# Vitrified Clay for the Production of UHPC

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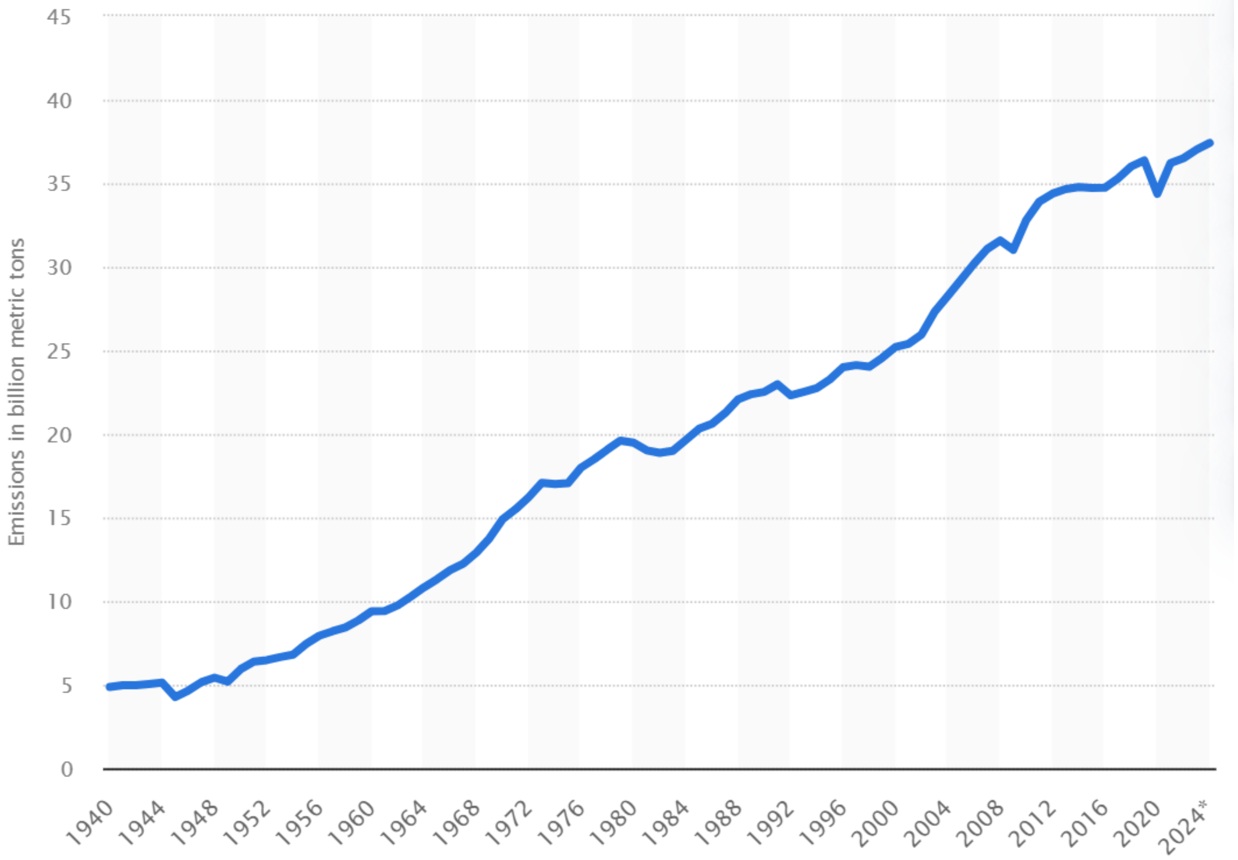
# Dr. RAMON CARRASQUILLO

**For his actions on behalf of our school, Dr. Ramon Carrasquillo is appreciated as a big brother to our professors and as a grandfather to our students.**

Dr. Ramon L. Carrasquillo, giving his keynote lecture at the 2nd Raymundo Rivera Villarreal Chair (2022)

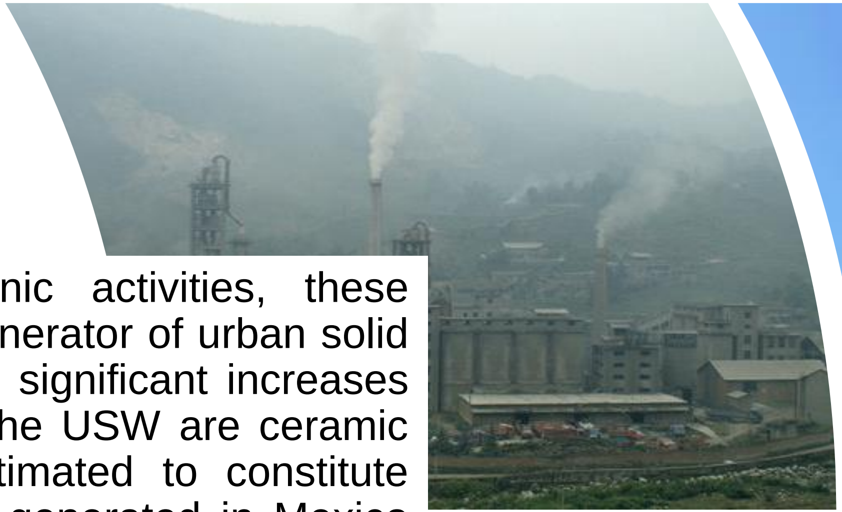
# INTRODUCTION

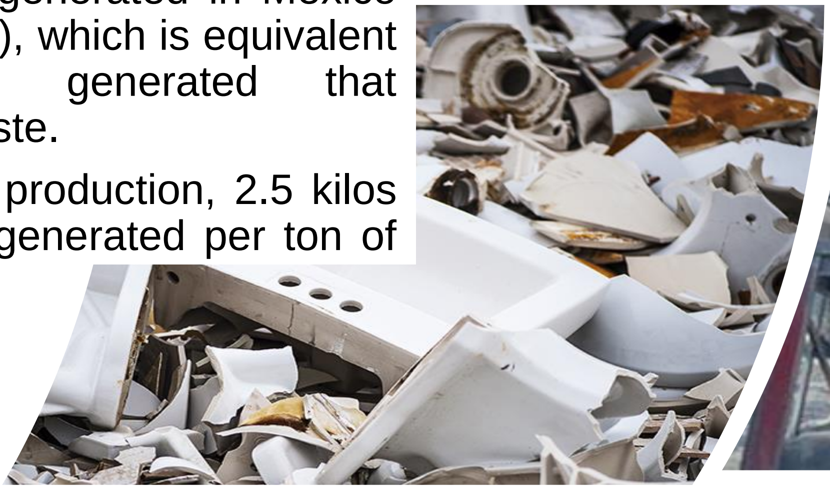
Global Warming is the increase in the temperature of the Planet due to the use of fossil fuels, industrial processes and anthropogenic activity, which lead to a constant accumulation of greenhouse gases ($CO_2$ emissions). With this pace of life, with the lack of interest in the environment and with the tendency to increase $CO_2$ emissions, it is expected that by 2050 global $CO_2$ emissions will increase to 43 billion metric tons, compared to the 37.41 billion metric tons of carbon dioxide that were recorded in 2024.




