Iowa Better Concrete Conference

Internal Curing of Ultra-High-Performance Concrete (UHPC) Using Natural Zeolite

- **Maziar Kazemian**
  Ph.D. Students
- **Behrouz Shafei, Ph.D., P.E.**
  Associate Professor

IOWA STATE UNIVERSITY

Institute for Transportation (InTrans)
Department of Civil, Construction and Environmental Engineering

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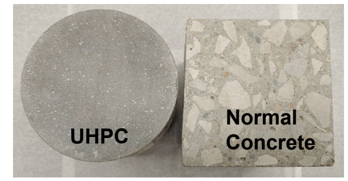
Introduction

- Characteristics of ultra-high-performance concrete (UHPC)
  - Very low water-to-binder ratio (w/b)
  - Small aggregate size
  - High cement content
  - Particle packing



- **Advantages of UHPC**
  - UHPC has high compressive, tensile, and flexural strength compared to normal strength concrete
  - UHPC benefits from superior durability properties, as a result of very low permeability

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Drawbacks of UHPC

- **Cost**
  - High cement content (3-4 times of that of normal concrete)
  - High superplasticizer content
  - Small and specially-graded aggregates
- **Environmental impact**
  - CO_2 emission: 8-9% of the total CO_2 emission is for cement production
  - Energy consumption: 2-3% of the global energy is used for cement production
- High autogenous shrinkage due to high cement content
- Low degree of hydration (DoH) of cement particles

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Addressing the Drawbacks

- With the consequences associated with high cement content, replacing a portion of cement with supplementary cementitious materials (SCMs) can be a promising method.
- SCMs:
  - are less expensive than Portland cement
  - have much lower environmental impact
  - have the potential to reduce autogenous shrinkage
  - have the potential to enhance the DoH of cement particles

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Research Objectives and Outline

- **Objectives:**
  - Enhancing the DoH of cement particles in UHPC with zeolite
  - Ensuring that zeolite maintains the superior properties of UHPC
- **Research Outline:**
  - Evaluating the internal curing capability of natural zeolite
  - Quantifying the effects of internal curing on the DoH of cement in UHPC
  - Investigating the effects of internal curing capability of natural zeolite on the dimensional stability and durability properties of UHPC

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Non-Proprietary UHPC

- **UHPC Mixture Design**

- The w/b is set at 0.1875.

- Polycarboxylate-base high-range water reducer (71.5% water).

- River sand with a maximum size of 3 mm was used, making 47.2% of the total sand. The remaining portion was masonry sand.

- Type I/II ordinary Portland cement.

- SCMs utilized in this study were **silica fume** and **natural zeolite**.

Material	Sand	Cement	SCM	Water
Ratio	1	1	0.14	0.214

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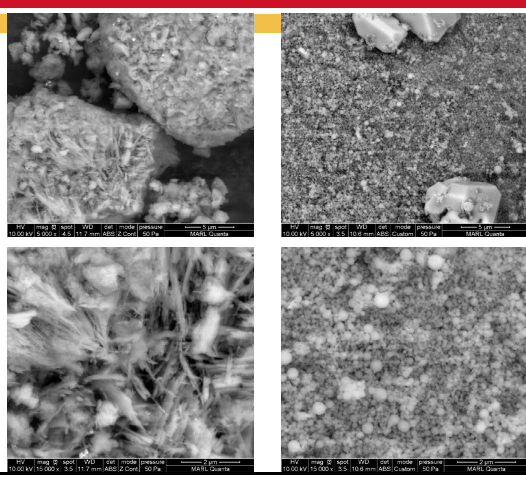
Morphology of Zeolite and Silica Fume

Natural zeolite 5000X

Silica fume 5000X



Natural zeolite 15000X

Silica fume 15000X

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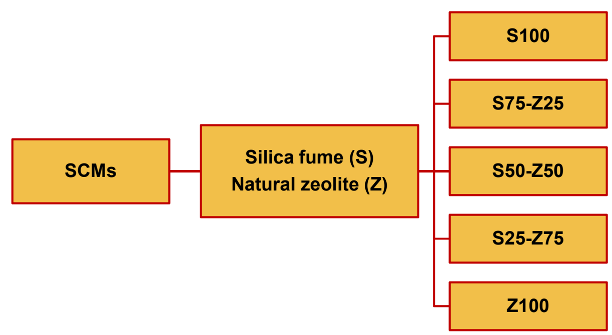
Mixture Design

- Silica fume was gradually replaced by Zeolite.
- SCM content remains unchanged.



