Material Efficiency in the Design of UHPC Paste

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Abstract:

High material costs and sustainability concerns due to the use of a larger amount of cement in ultra-high performance concrete (UHPC) has held back its wide spread practical application in the first place. In this research material efficient design of UHPC paste has been assessed. The proposed material efficiency parameter takes into consideration the influence of workability, compressive strength, cost and environmental impact. The global warming potential (GWP) is selected to represent the environmental impact.

Keywords: Ultra-high performance concrete, Sustainability, Efficiency, Cost

1. Introduction

Despite its superior performance, accelerated and wide spread application of UHPC remains held back by high material costs and environmental impact. In comparison to the cost of normal strength concrete (NSC) of about $130/m^3, commercially available UHPC is around 20 times more expensive [1-2]. The quality of the constituents in the design of UHPC is more demanding than NSC [3-6]. Furthermore, due to the higher amount of cement used in the design of UHPC, the environmental impact such as global warming potential (GWP) raises concerns for sustainability. The cement cost in UHPC ranges from 900 to 1100 kg/m^3 which is three times higher than in normal strength concrete (NSC) [7-8]. The cement industry is reported to be responsible for 5-7% of the total anthropogenic CO_2 emissions [9-10].

The objective of this research is to quantify the material efficiency in the design of UHPC paste with regards to workability, compressive strength, cost and environmental impact. The emphasis of the environmental impact is placed on the global warming potential (*GWP*). Three different *GWP* allocation methods are employed and compared in their influence on material efficiency.

2. Research Approach

UHPC pastes with varying material efficiency were proportioned. This is achieved by selecting a variety of locally available constituents with varying physical, chemical properties and costs thus ultimately different mechanical performance, material efficiency and economy. Four series are designed by voluminously replacing only the material in question (Table 1). One UHPC and one NSC paste were also designed as a reference. The design of the reference UHPC paste is based on a previous research [3]. The properties of cement, silica fume and other supplementary materials (SMs) such as fly ash (FA) and ground granulated blast furnace slag (GGBS) are presented in Table 3 through Table 5, respectively.

Table 1. Mixture Design of Four Series

Series	Mixture No.	Material in question
I (Table 3)	UHPC1-7*	Cement (C1-C7)
II (Table 4)	UHPC1, 8-11	Silica fume (SF1-SF5)
III (Table 5)	UHPC1, 12-16	Supplementary materials (FA1-FA3, GGBS1 and 2)
IV	UHPC1, 17-22	High range water reducer (HRWR1-7)

* Mixture 1 is the reference UHPC paste

Table 2. Mixture design of reference paste

Paste type	Mixture No.	Material	Amount (kg/m^3)	Percentage by weight (%)
UHPC	UHPC1	C1	1327.8	58.1
		SF1	332.0	14.5
		QP	332.0	14.5
		HRWR1	47.8	2.1
		Water	245.4	10.7
NSC	NSC1	C2	1129.7	64.5
		Water	621.3	35.5

Table 3. Properties of cement

Type	Name	C_2S (%)	C_3S (%)	C_3A (%)	C_4AF (%)	Blain (m^2/kg)	ω ($/ton)
White PC I	C1	13	74	5	1	395	250
PC II/V	C2	14	58	4	11	417	110
Oil well cement	C3	16	59	0.4	18	214	130
PC II/V	C4	17	59	4	15	430	115
White PC I	C5	17	62	9	1	582	250
Oil well cement	C6	15	59	0.3	18	417	130
White PC I	C7	11	70	10	1	518	250

Table 4. Properties of silica fume

Type	Name	Carbon (%)	SiO_2 (%)	Na_2O (%)	K_2O (%)	d_{50} (µm)[b]	ω [c] ($/ton)
Grey	SF1	0.3<0.7	>85	0.1	0.07	0.4	550
Grey	SF2	<0.8	>97.5	<0.3	<0.6	0.5	1100
Grey	SF3	2.5[a]<6.0[a]	>93	<0.4	<0.9	0.6	350
White	SF4	<0.2	>96	-	-	0.15	1000
Grey	SF5	0.6	95	-	-	0.96%[c]	500

[a] Loss of ignition (LOI); [b] Median particle size; [c] Unit cost

Table 5. Properties of supplementary materials

Type	Name	d_{50} (μm)	ω [b] (\$/ton)
Quartz powder	QP	1.7	879
Fly ash	FA1	25	60
Fly ash	FA2	9.4	46
Fly ash	FA3	12.7	46
Ground granulated blast furnace slag	GGBS1	1.5%[a]	100
Ground granulated blast furnace slag	GGBS2	2.0%[a]	102