https://www.statista.com/statistics/276629/global-co2-emissions/

# INTRODUCTION



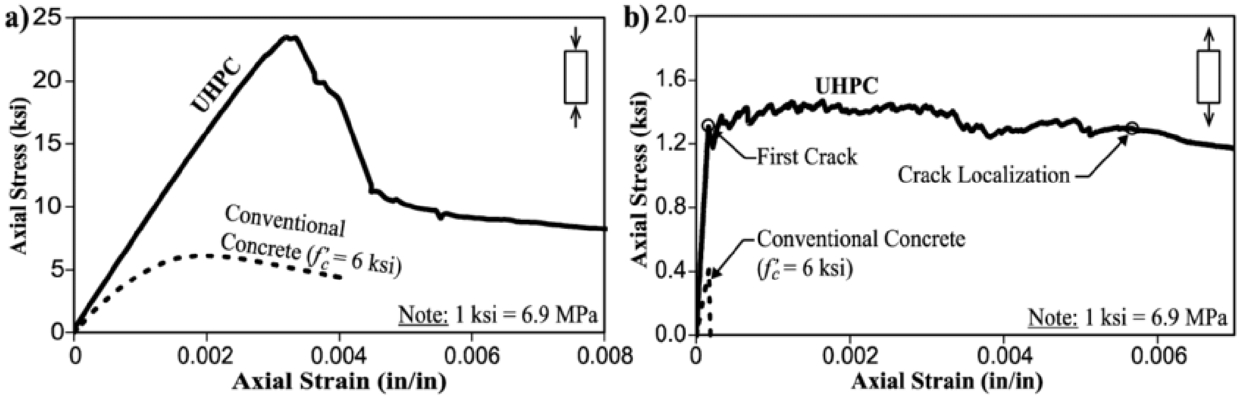


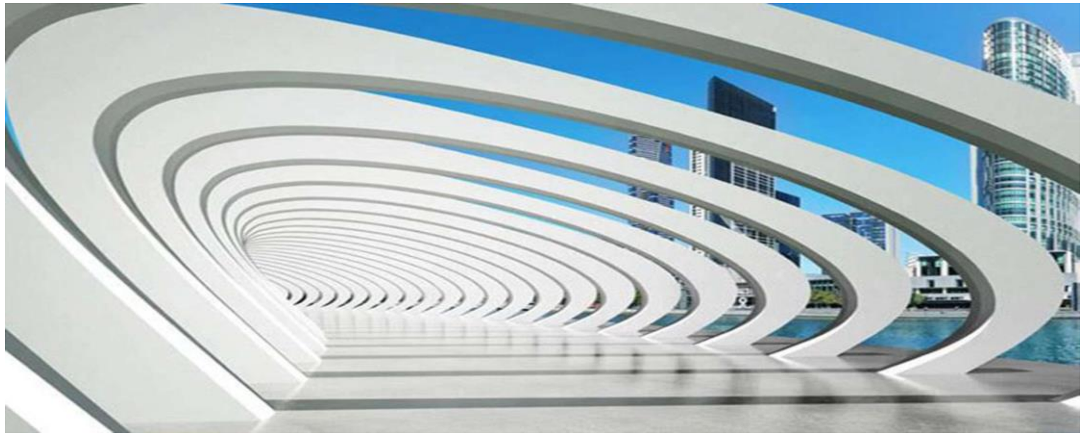
As regards anthropogenic activities, these represent a significant generator of urban solid waste (USW) that shows significant increases year after year. Among the USW are ceramic waste (C), which is estimated to constitute 0.46% of the total USW generated in Mexico (120,128 tons/day in 2017), which is equivalent to 201,695 tons/year generated that correspond to ceramic waste.

In the case of aggregate production, 2.5 kilos of limestone powder are generated per ton of aggregate produced.

# INTRODUCTION

- w/cm = 0.20 – 0.25
- Cement content = 800 – 1000 kg/cm$^2$
- Steel fibers 1 – 3 % by volume
- fc ≥ 120 MPa



Ultra-high performance concrete (UHPC) is a Portland cement-based material, with a specified minimum compressive strength of 120 MPa; high doses of Portland cement (800 to 1100 kg/$m^3$) and microsilice (8-10%); however, as regards its impact on the environment, the negative aspects that in the last three decades have been criticized for this matrix, consist of a high economic cost due to the high consumption of cement and silica fume, and also a significant waste of these materials, because many of them do not react in the system, due to the low water/cement ratio (less than 0.25%).

# MATERIALS AND METHODS

Cement

Silica Fume

Polycarboxylate HRWRA

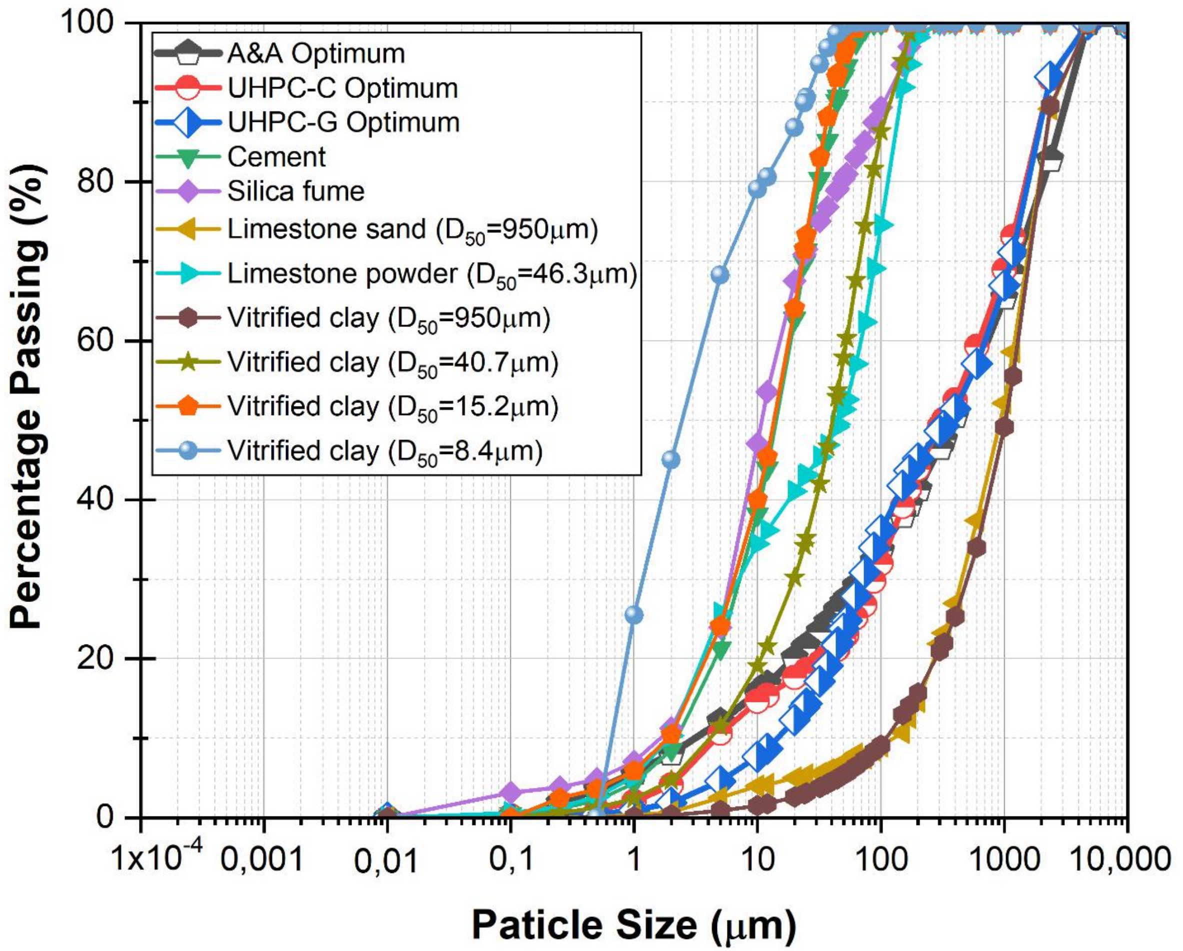
Limestone powder

Steel Fibers

**φ = 200 μm, L = 13 mm**

Vitrified Clay

Limestone Sand



# METHODS

**Grinding and Pulverizing**

The industrial waste was prepared in different sizes, with the aim of replacing them from limestone aggregate (less than 4.6 mm), limestone powder, cement substitute and silica fume substitute.