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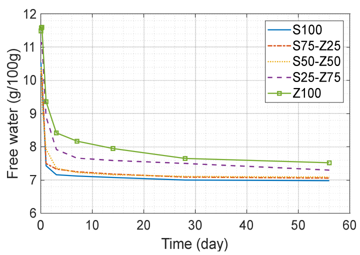
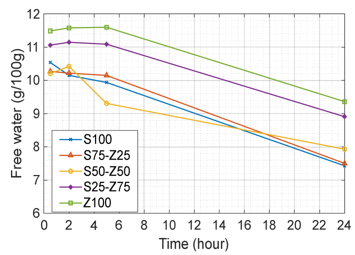
Internal Curing Capability of Zeolite

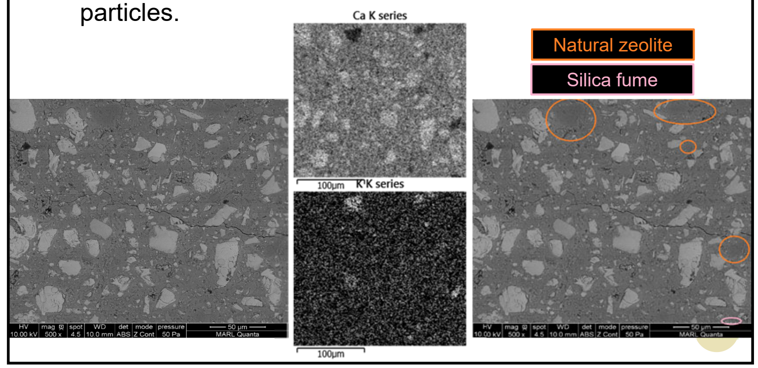
- Free water test was conducted on UHPC samples after 30 min, 2 h, 5 h, 1 d, 3 d, 7 d, 14 d, 28 d, and 56 d.
  - 3 disk-shaped samples were oven-dried at 105 °C for 3 days and the average weight loss was reported for them.
  - Z100 mixture maintained a higher free water than S100 mixture.





SEM Image Analysis

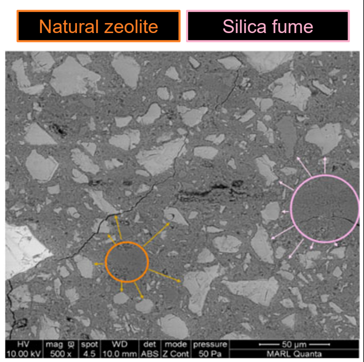
- BSE was used to capture chemical composition contrast.
- EDS was employed to distinguish silica fume and zeolite particles.



Internal Curing Capability of Zeolite

- The unhydrated cement particles around zeolite were:
- Located at a farther distance
- Grown smaller in number

- This can be attributed to the water desorption of natural zeolite, which proves its internal curing capability.



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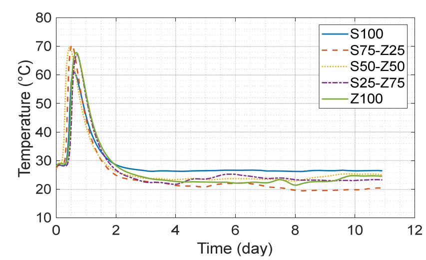
Monitoring of Temperature

- The temperature of the UHPC samples was measured at 10-minute intervals for 11 days.
  - Zeolite increased the maximum temperature, while the S100 mixture recorded the lowest maximum temperature.
  - S50-Z50 has the earliest setting, confirming the free water results.



