Alternative Materials for Use in Sustainable Concrete

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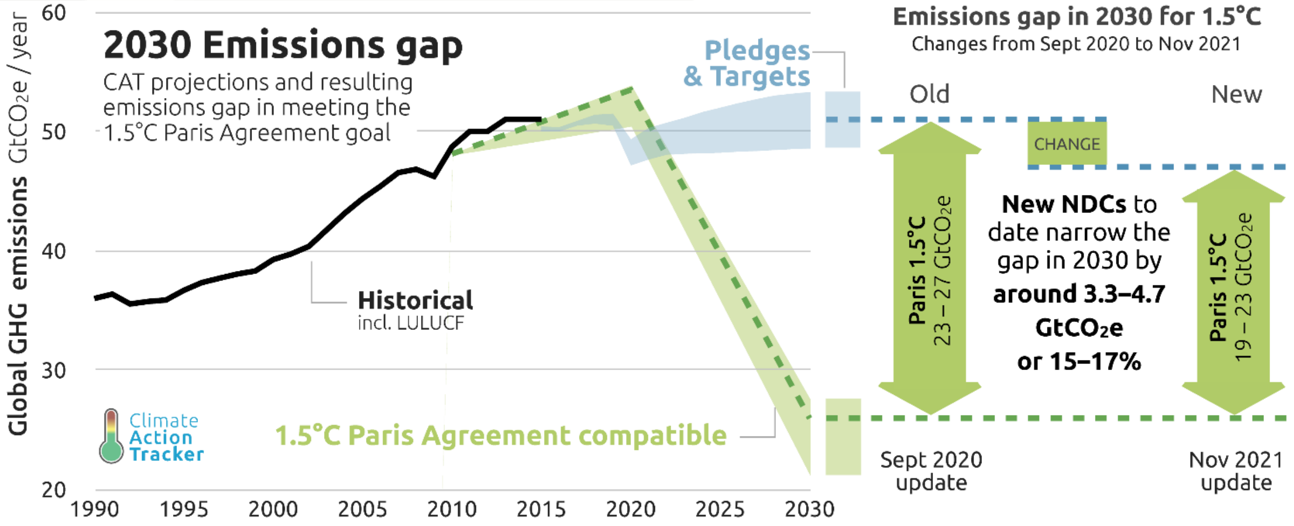
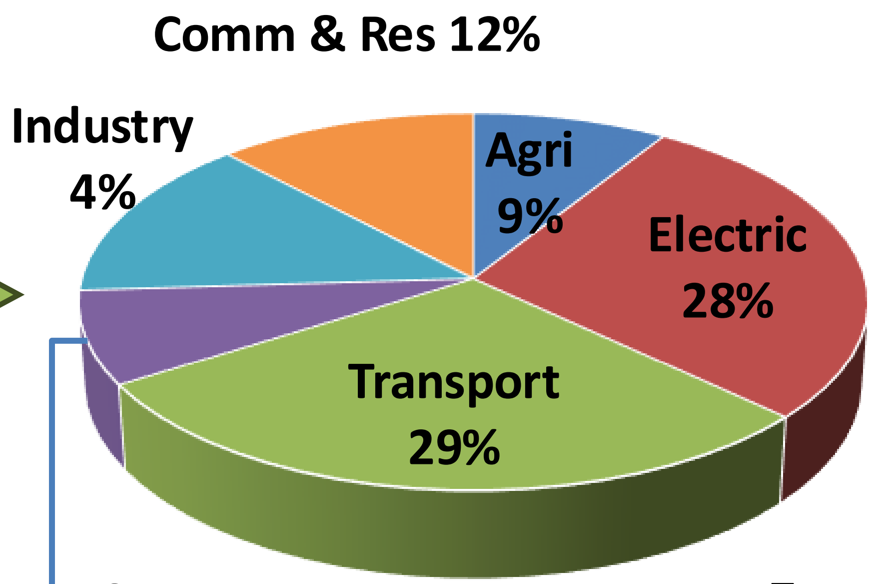
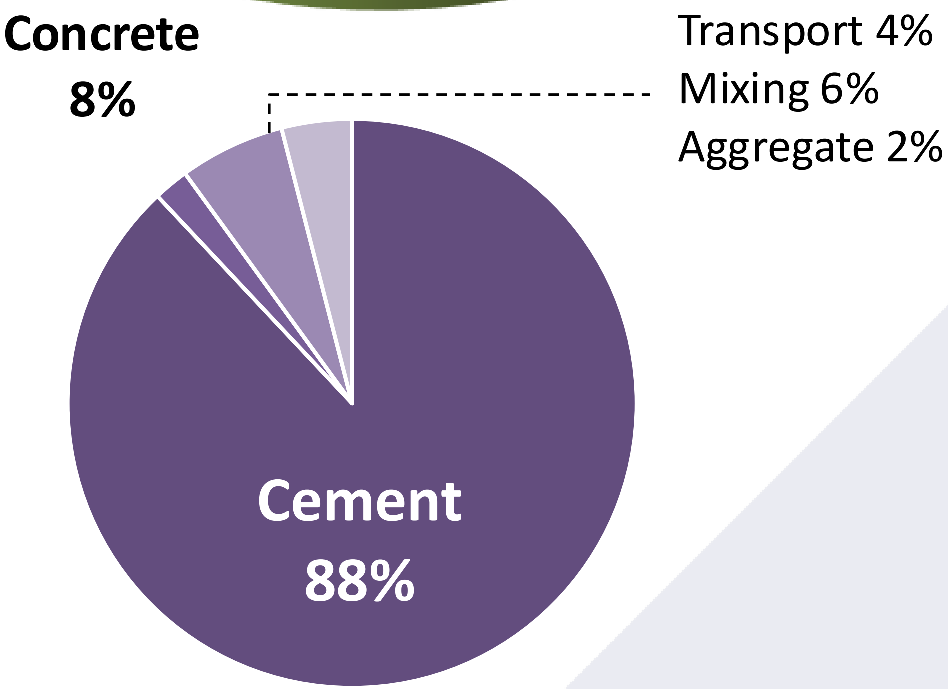
BACKGROUND AND MOTIVATION