[a] Percent retained on 45μm diameter sieve; [b] Unit cost

Once the constituents have been selected, mixtures are designed and tested in spread and compressive strength. Cost and global warming potential (*GWP*) are calculated. Three different *GWP* allocation procedures for the by-products incorporated in the design of UHPC paste such as silica fume, fly ash and ground granulated blast furnace slag were employed. Then a material efficiency parameter is proposed to quantify the influence of workability, compressive strength, cost and environmental impact as follows:

$$E = \frac{0.7 \times \frac{f_c^{'}}{f_{c0}^{'}} + 0.3 \times \frac{\Gamma}{\Gamma_0}}{\left(\frac{\omega / \omega_0}{\eta}\right)\left(\frac{GWP / GWP_0}{\eta}\right)} \tag{1}$$

where $f_c^{'}$, Γ, ω and *GWP* represent the compressive strength, spread value, cost and global warming potential of the UHPC paste under investigation, respectively; $f_{c0}^{'}$, Γ_0, ω_0 and GWP_0 are compressive strength, spread value, cost and global warming potential of the reference NSC paste, respectively; η is the durability factor, which is defined as the ratio of service life without rehabilitation of UHPC paste under investigation to that of the reference NSC paste.

$$\eta = \frac{S}{S_0} \tag{2}$$

where S and S_0 are the service life without rehabilitation of the UHPC paste and the reference NSC paste, respectively. Durability factor is incorporated in the efficiency parameter. It is based on the fact that rehabilitation is usually needed during the service life of infrastructures made of NSC while no or minimum maintenance is needed for those made of UHPC.

To summarize, three steps are defined in this research:

- Select a variety of constituent materials varying in their physical, chemical properties and costs thus achieve a wide range of material efficiency.
- Design four series of mixtures by voluminously replacing only the material in question and test the flow spread and compressive strength and calculate their costs and global warming potential.
- Quantify the material efficiency of designed UHPC paste and assess the influence of different constituents on the efficient design of UHPC paste.

3. Testing Methods

Mini cone spread test in accordance with ASTM C230/C230M [11] was employed to investigate the workability of different pastes. The reported spread value is the average of two testing for each mixture. The compressive strength was determined based on ASTM C39 [12]. Freeze-thaw (F-T) durability of reference UHPC and NSC paste were tested following ASTM C666 procedure A [13].

4. Results

Freeze thaw durability is used in this research to represent the service life and the test result is illustrated in Figure 1.

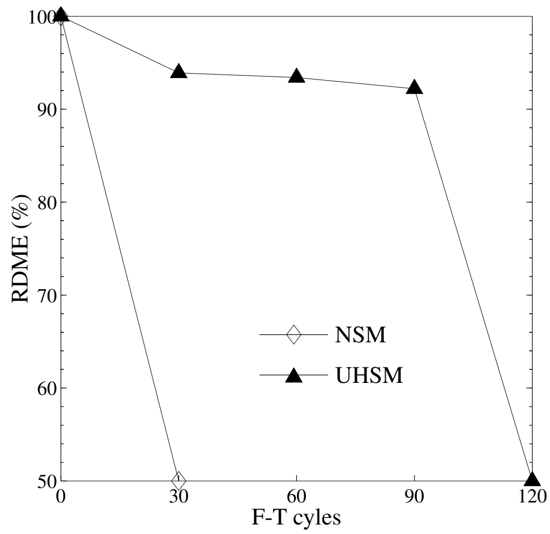

Figure 1. Durability of UHPC and NSC paste

Table 6 presents the calculated *GWP* for different the by-products using different allocation procedures. The mass allocation coefficient C_m can be calculated as the mass ratio between primary product and by-product using Eq.(3) as follows:

$$C_m = \frac{m_{by-product}}{m_{primary-product} + m_{by-product}} \tag{3}$$

where $m_{by-prodcut}$ and $m_{\text{primary-product}}$ are the mass of by-product and primary product, respectively. The global warming potential for by-product employing mass allocation method can then be calculated using Eq.(4).

$$GWP_m = C_m \times GWP_{pr} \tag{4}$$

where GWP_{pr} is the global warming potential for the production of the primary product, C_m is the mass allocation coefficient and GWP_m is the global warming potential for the by-product following mass allocation procedure.

The economic allocation coefficient C_e can be calculated by Eq.(5) as follows:

$$C_e = \frac{p_{by-product}\omega_{by-product}}{p_{primary-product}\omega_{primary-product} + p_{by-product}\omega_{by-product}} \tag{5}$$

where $\omega_{by-product}$ and $\omega_{primary-product}$ are the unit price of the by-product and primary product, respectively; $p_{by-product}$ and $p_{primary-product}$ are the weight of the by-product and primary product in percentage during the production process, respectively.

The global warming potential of by-product in accordance with economic allocation procedure can be calculated using Eq.(6).

$$GWP_e = C_e \times GWP_{pr} \tag{6}$$

where GWP_{pr} is the global warming potential for the production of the primary product, C_e is the economic allocation coefficient and GWP_e is the global warming potential for the by-product following economic allocation procedure.

Table 7 lists the test results of spread Γ, compressive strength $f_c^{'}$, cost ω and material efficiency E of the proportioned UHPC pastes.

