An Investigation of Supplementary Cementitious Materials in Ultra-High Performance Concrete

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a special construction material with significantly greater compressive strength than conventional concrete. However, to acquire its high strength, UHPC generally requires more cement, directly leading to an increase in the material's cost and carbon footprint. In this study, proportions of Ground Granulated Blast Furnace Slag (GGBFS), a type of supplementary cementitious material (SCM) are evaluated in a mix design based on three principles: improved microstructure, low porosity, and dense particle packing. By incorporating these principles, an optimum amount of slag for high compressive strength was determined. The systematic approach developed in this study can be similarly used for the optimization of other SCMs, further benefiting both the environment and society.

INTRODUCTION

Background

- Compressive strength has a direct, positive correlation with durability.
- The durability of a material used for infrastructure determines the infrastructure's need for maintenance and its length of service life.
- Conventional concrete (compressive strength of 40 MPa), the most widely used material on Earth, has low durability.

Figure 1: Structural Deficiency Problem in United States infrastructure

New Concrete Material

Table 1: The Advantages and Disadvantages of UHPC

UHPC	
Advantages	**Disadvantages**
• Compressive strength > 125 MPa. • More durable than conventional concrete. • Significant long-term benefits due to a lesser need for maintenance. • Can help solve the problem of structural deficiency.	• High cement content, directly leading to: ➢ High initial costs. ➢ Detrimental impact on the environment. • No standardized mix design process in place.

The Problem

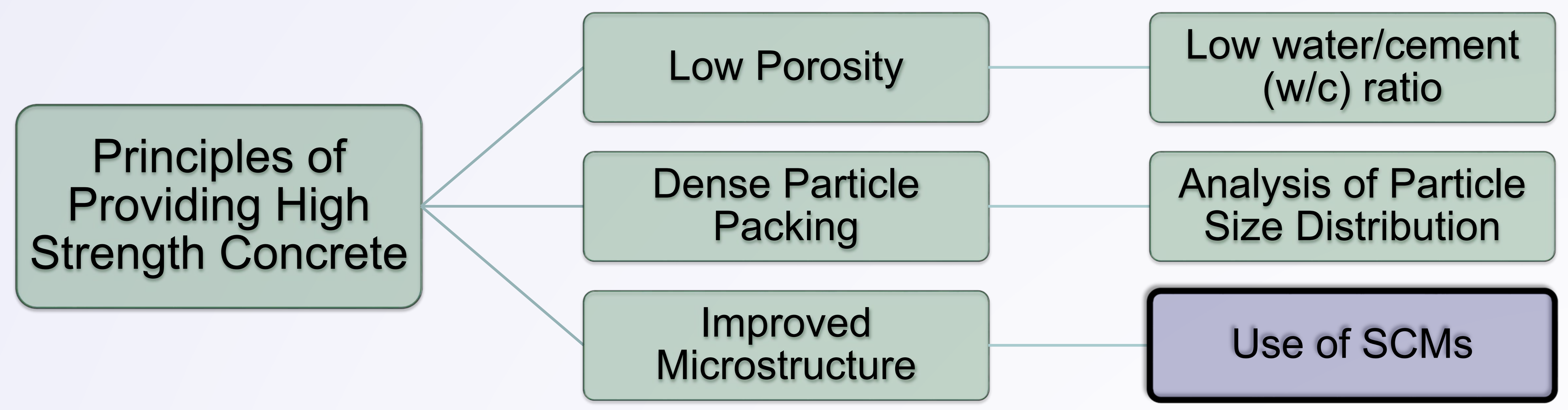
- The disadvantages of UHPC have restricted its wide industrial implementation.
- Cement is a high energy intensive material. Its production constitutes 7% of global carbon dioxide emissions. It also makes up half of the total cost of ingredients of concrete.
- Reducing cement content will allow us to eliminate two disadvantages at once.

RESEARCH OBJECTIVE

Hypothesis

A substantial amount of the cement commonly used in UHPC can be replaced by SCMs. The objective is to find optimum amounts of cement that can be replaced by GGBFS, by varying the slag/cement (s/c) ratio, without compromising the compressive strength of the UHPC.

Motivation for Research Objective



$$\text{Cement} + H_2O \rightarrow C_3S_2H_8 + CH$$

- In the chemical reaction of cement with water, the compounds Calcium Silicate Hydrate (CSH) and Calcium Hydroxide (CH) are produced. CSH is a source of strength for concrete, the reason behind the use of SCMs. Supplementary cementitious materials will react with CH to further produce CSH. Thus, on a microstructural level, the source of strength in a concrete mix is increased.
- Other benefits of using SCMs:
  - ➢ Readily available
  - ➢ Low cost
  - ➢ Reduced detrimental impact on environment.