Cement substitution with supplementary cementitious materials (SCMs)

1. Waste derived SCMs (**recycled Ground Glass Pozzolan (RGGP)**, municipal ashes, etc.)

2. Industry byproducts (**slag**, fly ash, silica fume, etc.)

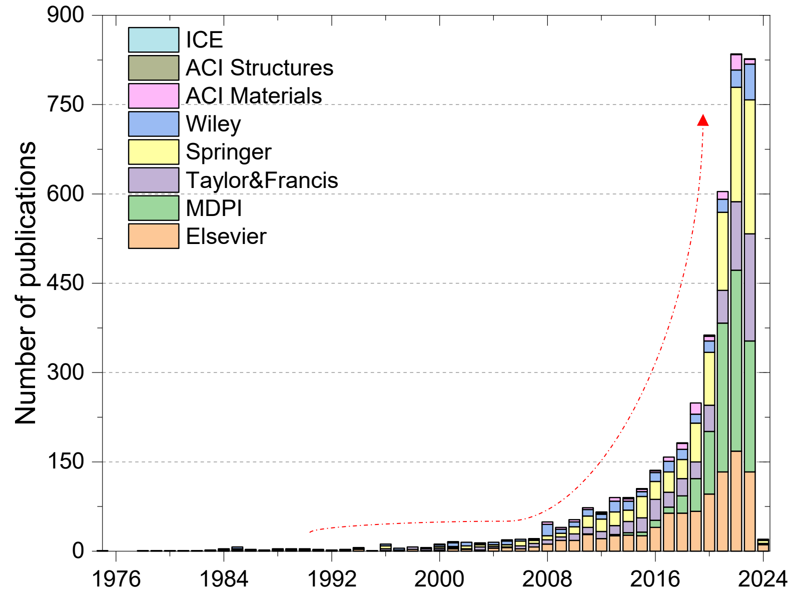
3. Class N Natural Pozzolans (**metakaolin (MK), diatomaceous earth (DE)**, montmorillonite, etc.)