Table 6. Summary of test results

Name	GWP (kg CO_2 eq.)		
	Waste	Mass allocation	Economic allocation
SF1			0.399
SF2			0.713
SF3	3.1×10^{-4} [14]	1.1	0.267
SF4			0.660
SF5			0.366
FA1			0.590
FA2	7.82×10^{-3} [15]	2.437	0.452
FA3			0.452
GGBS1	1.56×10^{-2} [15]	1.096	0.073
GGBS2			0.075

Table 7. Summary of results

Series	Mix No.	w/c	Γ	f_c'	ω	E		
						WA*	EC*	MA*
			(mm)	(MPa)	($/m^3)	-	-	-
Reference NSC	NSC1	0.55	220	29	104	1.00	1.00	1.00
Reference UHPC (I/II/III/IV)	UHPC1	0.21	315	171	806	1.90	1.70	1.43
I	UHPC2	0.23	330	184	604	2.80	2.50	2.10
	UHPC3	0.23	350	183	630	2.68	2.39	2.02
	UHPC4	0.23	300	196	611	2.91	2.59	2.18
	UHPC5	0.23	300	221	785	2.53	2.25	1.90
	UHPC6	0.23	300	177	630	2.57	2.29	1.93
	UHPC7	0.24	319	186	775	2.23	1.98	1.67
II	UHPC8	0.33	400	175	851	2.19	1.80	1.65
	UHPC9	0.31	366	192	652	3.01	2.79	2.26
	UHPC10	0.25	329	175	907	1.83	1.52	1.37
	UHPC11	0.23	290	174	769	2.07	1.86	1.55
III	UHPC12	0.23	340	192	520	3.38	2.87	1.94
	UHPC13	0.23	364	197	516	3.51	3.09	2.02
	UHPC14	0.23	341	192	516	3.41	3.00	1.96
	UHPC15	0.24	295	202	526	3.49	3.44	2.63
	UHPC16	0.24	300	181	527	3.16	3.11	2.38
IV	UHPC17	0.25	223	191	765	2.28	2.03	1.71
	UHPC18	0.26	248	191	755	2.35	2.10	1.77
	UHPC19	0.26	223	166	755	2.05	1.83	1.54
	UHPC20	0.26	250	171	755	2.13	1.90	1.60
	UHPC21	0.27	220	175	746	2.21	1.97	1.66
	UHPC22	0.26	220	167	755	2.06	1.84	1.55

*WA, EC and MA represent waste, economic allocation and mass allocation procedure employed for GWP calculation for the by-product incorporated in the UHPC paste design

5. Discussion

It can be seen from Table 7 that the type of cement (series I) significantly affects the compressive strength and the costs of UHPC paste. A unit cost reduction up to 25.1% (UHPC2) can be achieved while maintaining comparable compressive strength and workability. Partial replacement of cement by silica fume can lead to improved workability but cost increase is also possible. Other supplementary materials (SMs) such as fly ash (FA) and ground granulated blast furnace slag (GGBS) can result in significantly lower costs (up to 36.0% for UHPC13 and 14) and at comparable compressive strengths. Carefully selected high range water reducer (HRWR) can moderately reduce the cost up to 6.3% (UHPC18-20), while maintaining reasonable workability and compressive strength. It is worth pointing out that all series demonstrate a compressive strength above 150 MPa, which is considered as a threshold level to quantify as UHPC [1].

Accelerated F-T test results demonstrates that UHPC paste can outperform NSC paste by four times (Figure 1). However, a conservative durability factor of 2 was selected in this study because current codes do not require a corresponding extension of the design service life of building and structures so that it would be difficult to argue the actual benefit when applying a higher factor. It is worth pointing out that the selected factor is even more conservative considering the increased slenderness of structural members made by UHPC. In general, the material efficiency of UHPC is higher than the NSC paste when durability is taken into consideration regardless of the employed global warming potential allocation procedure method. Waste treatment of by-products for global warming potential purpose underestimates their influence as indicated by the negligible *GWP* shown in Table 6. In contrast, mass allocation overestimates such impact as can be seen from the calculated higher than cement *GWP*. Therefore economic allocation is the most appropriate procedure to account for the environmental impact of by-products used for UHPC design. The material efficiency of UHPC paste is approximately two to three times higher than for NSC paste with economic allocation procedure that is used to determine the *GWP*.

6. Conclusions

This research investigated the material efficiency of different constituents in the design of UHPC. The environmental impact of industrial by-product incorporated in the design of UHPC is assessed by global warming potential through three different treatments: waste, mass allocation and economic allocation. An efficiency parameter was proposed to quantify the material efficiency in terms of workability, compressive strength, cost and environmental impact. Based on the series investigated in this research, several conclusions can be drawn:

- Use of locally available material can reduce the cost of UHPC paste while maintains appropriate spread (>220mm) and compressive strength exceeding 150 MPa.
- Partial replacement of cement with industrial by-products, especially fly ash (FA) and ground granulated blast furnace slag (GGBS) can significantly reduce the cost and improve material efficiency.
- The material efficiency in the design of UHPC is higher than NSC from a life cycle perspective.

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