EXPERIMENTAL PROGRAM

Mixing of all the materials in the concrete mixer
Slag • Sand • Silica Fume • Silica Powder • Water • High-Range Water Reducing Admixture (HRWRA)

Measuring the fresh concrete properties
Performing Mini-Slump Test (Fig. 3)

Casting of specimen
Three 50mm x 50mm x 50mm cubes

De-molding specimen after 48 hours

Curing of specimen
Submerging cubes in water for 26 days

Drying of specimen
Heating cubes in oven for 24 hours

Testing of specimen
Performing compression test on cubes

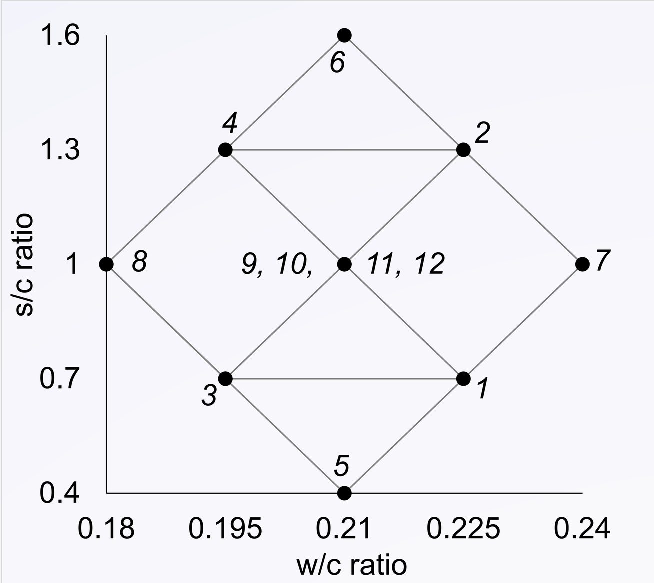


Figure 2: Representation of design variables
A central composite factorial experimental program was used to investigate the relationship between compressive strength and variables (w/c and s/c ratios).

Figure 3: Mini-Slump Test:
Measures how workable a mix is through spread values in *mm* (size of diameter mix forms after 30 seconds).

RESULTS

Spread Values

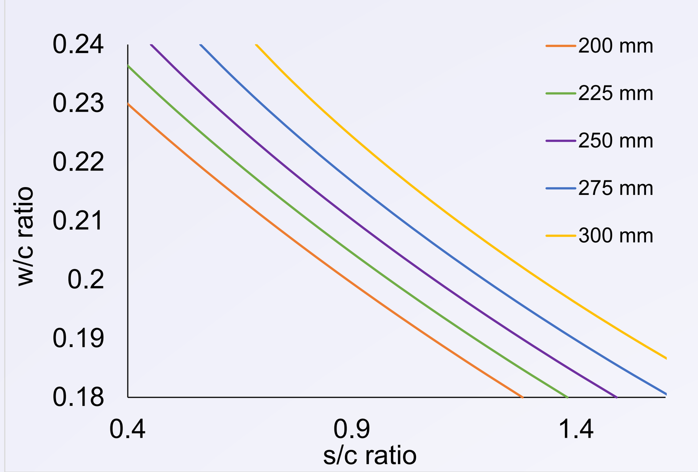


Figure 4: Contours of measured spread values
Spread values increase with increase in slag content.