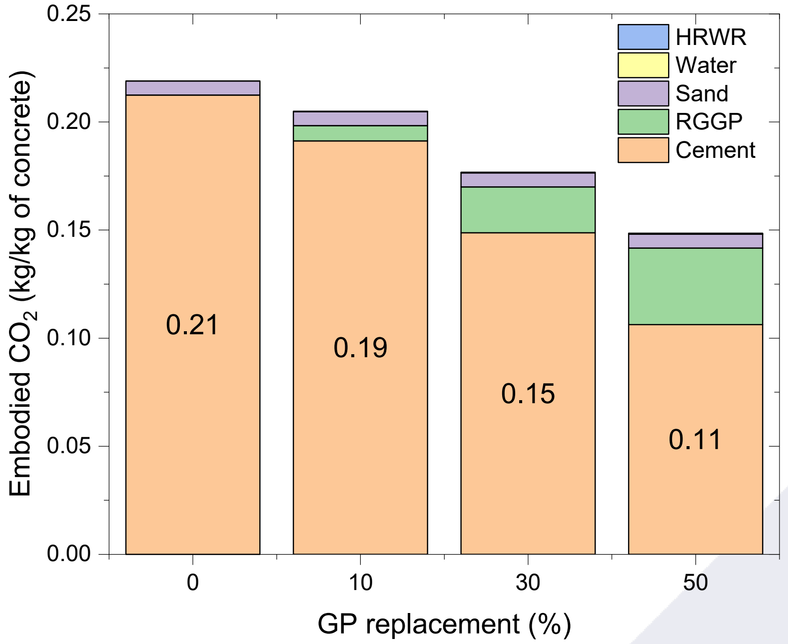
WHY RGGP?

- The United States reported a disposal of 52.9% of the waste glass to landfill and recycled 26.6% of the waste glass in 2017.
- Glass is a non-biodegradable material that occupies significant landfill space.
- Recycled Ground Glass Pozzolan (RGGP) crushed below 45 µm can have pozzolanic behavior and improve mechanical properties due to the abundance of SiO_2 (70-73%) and CaO (~10%) rendering it a promising pozzolan to replace cement.

However:

- High alkali (Na_2O_{eq}) content of ~13% can caused alkali-silica reaction (ASR)
- Must be crushed to a fine powder (<45 µm) to eliminate ASR and ensure high pozzolanic reactivity
- High-volume replacement of RGGP (>30%) may compromise mechanical properties and workability