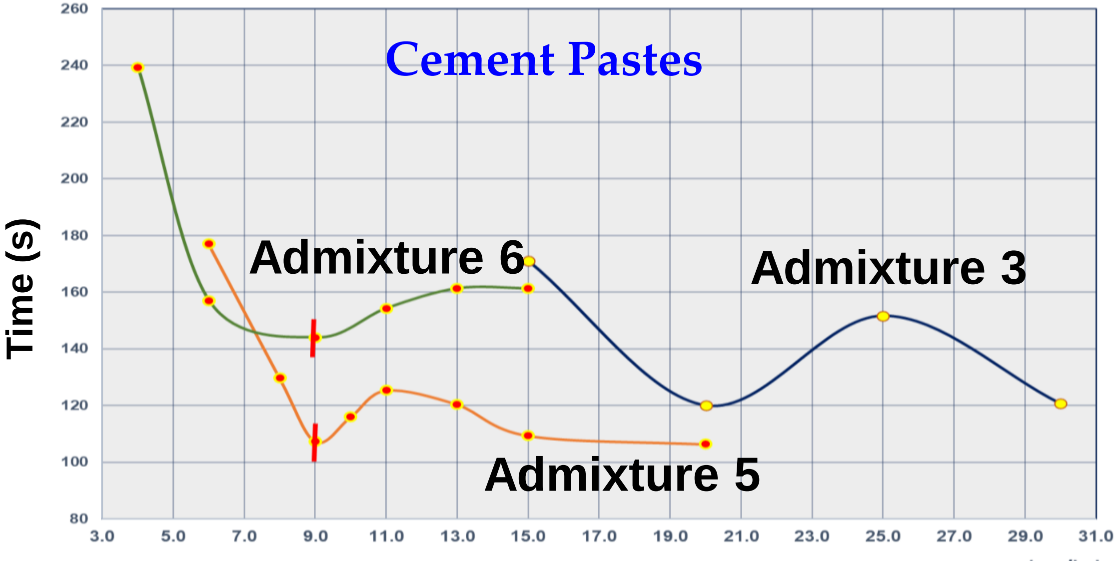

| | Vitrified Clay | to | substitute |
|---|---|---|---|
| A) | VC Sand<br>D50 = 950 µm | → | Limestone sand<br>D50 = 950 µm |
| B) | VC Powder<br>D50 = 40.7 µm | → | Limestone powder<br>D50 = 46.3 µm |
| C) | VC Fine 1<br>D50 = 15.2 µm | → | Cement<br>D50 = 13.0 µm |
| D) | VC Fine 2<br>D50 = 8.4 µm | → | Silica fume<br>D50 = 10.0 µm |

