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Material efficiency in the design of UHPC paste from a life cycle point of view

Rui Zhong [a], Kay Wille [b,*], Roberto Viegas [b]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Unit 3037, Storrs, CT 06269-3037, United States

HIGHLIGHTS

- Evaluation of material efficiency of UHPC mixture design.
- Introduction of efficiency parameter.
- Consideration of strength, workability, cost and global warming potential.
- Recommendations for efficient UHPC paste design.

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ABSTRACT

In comparison to conventional concrete, ultra-high performance concrete (UHPC) is characterized by a significant improvement of mechanical properties and durability performance as a result of enhanced densification of the microstructure. The mixture design for enhanced material performance requires the use of higher quality material constituents and as a result, an increased cost, compared to conventional concrete. In this research, various UHPC pastes are designed and their material efficiency is evaluated. One such material efficiency parameter that is proposed here accounts for the influences of compressive strength, workability, unit cost and sustainability. The global warming potential (*GWP*) is selected to evaluate the environmental impact. Waste treatment, mass and economic allocation procedures of *GWP* for by-products are compared based on life cycle assessment (LCA) methodology. In order to better understand and quantify the contribution from each individual aspect on material efficiency, mechanical, economic and environmental indices are defined. As a result recommendations are made for efficient design of UHPC paste.

1. Introduction

In 2013, the American Society of Civil Engineers rated the aging U.S. infrastructure with a D+ overall [1]. Corrosion of steel reinforcement and concrete deterioration through invasion of corrosive ions are the two most prominent reasons for the conditions of the ageing infrastructure. In comparison to conventional concrete, ultra-high performance concrete (UHPC) is characterized by a significant improvement of mechanical and durability properties. UHPC has the potential to effectively address the current conditions of the crumbling infrastructure. A series of conferences held in Kassel, Germany in 2004, 2008, 2012, 2016 [2–5], Marseille, France in 2009, 2013 [6,7] and Des Moines, USA in 2016 [8] have demonstrated the material's performance and application potential. Despite its performance, wide spread application of UHPC is held back by high material costs and concerns of sustainability. In comparison to the cost of normal strength concrete (NSC) which is about $130/m^3, commercially available UHPC is around 20 times more expensive [9]. The increased cost is a result of a variety of criteria needed in UHPC. This includes the need for higher quality materials, expensive fiber reinforcements, and the corresponding quality control [10–13]. Attempts have been made to reduce the cost by using less expensive, locally available constituents [11,14,15]. The high amount of cement traditionally used in the design of UHPC raises concerns for sustainable development, specifically regarding the global warming potential (*GWP*). The amount of cement in UHPC ranges from 900 to 1100 kg/m^3, which is roughly three times greater than NSC [16–17]. The production of cement results in a significant emission of carbon dioxide gas (CO_2). This is caused by the process of de-acidification of limestone

* Corresponding author.
E-mail addresses: rui.zhong@polyu.edu.hk (R. Zhong), kay.wille@uconn.edu (K. Wille), roberto.viegas@uconn.edu (R. Viegas).

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Notation

C	cement
C_m	mass allocation coefficient
C_e	economic allocation coefficient
D	freeze-thaw durability of UHPC
D_0	freeze-thaw durability of NSC
EA	economic allocation
E	material efficiency parameter
ΔE	normalized increase in material efficiency
Ec	economic index
ΔEc	normalized increase in economic index
En	environmental index
ΔEn	normalized increase in environmental index
FA	fly ash
f'_c	compressive strength of UHPC
f'_{c0}	compressive strength of NSC
GGBFS	ground granulated blast furnace slag
GWP	global warming potential
GWP_0	global warming potential of reference NSC
GWP_{pr}	global warming potential of the primary product
GWP_m	global warming potential of by-product by mass allocation method
GWP_e	global warming potential of by-product by economic allocation method
HRWR	high range water reducer
LCA	life cycle assessment
MA	mass allocation
Me	mechanical index
ΔMe	normalized increase in mechanical index
MEET	Mechanical-Economic-Environmental triangle
$m_{by\text{-}product}$	mass of by-product
$m_{primary\text{-}product}$	mass of primary product
NSC	normal strength concrete
$p_{by\text{-}product}$	weight of the by-product in percentage during the production process
$p_{primary\text{-}product}$	weight of the primary product in percentage during the production process
QP	quartz powder
S	service life of UHPC
S_0	service life of NSC
SF	silica fume
SM	supplementary material
UHPC	ultra-high performance concrete
WT	waste treatment
Γ	spread value of UHPC
Γ_0	spread value of NSC
η	durability factor
ω	unit cost of material
$\omega_{by\text{-}product}$	unit price of the by-product