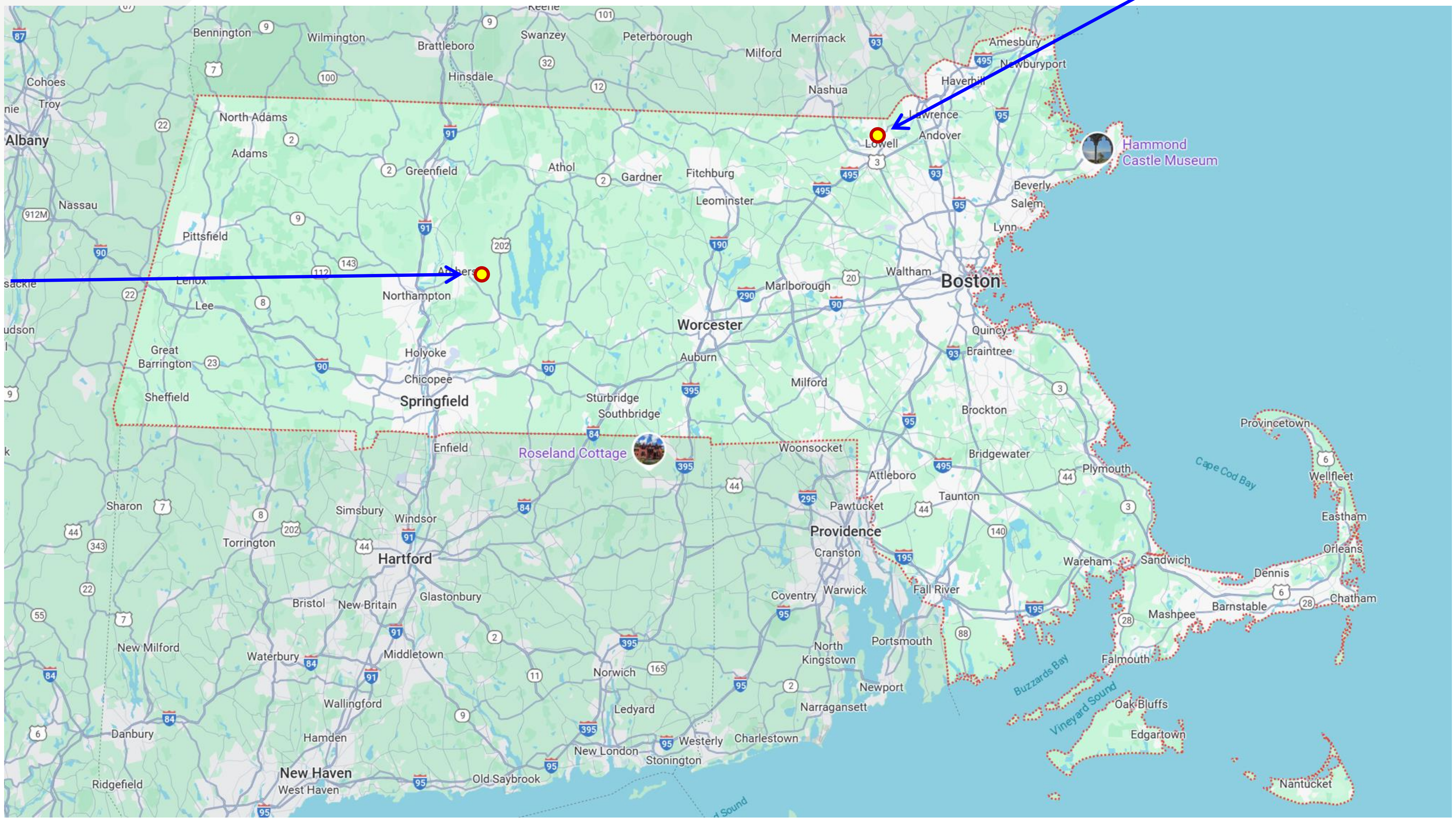




RESEARCH LOCATIONS

UMass Lowell

UMass Amherst



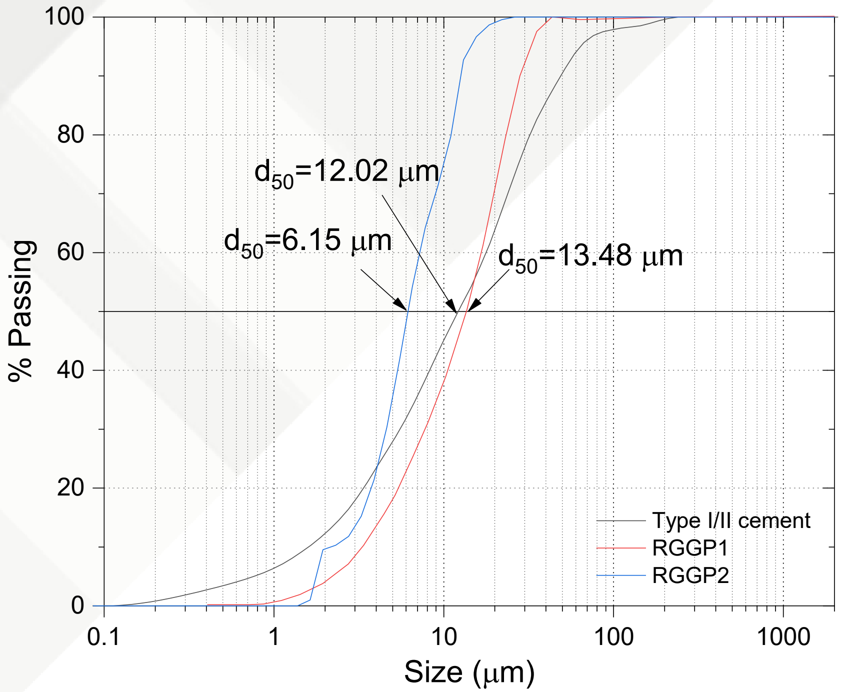
KEY WORK TO USE RGGP AS A CEMENT SUBSTITUTE