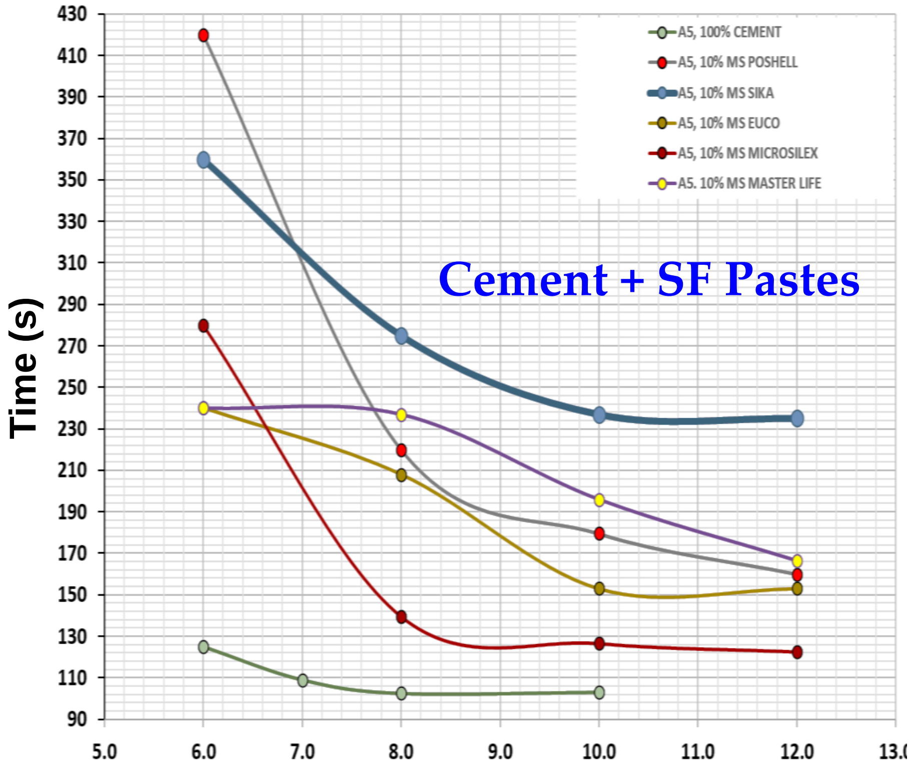
# OPTIMIZATION OF MIXTURE PROPORTIONS

Selection and optimization of admixture dosages

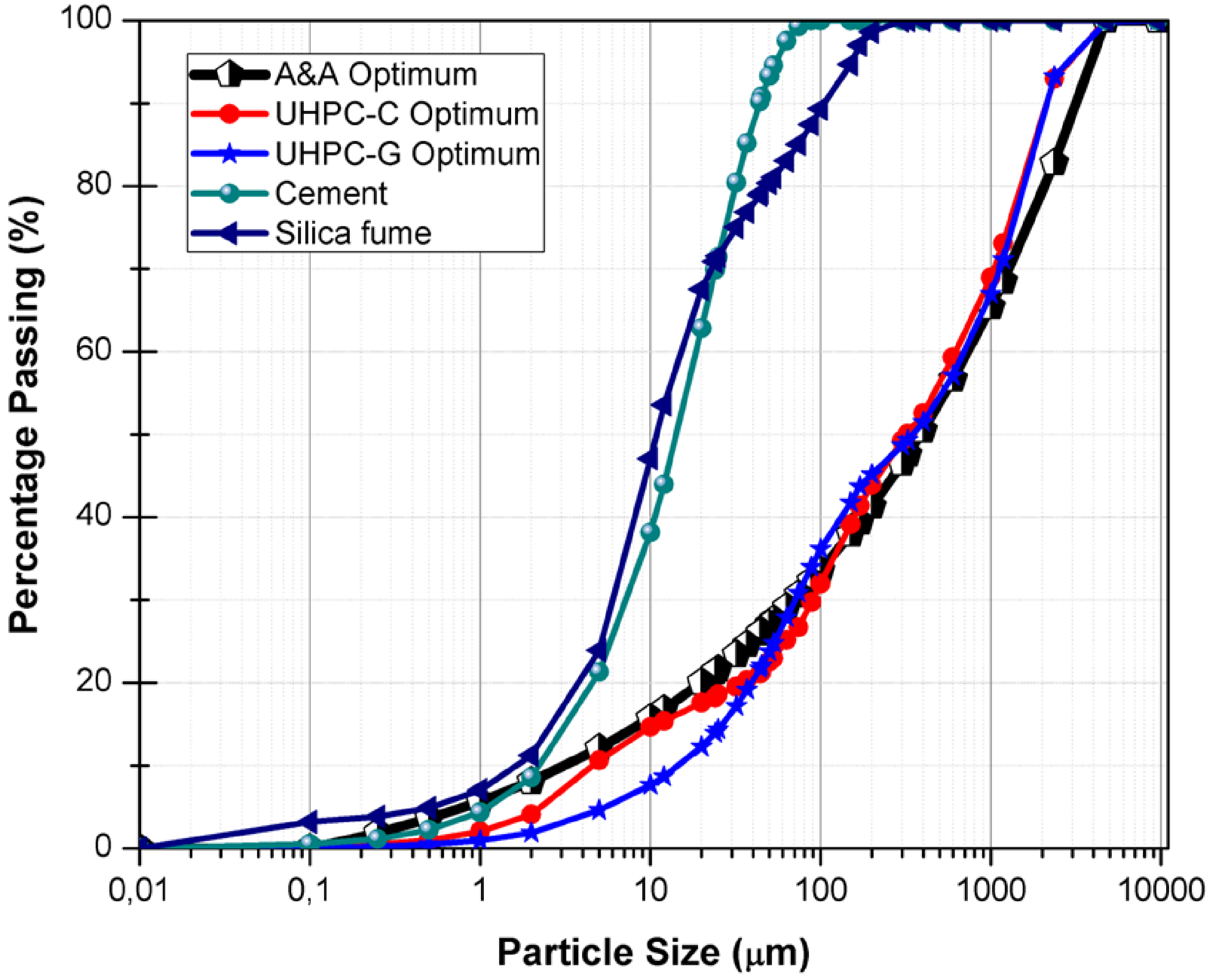
**Homogeneous** **Segregated**

ASTM C939 flow cone



# OPTIMIZATION OF MIXTURE PROPORTIONS




**Andreasen and Andersen Model**

$$P(D) = \frac{D^q - D^q min}{D^q max - D^q min}$$

Where:

**P(D)**: is a fraction of the total solids that are smaller than size D

**D**: is the particle size in micrometers

**D max**: is the maximum particle size in micrometers

**D min**: is the minimum particle size in micrometers

**q**: is the distribution modulus

# METHODS

**Types of mix**

| UHPC-C | UHPC-G |
| --- | --- |
| **REFERENCE** | **GREEN** |
| Portland cement | Portland cement + VC Fine 1 |
| Silica fume | Silica fume + VC Fine 2 |
| Limestone sand | Limestone sand + VC Sand |
| Limestone powder | Limestone powder + VC Powder |

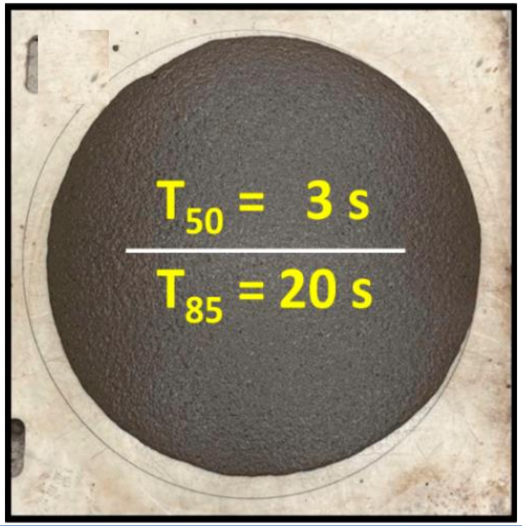
# METHODS

**Types of mix**

| UHPC-C | UHPC-G |
| --- | --- |
| REFERENCE | GREEN |

**w/c = 0.25, OPC content = 800 kg/m$^3$, Target spread of 325 ± 25 mm.**

**UHPC-G was optimized in terms of compressive strength and consistency**




- **30% of limestone sand by VC Sand**
- **30% of limestone powder by VC Powder**
- **30% of Portland cement by VC Fine 1**
- **100% of silica fume VC Fine 2**

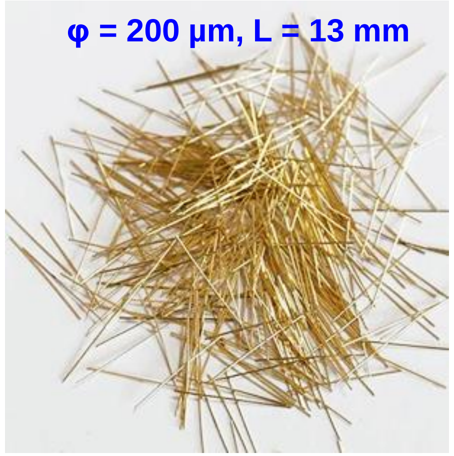
# METHODS

## UHPC-C
REFERENCE

## UHPC-G
GREEN

## SFR-UHPC-C
REFERENCE WITH STEEL FIBER

## SFR-UHPC-G
GREEN WITH STEEL FIBER




### Mix Proportions

| Materials | UHPC-C | | UHPC-G | |
|---|---|---|---|---|
| | W/o SFR | With SFR | W/o SFR | With SFR |
| | Kg/m$^3$ | Kg/m$^3$ | Kg/m$^3$ | Kg/m$^3$ |
| Water | 196.0 | 192.2 | 196.0 | 193.7 |
| Superplasticizer | 7.9 | 7.7 | 7.9 | 7.8 |
| Air-Occluding | 1.2 | 1.1 | 1.2 | 1.2 |
| CPO | 720.0 | 705.9 | 504.0 | 498.0 |
| SF | 80.0 | 78.4 | 0.0 | 0.0 |
| VC ($D_{50}$ = 8.4 μm) | 0.0 | 0.0 | 80.0 | 79.1 |
| VC ($D_{50}$ = 15.2 μm) | 0.0 | 0.0 | 216.0 | 213.4 |
| VC ($D_{50}$ = 40.7 μm) | 0.0 | 0.0 | 126.2 | 124.7 |
| VC ($D_{50}$ = 950 μm) | 0.0 | 0.0 | 234.3 | 231.6 |
| LS ($D_{50}$ = 950 μm) | 868.8 | 851.8 | 608.2 | 600.9 |
| LP ($D_{50}$ = 46.3 μm) | 467.9 | 458.7 | 327.5 | 323.6 |
| Steel Micro-Fiber | 0.0 | 154.9 | 0.0 | 156.1 |
| Air content (%) | 3.2 | 3.2 | 2.3 | 1.5 |

# RESULTS

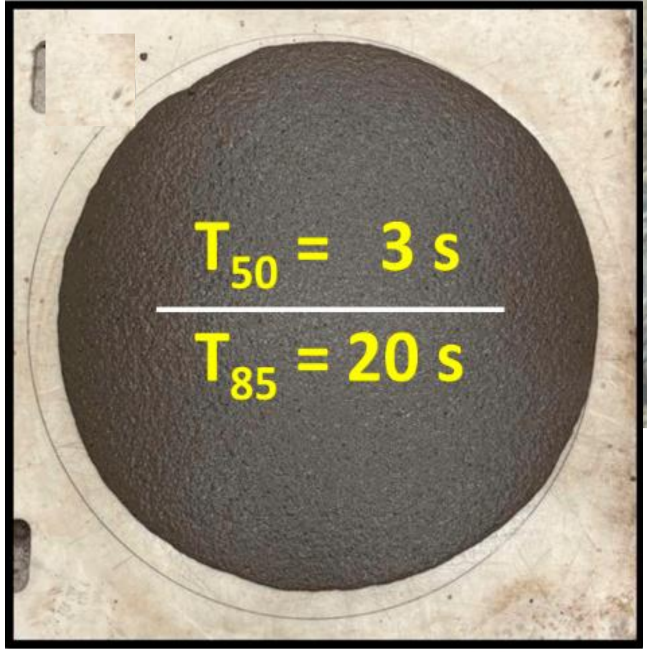
## Fresh State Properties

### Setting time in concretes.

| Mix | Initial Setting Time (Hours:Minutes) | Final Setting Time (Hours:Minutes) |
|---|---|---|
| UHPC-C | 3:52 | 5:02 |
| UHPC-G | 3:17 | 5:08 |