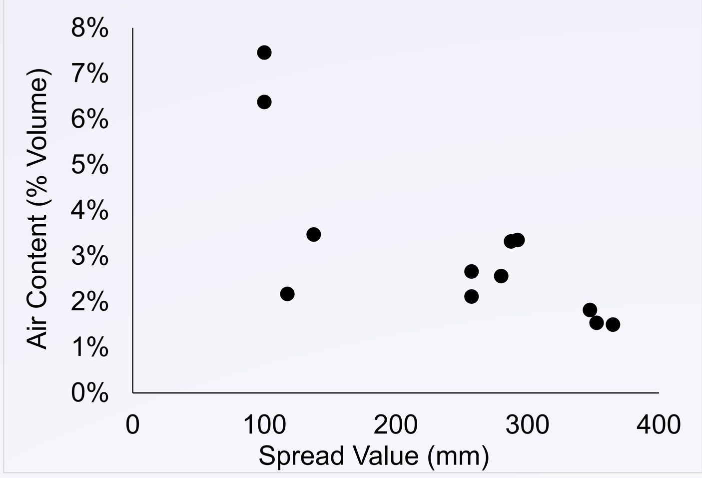
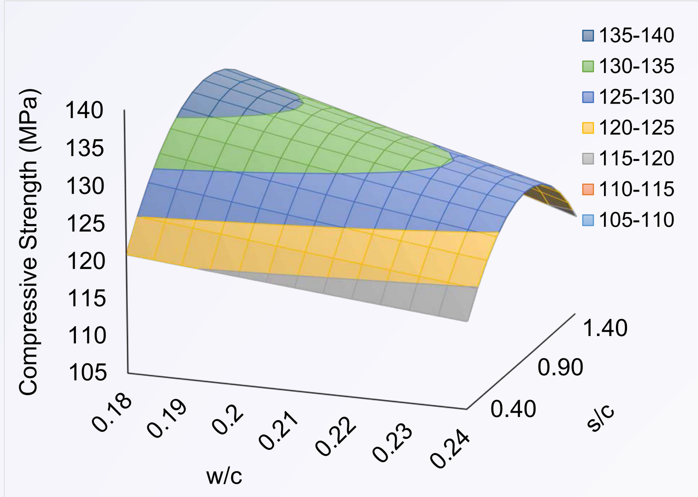
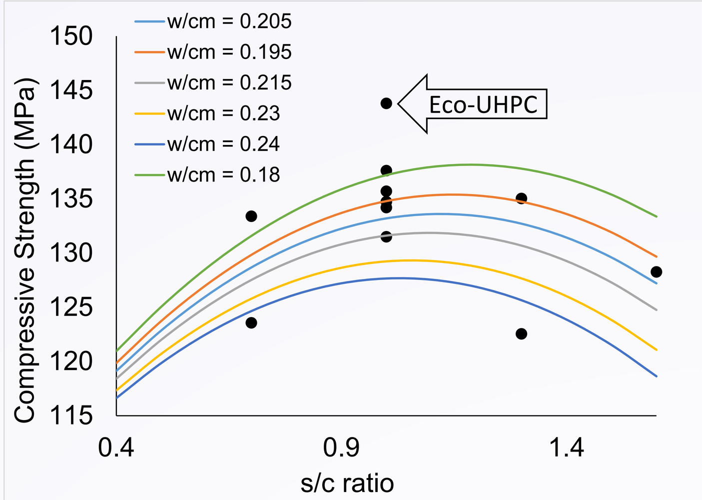


Figure 5: Air content vs. spread value
With a higher spread value, air content was found to be low.

Compressive Strength at 28-Day Age





Figures 6 and 7: Relationship between compressive strength and design variables
An optimal value for slag/cement ratio was observed to be around 1.1.

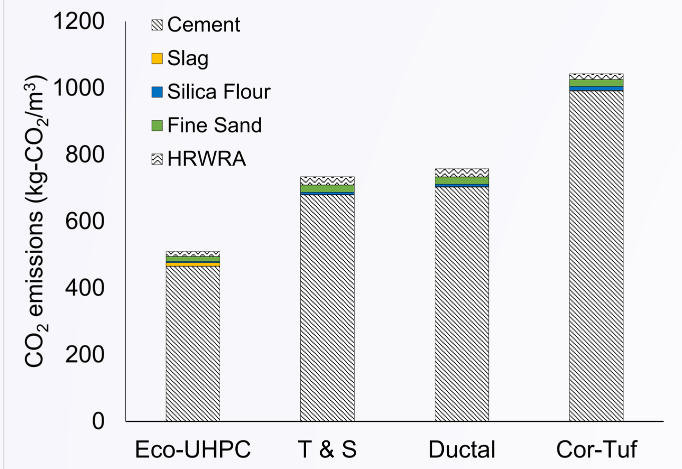


Figure 8: Comparison of carbon emissions
The materials of commercially available UHPCs and their corresponding carbon emissions were compared to those of Eco-UHPC (the specific mix from this study that displayed the highest compressive strength, a 28-day strength of 140 MPa).

CONCLUSIONS

- Eco-UHPC resulted in an overall lower carbon-intensive UHPC because of its significant decrease in the usage of cement as an ingredient. Carbon emissions were found to be 30-50% smaller than that of commercially available UHPCs.
- The systematic approach developed can be used to determine optimum amounts of other types of SCMs, while maintaining comparable compressive strength values.

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