The feasibility of using RGGP as a high-volume replacement for cement was evaluated by

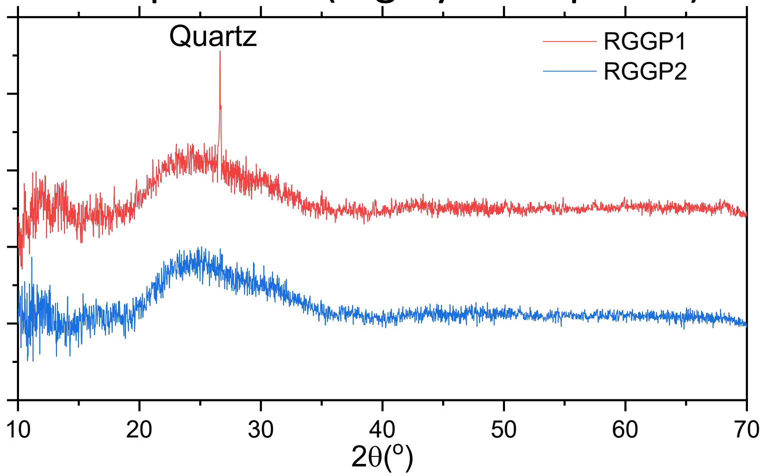
- **Characterizing the pozzolanic reactivity of RGGP** via isothermal calorimetry, thermogravimetric analysis (TGA) and quantitative X-ray diffraction (QXRD)
- **Understanding the early-age reaction kinetics** of RGGP-cement blends via isothermal calorimetry
- **Investigating the evolution of hydration products** via QXRD, TGA and Fourier transform infrared spectroscopy (FTIR)
- **Evaluating the fresh and hardened properties** of cement-RGGP composites

MATERIALS AND SAMPLE PREPARATION

Particle size distribution (laser diffraction)



XRD patterns (highly amorphous)



Chemical composition

Oxides	Cement (wt%)	RGGP1 (wt%)	RGGP2 (wt%)	ASTM C1866 limits (wt%)
CaO	62.7	10.88	10.0	2.0-15.0
SiO_2	20.1	72.29	70.0	68.0-80.0
Al_2O_3	4.8	1.89	1.0	0.3-5.0
SO_3	3.5	0.12	-	-
Fe_2O_3	3.2	0.33	0.5	0.1-1.0
MgO	3.4	-	-	
LS	1.2	0.42	0.2	0-0.5
Total alkalis	0.6	13.03	13.0	7.0-15.0

Mineralogical composition

Phases	Cement (wt%)	Phases	RGGP1 (wt%)	RGGP2 (wt%)
C_3S	54	Amorphous	95.2	95.3
C_2S	17	Calcite	0.7	0.9
C_3A	7	Quartz	1.5	0.9
C_4AF	10	Wollastonite	2.6	2.9

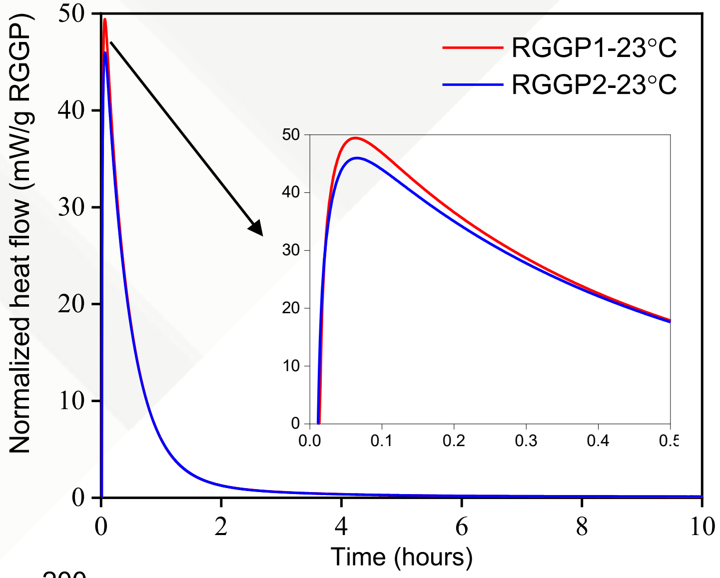
Mixture proportions for cement-RGGP composites