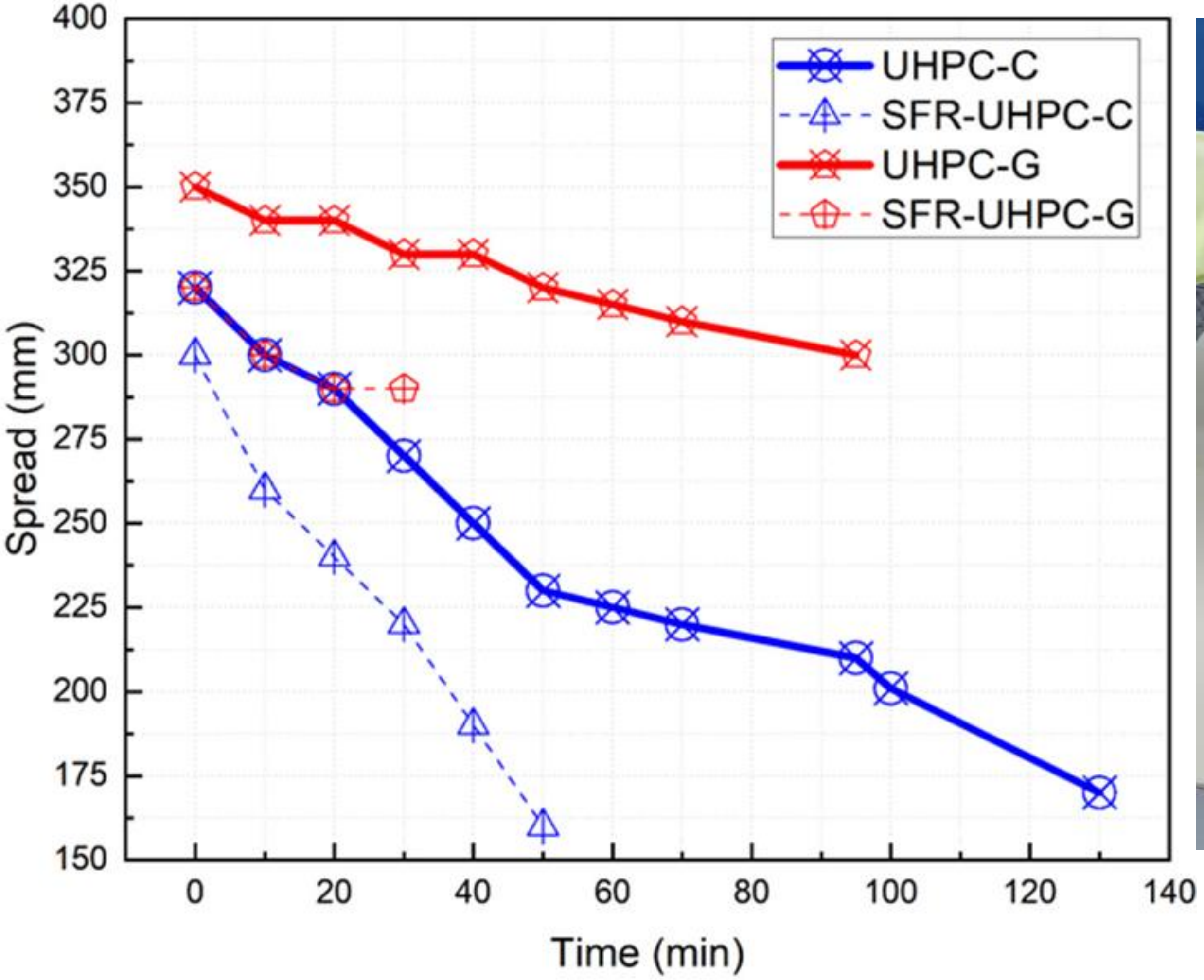
### Volumetric weight and Air content of UHPC

| Mix | Volumetric Weight (kg/m³) | Content Air (%) |
|---|---|---|
| UHPC-C | 2458 | 3.2 |
| SFR-UHPC-C | 2565 | 3.2 |
| UHPC-G | 2377 | 2.3 |
| SFR-UHPC-G | 2465 | 1.5 |