and the calcinations of raw materials. The cement industry is reported to be responsible for 5–7% of the total anthropogenic carbon dioxide emissions [18,19]. It is estimated that the production of 1 ton of Portland cement releases 1 ton of CO_2 [20]. Furthermore, the worldwide production of cement in 2012 amounted to about 3.6 Gt [21] and the demand is increasing at a rate of about 3–5% per year. Partial replacement of cement with industrial by-products is one promising solution to reduce the environmental impact of UHPC. Silica fume (SF) from zirconium production, fly ash (FA) from coal fired power plants and ground granulated blast furnace slag (GGBS) from steel production are the most commonly used industrial by-products to partially replace cement.

The objective of this research is to quantify the material efficiency and assess the individual influences of mechanical performance, economic contribution and environmental impact on the design of UHPC paste. Emphasis of the environmental impact is placed on the global warming potential (*GWP*). Three different *GWP* allocation methods are employed and compared for their influence on material efficiency.

2. Research approach

In this research, the material efficiency in the design of UHPC paste accounts for the workability, compressive strength, unit cost and global warming potential (*GWP*). Optimization of the particle packing density of paste results in increased workability and mechanical performance [10]. Additionally, the unit cost and *GWP* (economic allocation method) of constituents, such as silica fume (SF) and supplementary materials (SMs), are correlated to the particle size. Therefore by changing the particle size of SF and SMs, a series of UHPC pastes with varying material efficiency can be developed. The properties of selected SF and SMs are listed in Tables 1 and 2, respectively. It is worth noting that high range water reducers (HRWR) play an important role in distributing fine particles and thus influencing the particle packing density of the UHPC paste. Therefore, eight different HRWR are also used in the design of UHPC pastes for this research.

Cement is an additional component that affects the material efficiency in the design of UHPC paste. Different cements can vary in chemical composition and fineness, and therefore cost and environmental impact. These cements are chosen to design UHPC pastes which represent a wide range of material efficiency.

Several types of cements were also used in this study. These parameters include varying content of tricalcium silicate (C_3S), dicalcium silicate (C_2S) and tricalcium aluminate (C_3A). The Blain fineness of cement was also varied. Table 3 summarizes the properties of the cements used in this research.

Once the constituents have been selected, mixtures are designed and tested for their workability (spread value) and uniaxial compressive strength. Unit cost and *GWP* are also calculated. If SF and SMs are considered as waste, no environmental impact is allocated. However, a recent European Union directive [22] separates waste from by-product if the following four criteria are met:

"(I) further use is certain; (II) the substance is produced as an integral part of a production process; (III) the substance can be used directly without any further processing other than normal industrial practice; and (IV) further use is lawful" [22].

Commonly used SF and SMs in the design of UHPC paste meet these criteria. Therefore these constituents need to be treated as by-products instead of waste. Mass allocation and economic allocation methods are used to account for their environmental impact [23–25]. In this research, both treatments of waste and by-product (mass allocation and economic allocation) are adopted to compare *GWP* for different constituents. After these effects are considered, the material efficiency is assessed.

In order to quantify the material efficiency, a dimensionless material efficiency parameter E is defined as follows:

$$E = \frac{0.7 \times \frac{f'_c}{f'_{c0}} + 0.3 \times \frac{\Gamma}{\Gamma_0}}{\left(\frac{\omega/\omega_0}{\eta}\right)\left(\frac{GWP/GWP_0}{\eta}\right)} \quad (1)$$