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Degree of Hydration (DoH)

- Portland cement contains 4 main crystalline phases, which react with water and produce the C-S-H gel:
  - Tricalcium Silicate (C_3S)
  - Dicalcium Silicate (C_2S),
  - Tricalcium Aluminate (C_3A),
  - Tetracalcium Ferroaluminate (C_4AF)
- Consumption of these phases indicates the DoH:

$$\mathbf{DoH(t)\ \%} = \left(\mathbf{1} - \frac{\mathbf{(C_3S + C_2S + C_3A + C_4AF)(t)}}{\mathbf{(C_3S + C_2S + C_3A + C_4AF)(t = 0)}}\right) \times \mathbf{100}$$

- TGA and XRD were used to quantify crystalline phases in the mixtures.

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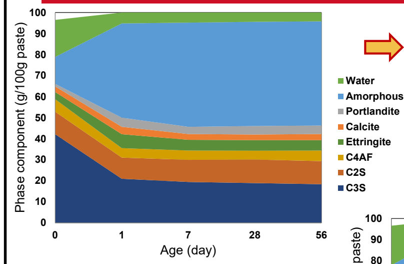
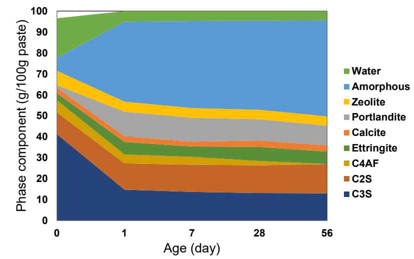
Hydration Kinetics



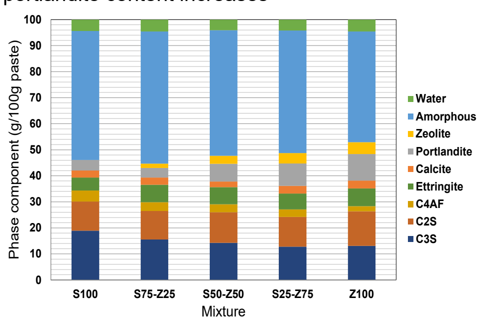
S100 mixture:
- Low portlandite content
- Rapid consumption of C_3S
- C_3A is fully consumed
- Negligible change in the content of C_2S and C_4AF

Z100 mixture:
- Small changes in zeolite content
- Higher portlandite content
- Higher consumption of C_3S
- C_3A is fully consumed
- C_4AF is fully consumed at 56 d
- Negligible changes in C_2S



Hydration Kinetics

- 28-day data show that by increasing the zeolite content:
  - The C_3S and C_4AF consumption increases
  - The portlandite content increases



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Degree of Hydration

- The DoH of cement particles are calculated:
  - Z100 mixture had a higher DoH at all ages compared to S100.
  - Hydration was almost stopped for S100 after 7 days, while Z100 shows hydration development up to 56 days.
  - Increasing the zeolite content increased the DoH, and it reached maximum in S25-Z75. This proves the synergistic effect of silica fume and natural zeolite.

Mix ID	Age (day)			
	1	7	28	56
S100	40.9	42.8	43.0	42.9
S75-Z25	-	-	50.8	-
S50-Z50	-	-	51.6	-
S25-Z75	-	-	54.1	-
Z100	46.4	48.4	51.9	54.3

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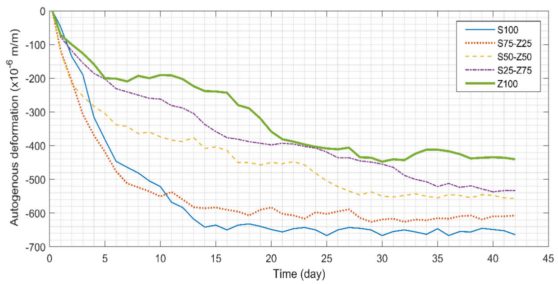
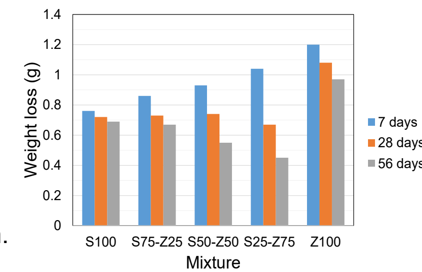
Autogenous Shrinkage

- Incorporation of zeolite in UHPC reduced autogenous shrinkage-induced strains. A 25%, 50%, 75%, and 100% replacement of silica fume with zeolite resulted in 9%, 16%, 20%, and 34% lower deformations, respectively.