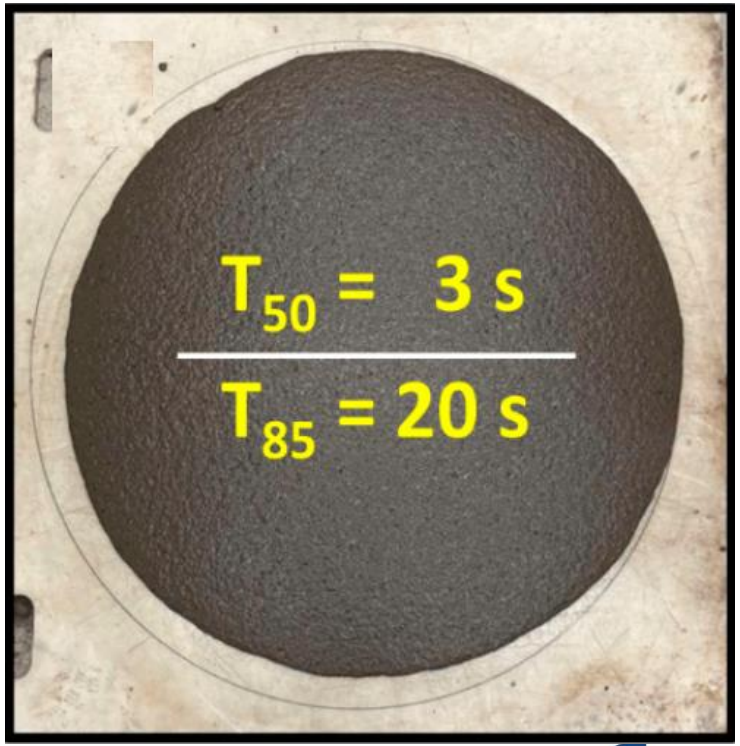



# RESULTS

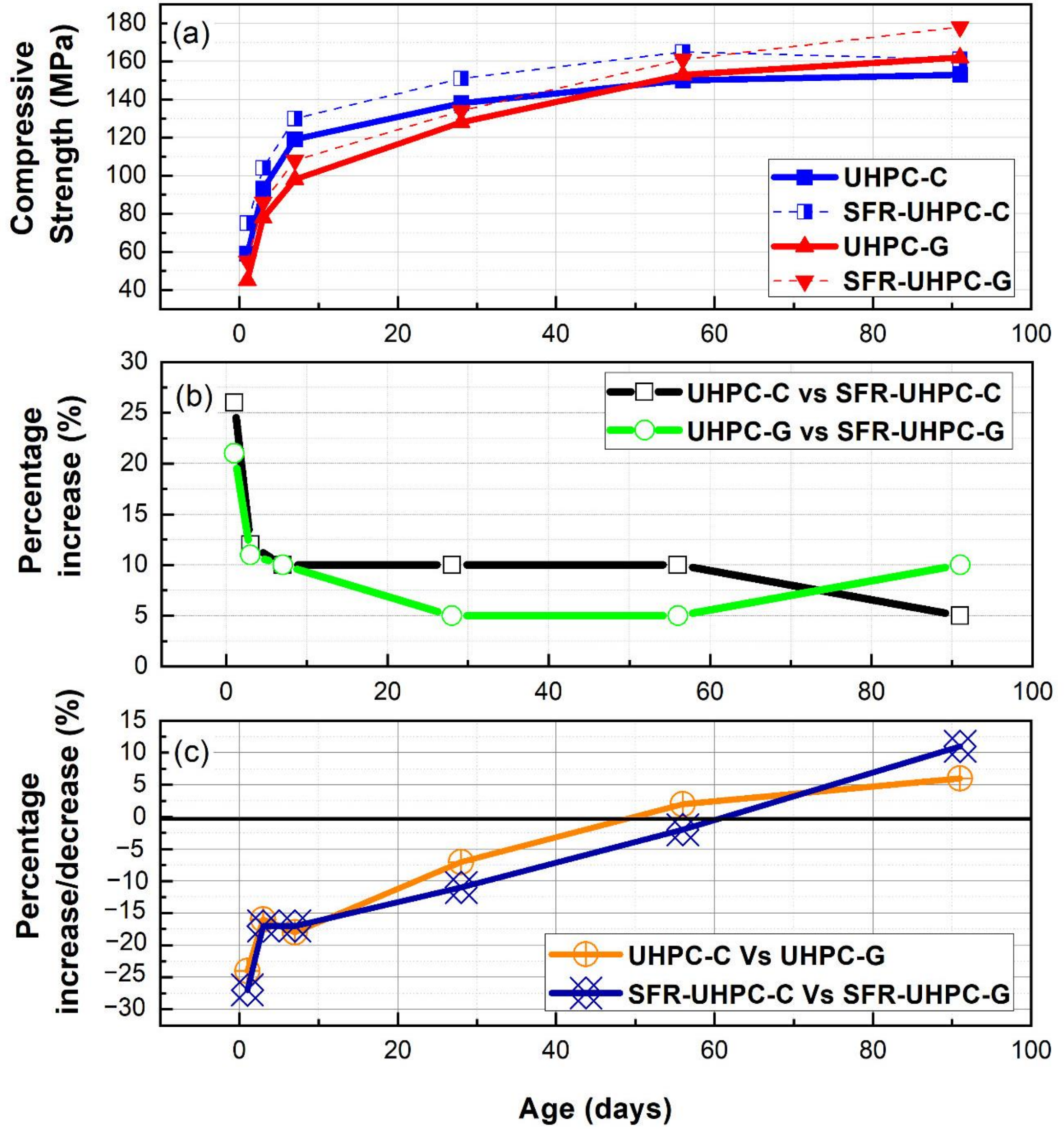
**Loss of extensibility**







# RESULTS




## Compressive Strength

| Mix | Compressive Strength (MPa) [Standard Deviation] | | | | | | Slope (m, in MPa/day) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 d | 3 d | 7 d | 28 d | 56 d | 91 d | 1–7 d | 7–28 d | 7–91 d | 28–91 d |
| UHPC-C | 59 [0.6] | 93 [1.1] | 119 [0.7] | 138 [8.0] | 150 [5.9] | 153 [1.4] | **10.00** | 0.90 | 0.41 | 0.24 |
| SFR-UHP-C | 75 [6.6] | 104 [1.3] | 130 [0.6] | 151 [0.1] | 165 [2.3] | 161 [2.1] | **9.20** | 1.00 | 0.37 | 0.16 |
| UHPC-G | 45 [0.6] | 78 [2.5] | 98 [4.5] | 128 [4.9] | 153 [4.7] | 162 [4.2] | **8.80** | 1.40 | 0.76 | 0.54 |
| SFR-UHPC-G | 55 [0.1] | 86 [2.5] | 108 [1.3] | 134 [4.2] | 161 [1.3] | 178 [1.1] | **8.80** | 1.20 | **0.83** | **0.70** |

# RESULTS

## Modulus of Elasticity

| Mix | Modulus of Elasticity (Gpa) |
|---|---|
| UHPC-C | 34.7 |
| SFR-UHPC-C | 33.5 (3.46 %) |
| UHPC-G | 39.7 |
| SFR-UHPC-G | 35.2 (11.34 %) |

