7,8] and international conferences [2–6] the American Concrete Institute (ACI) committee 239 drafted the definition for UHPC as follows: "Concrete, ultra-high performance – concrete with a minimum specified compressive strength of 150 MPa (22,000 psi) with specified durability, tensile ductility and toughness requirements; fibers are usually required to achieve specified requirements." A summary of chronological advances in matrix and fiber development, as well as the historical

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development of different high and ultra-high performance concrete mix designs from the 1970s on, is provided by Naaman and Wille [9]. To the best of the author's knowledge the first non-proprietary concrete mix design achieving ultra-high compressive strength in excess of 150 MPa by using materials available in the U.S. without the application of heat or pressure treatment has been reported by Wille et al. [10]. Research efforts by Wille et al. [11–14] show that UHPC can be designed achieving compressive strength in excess of 200 MPa (29 ksi) by using materials available in the U.S. under ambient curing conditions without the need of special treatment. The basic principles of UHPC design include high particle packing density (low porosity), high material quality (low impurity), cement hydration chemistry (high density calcium–silicate–hydrate [C–S–H]), pozzolanic reactions and filler effect of supplemental materials (C–S–H formation and low porosity), high particle dispersion quality (low porosity and enhanced workability), optimized particle to high range water reducer (HRWR) interaction (enhanced particle dispersion) and excess paste (enhanced workability and robustness). Based on these principles and on the experimental results of prior research [11–14] the material constituents for designing UHPC are pre-defined and their approximated median particle size, as well as their range of particle size distribution, are listed as recommendations in Table 1.

Additionally prior research results [11–14] suggest the following mixture proportions for designing UHPC:

- Cement (C):silica fume (SF):supplemental material (SM) = 1:0.25:0.25 by weight,
- Water (W) to cement (C) = 0.2–0.3 by weight,
- Aggregate (A):cement (C) = 1.0–2.0 by weight,
- Fiber volume fraction (V_f) = 1.0–2.0 Vol.%.

3. Research approach

In order to satisfy time efficiency and material performance in the UHPC design the following three step progression is proposed and used in this research: (Level 1) investigation of the cementitious paste (C + SF + SM + HRWR + W), (Level 2) investigation of the cementitious matrix (paste + aggregate), and (Level 3) investigation of the cementitious composite (matrix + fiber). The key component in UHPC design is the optimization of the paste in its particle packing density providing the basis for mechanical and durability performance. Based on the strong correlation between rheological and mechanical performance of the cementitious paste [11], changes in particle packing density can be assessed indirectly through a spread test in accordance with ASTM C 230/C 230 M. To increase the flowability of the paste while maintaining the amount of water constant (or to maintain the same flowability while reducing the water content), the packing density has to be increased such that the volume of water-filled voids is reduced. Therefore, less water is physically trapped, leaving more of the remaining water available to cover the surface of the particles. This increases the thickness of the water film on the surface of the particles and decreases the overall viscosity of the paste. Thus, by improving the rheological behavior, the water to cement ratio (w/c) can be reduced to maintain the same workability, which is one necessary condition to achieve an ultra-high strength paste and thus UHPC. Furthermore, increasing the particle packing density decreases the porosity of the paste, which is the key parameter for improving durability performance [15]. Therefore, focusing material design on particle packing optimization and costs simplifies the research activities.

Based on the relative workability (spread), the relative compressive strength (f'_c) and the relative costs of the paste, the dimensionless efficiency parameter E is introduced (Eq. (1)):

$$E = \frac{0.7 \times \frac{f'_{c,N}}{f'_{c,N,\varnothing}} + 0.3 \times \frac{\text{spread}_N}{\text{spread}_{N,\varnothing}}}{\frac{\text{cost}_P}{\text{cost}_{P,\varnothing}}}, \quad (1)$$

where $f'_{c,N}$ is the 28-day compressive strength normalized at w/c = 0.25 and at an air content of 3%, $f'_{c,N,\varnothing}$ is the average normalized 28-day compressive strength over all pastes of one series, spread_N is the spread value normalized at w/c = 0.25, $\text{spread}_{N,\varnothing}$ is the average normalized spread value over all pastes of one series, cost_F is the cost of the paste per m^3, and $\text{cost}_{P,\varnothing}$ is the average cost over all pastes of one series.

The efficiency parameter has been derived to reflect the paste performance over its material costs. Based on the research approach targeting pastes with low porosity and high particle packing density, thus high compressive strength and workability, the performance is indicated by the relative strength and relative workability. The factors 0.7 and 0.3 have been chosen to consider strength with higher priority over workability. While the relative performance is defined to be directly proportional to the efficiency parameter, the relative costs has been defined to be indirectly proportional.

The effect of each material component on the paste's relative strength, spread and cost is evaluated. Then the material component with the best efficiency out of each series is chosen to form the optimized paste, which is used for the material design of Level 2 (matrix) and Level 3 (composite).

Once the paste has been designed the addition of aggregates follows leading to design Level 2. In accordance to Level 1 the investigation of the matrix is focused on its compressive strength, its workability and its cost efficiency. Investigation parameters include the type and form of aggregate, the maximum aggregate size, the particle size distribution, and the aggregate to cement

Table 1
Recommended material constituents for UHPC matrix design based on [11–14].

Type	Cost[a]	Particle size in μm			Comments
	$US/ton	Median	D10%	D90%	
Water (W)	–	–	–	–	–
HRWR	13–20[b]	–	–	–	Best in workability and air release
Silica fume (SF)	350–1100	0.2–1	0.1	2	Low carbon content
Supplemental material (SM)	46–879	2–5	1	10	Filler effect, spherical shape and pozzolanic reaction preferred
Cement (C)	92–250	10–20	3	40	Low C_3A, high $C_3S + C_2S$
Fine agg. 1	8.5–162.5	100	>50	<300	High quality, high strength, low water absorption, optimized particle packing
Fine agg. 2	8.5–162.5	500	>300	<1000	
Coarse agg.	8.25–19		>1000	<9000	
Fibers	2800–13,300				Tailored bond with matrix, sufficient tensile strength to prevent fiber failure

[a] Costs of the material components used in this research.
[b] Costs per gallon (3.8 L).