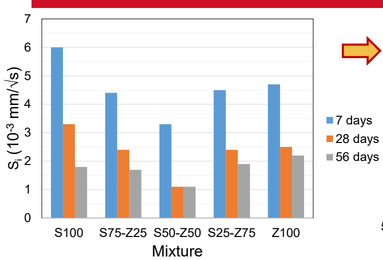


Abrasion Resistance

- At 7 days, S100 showed the highest abrasion resistance, which can be attributed to the high pozzolanic reactivity of silica fume particles.
  - This was supported by the TGA results.
- At 28 days, mixtures containing both silica fume and zeolite demonstrated a superior abrasion resistance compared to the mixtures made with only one of them.



Rate of Capillary Water Absorption

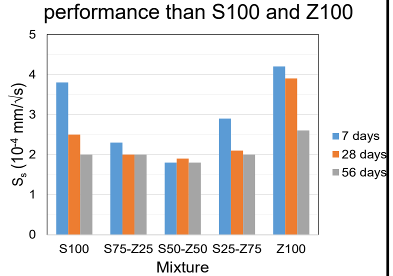


Initial water absorption

- Capillary suction governed
- At 7 days, S100 had the highest S_i
- The mix with silica fume had a higher chance of pore refinement
- Using both SCMs led to a better performance than S100 and Z100

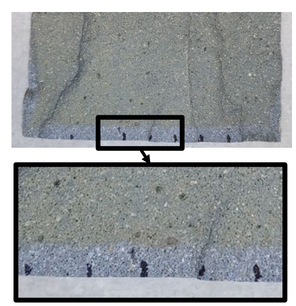
Secondary water absorption

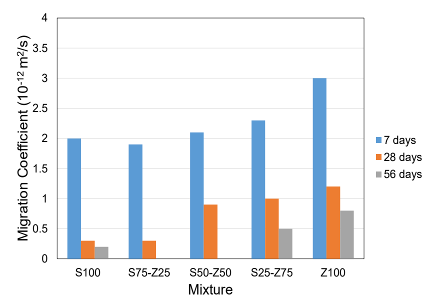
- Capillary pores were filled and a combination of permeability mechanisms governed
- Thus, S_s was lower than S_i
- Using both SCMs led to a better performance than S100 and Z100



Chloride Resistance

- After 56 days of sealed curing, the S75-Z25 and S50-Z50 mixtures completely hindered the penetration of chloride ions.





Summary and Conclusions

- In a concrete with a **w/b of 0.40**, 70-80% of cement particles were hydrated after 84 days of curing, whereas in UHPC made with a **w/b of 0.18**, that was measured to be less than 40%.
- This study focused on the effects of natural zeolite on the hydration kinetics, dimensional stability, and durability of UHPC. For this purpose, a holistic set of micro- and macro-scale investigations were performed.
- The SEM images revealed that zeolite particles are capable of internally curing the surrounding cement particles through water desorption. This was further supported by the free water data.

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Summary and Conclusions

- The free water content of the UHPC mixtures followed a descending trend, however, the addition of natural zeolite can interrupt this trend by increasing the free water in the initial hours of mixing.
- Water desorption of Zeolite helps decrease the autogenous deformation of UHPC by 32%.
- When used together, silica fume and natural zeolite showed a synergistic effect. The S25-Z75 mixture recorded the highest DoH (more than 50%) and abrasion resistance, while S50-Z50 showed the best chloride resistance, as well as the lowest capillary water absorption.

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Acknowledgement

The support of the Iowa Highway Research Board and Iowa Department of Transportation is gratefully acknowledged.

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