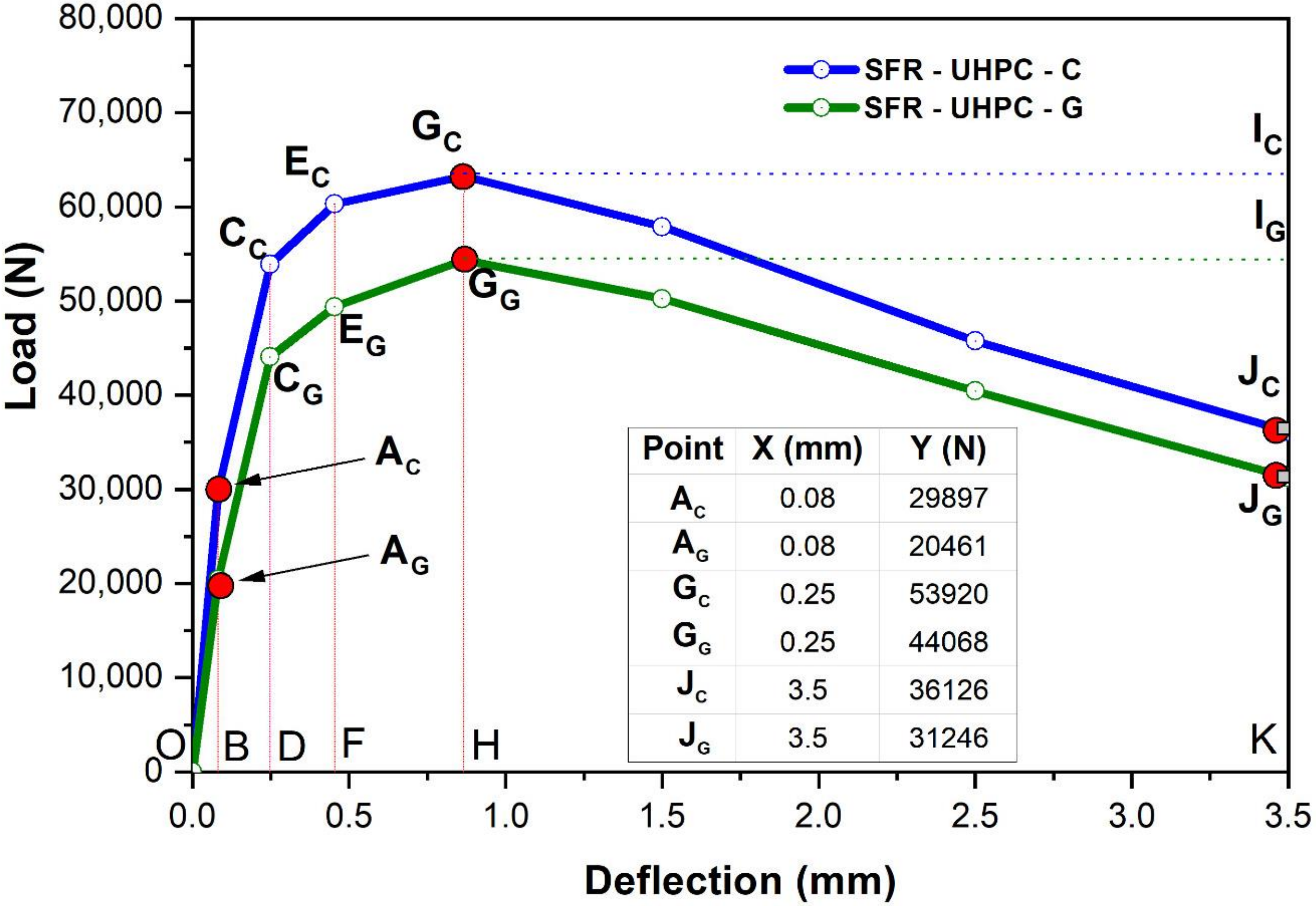
## Modulus of Rupture

UHPC-C MR = 5.2 MPa

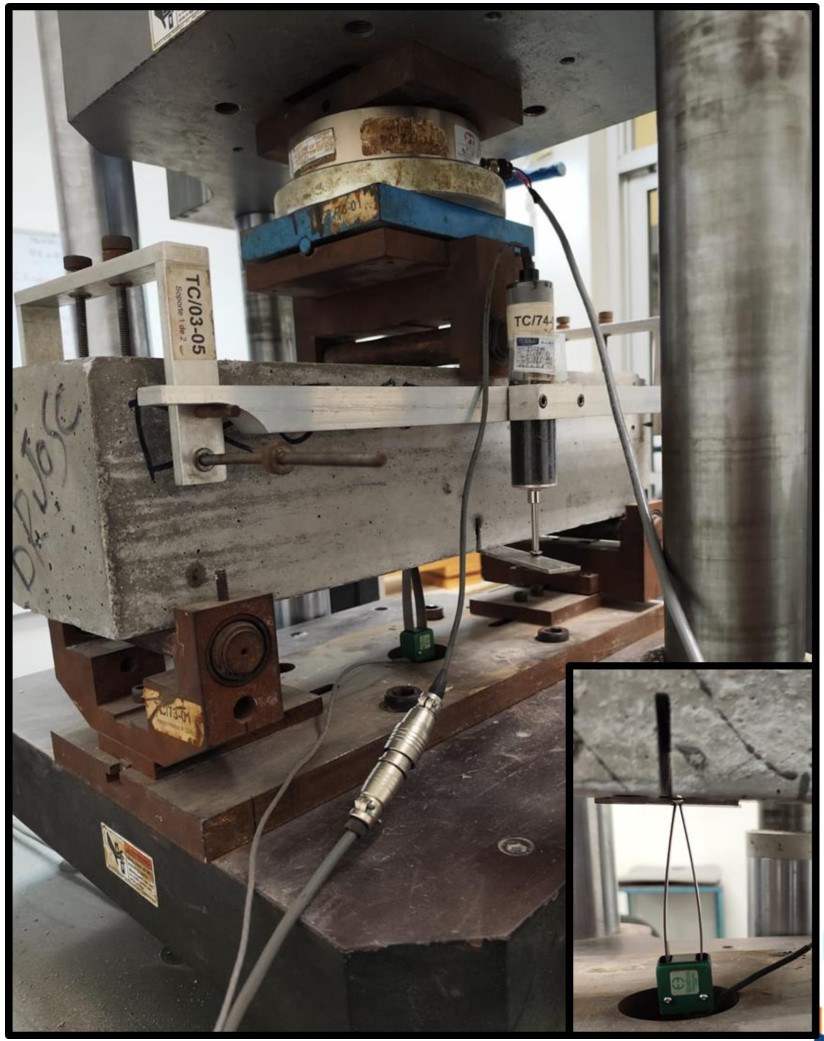
UHPC-G MR = 5.1 MPa

# RESULTS

**Post-Cracking Residual Strengths**

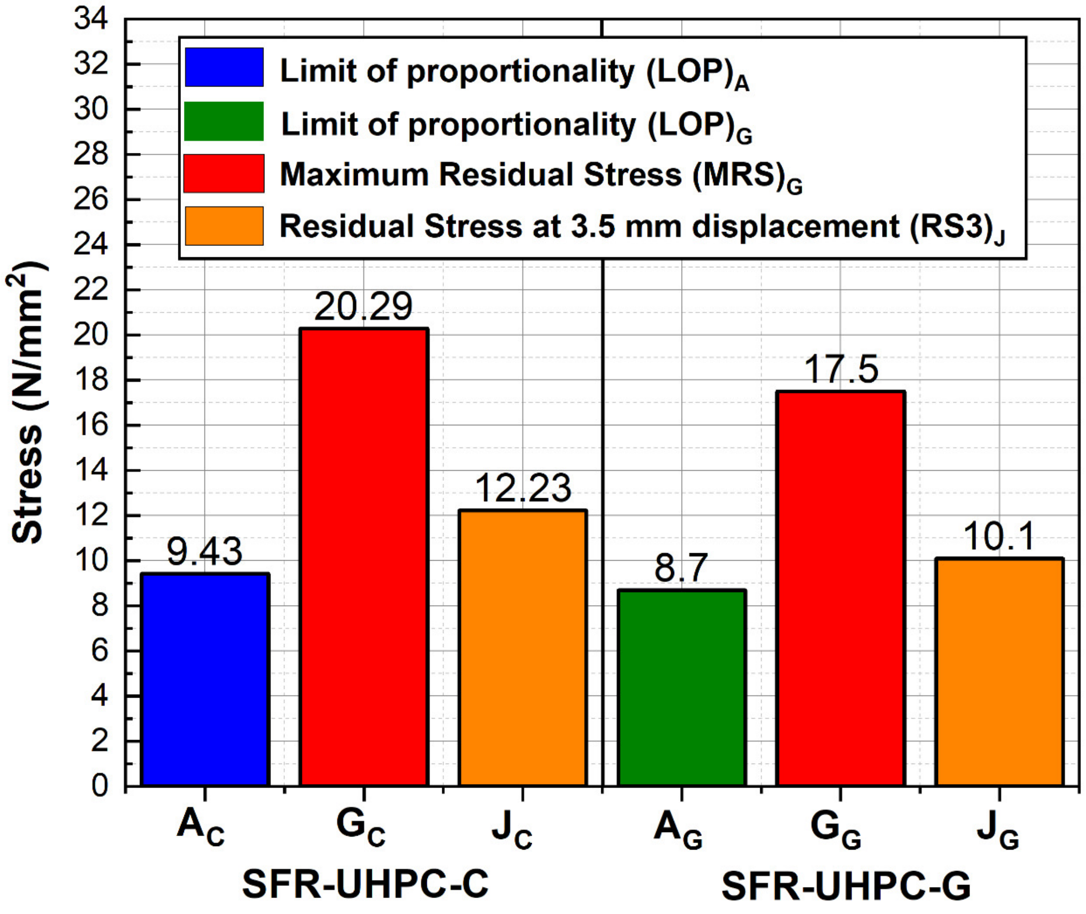



| Point | X (mm) | Y (N) |
|---|---|---|
| $A_C$ | 0.08 | 29897 |
| $A_G$ | 0.08 | 20461 |
| $G_C$ | 0.25 | 53920 |
| $G_G$ | 0.25 | 44068 |
| $J_C$ | 3.5 | 36126 |
| $J_G$ | 3.5 | 31246 |



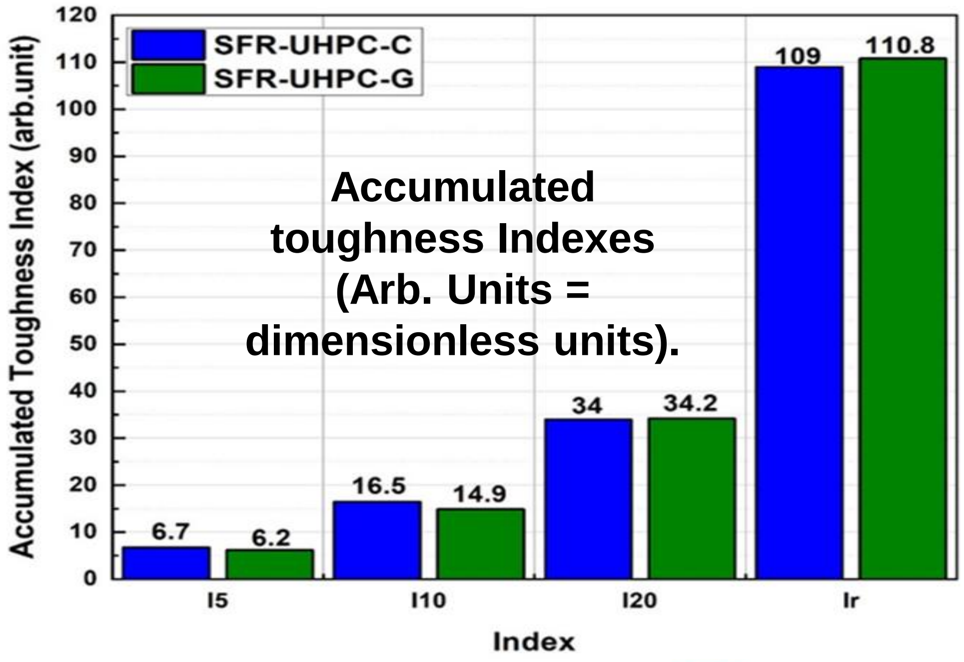
# RESULTS

## Limits of proportionality, residual strengths, and coefficients of variation for three specimens.




## Toughness indexes for several types of concretes

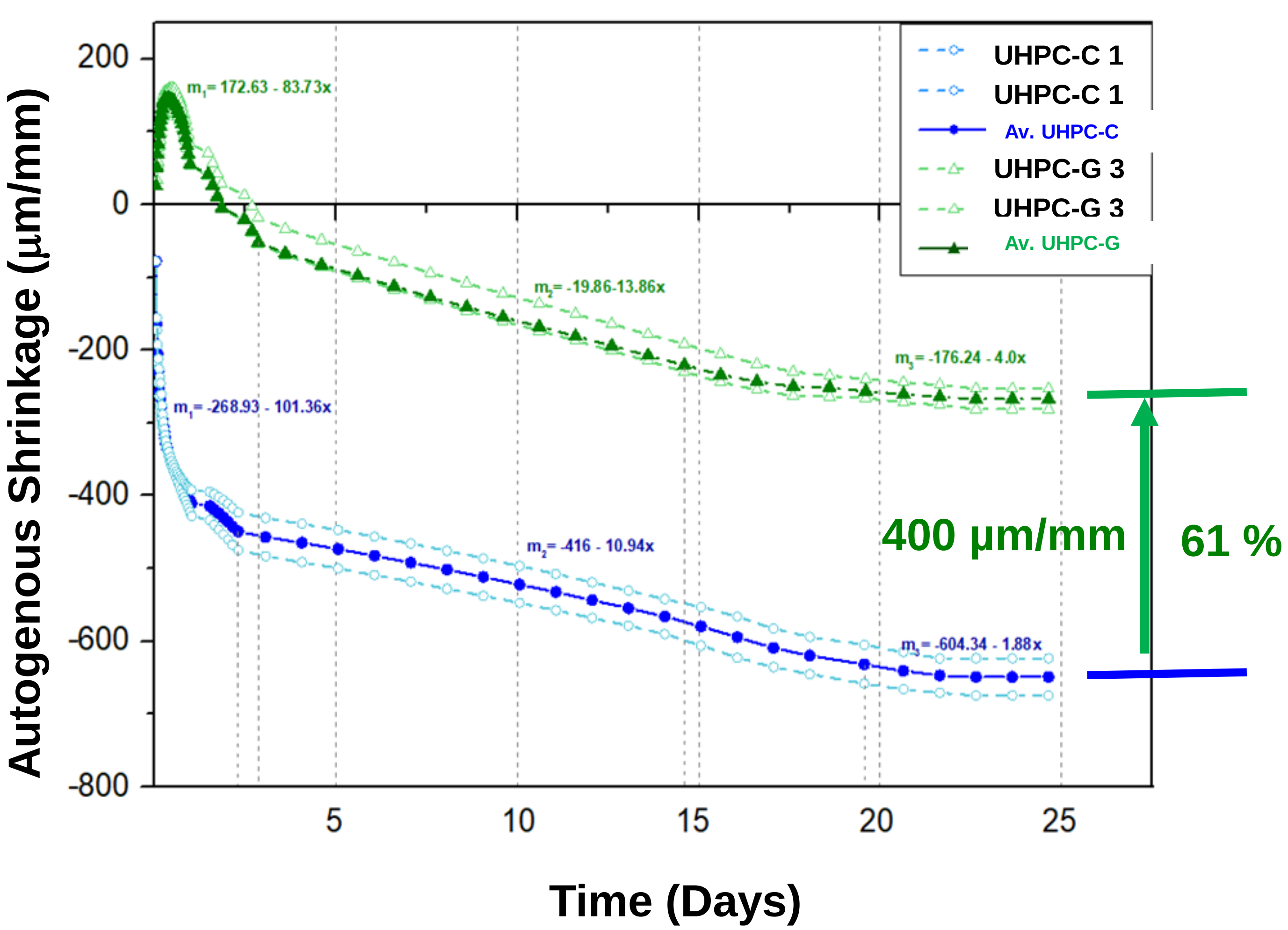
| Materials | Toughness Index (Arb. Units) | | | |
|---|---|---|---|---|
| | $I_5$ | $I_{10}$ | $I_{20}$ | $I_r$ |
| Plain Concrete | 1 | 1 | 1 | N.A. |
| Elastic-Plastic Material (E-P M) | 5 | 10 | 20 | N.A. |
| Fiber-Reinforced Concrete (FRC) | 1–6 | 1–12 | 1–25 | N.A. |
| UHPC | 5.1–5.7 | 11.4–12.9 | 20.6–29.0 | N.A. |
| SFR-UHPC-C | 6.7 | 16.5 | 34.0 | 109.0 |
| SFR-UHPC-G | 6.2 | 14.9 | 34.2 | 110.8 |




Accumulated toughness Indexes (Arb. Units = dimensionless units).

# RESULTS

Autogenous Shrinkage of concrete




# RESULTS

## Estimation of Embodied $CO_2$

| Items | Embodied $CO_2$ [$kgCO_2/kg$] | UHPC-C $kgCO_2/m^3$ | SFR-UHPC-C $kgCO_2/m^3$ | UHPC-G $kgCO_2/m^3$ | SFR-UHPC-G $kgCO_2/m^3$ |
|---|---|---|---|---|---|
| Superplasticizer | 0.720 | 5.7 | 5.5 | 5.7 | 5.6 |
| CPO | 0.830 | 597.6 | 597.6 | 418.4 | 413.3 |
| SF | 0.000 | 0 | 0 | --- | --- |
| VC ($D_{50}$ = 8.4 μm) | 0.040 | --- | --- | 3.2 | 3.16 |
| VC ($D_{50}$ = 15.2 μm) | 0.040 | --- | --- | 8.6 | 8.5 |
| VC ($D_{50}$ = 40.7 μm) | 0.020 | --- | --- | 2.5 | 2.5 |
| VC ($D_{50}$ = 950 μm) | 0.003 | --- | --- | 0.7 | 0.7 |
| LS ($D_{50}$ = 950 μm) | 0.002 | 1.7 | 1.7 | 1.2 | 1.2 |
| LP ($D_{50}$ = 46.3 μm) | 0.017 | 8.0 | 7.8 | 5.6 | 5.5 |
| Water | 0.000 | 0.1 | 0.1 | 0.1 | 0.1 |
| Air excluder | 0.086 | 0.1 | 0.1 | 0.1 | 0.1 |
| Steel fibers | 1.490 | 0.0 | 230.8 | 0.0 | 232.6 |
| Total (kg of $CO_2/m^3$) | | 613.1 | 843.6 | 446.1 | 673.3 |
| | | | | (27.24 %) | (20.19 %) |

# CONCLUSIONS

Based on the results obtained in this work, the following conclusions can be drawn.

1. The results of this work evidence the technical feasibility of a specific vitrified clay to be used in the production of ultra-high-performance concrete (UHPC), incorporating it as a substitute for cement (30%), silica fume (100%), and limestone sand-powder (30%), without detracting from the fresh stage properties, the compressive strength, the static modulus of elasticity, the flexural strength, and the flexural post-cracking residual strengths, and leading to reductions in the estimated embodied $CO_2$ between 20.19 and 27.24 %.

2. Although the results and uncertainty indicators reported in this work were obtained for experimental laboratory tests, these constitute an exhortation for the the precast concrete industry segment, since it is a sector in which rigorous procedures are commonly implemented for quality assurance, through which it would be expected that the variations in the results in relation to those obtained in this work would be minimal or negligible.