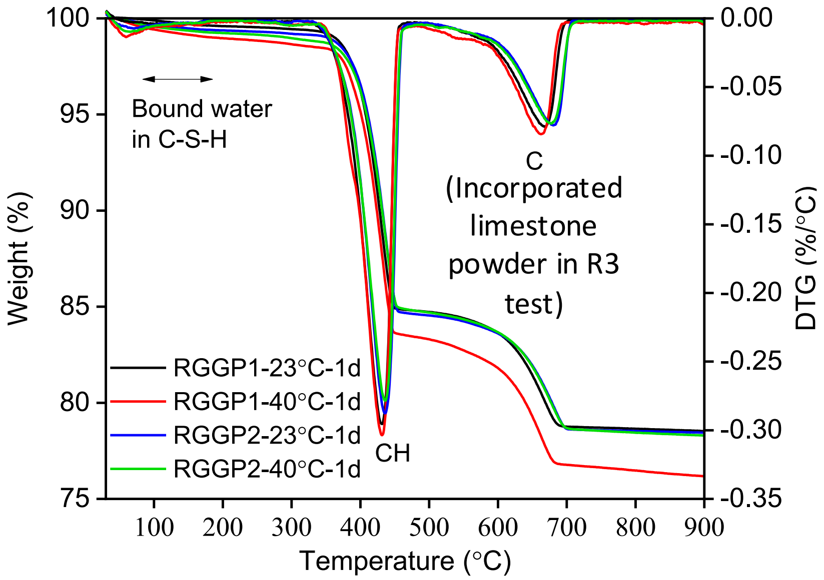
Samples	Cement (wt%)	RGGP (wt%)	Sand (wt%)	Water (w/b)	HRWR (% of binder)
PC	1	0	2.75	0.485	0
RGGP1-5	0.95	0.05			0.03
RGGP1-10	0.9	0.1			0.04
RGGP1-30	0.7	0.3			0.08
RGGP1-50	0.5	0.5			0.1
RGGP2-5	0.95	0.05			0.06
RGGP2-10	0.9	0.1			0.08
RGGP2-30	0.7	0.3			0.1
RGGP2-50	0.5	0.5			0.15

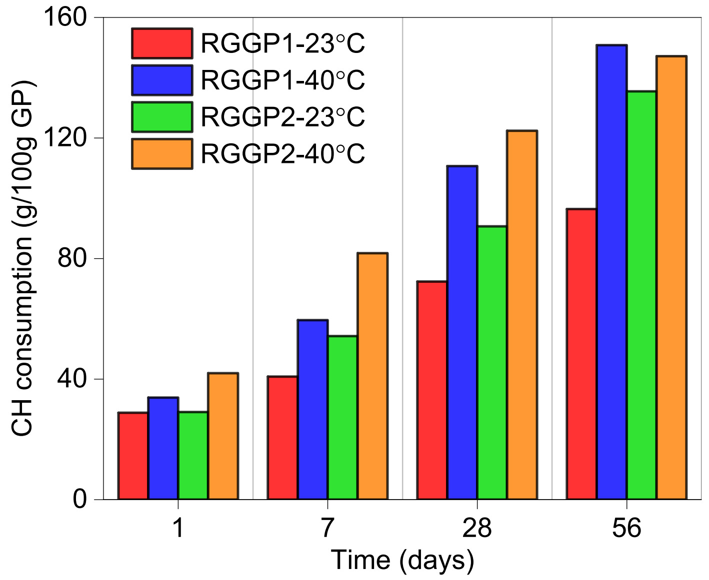
RGGP1: Urban mining
RGGP2: R.E.D.

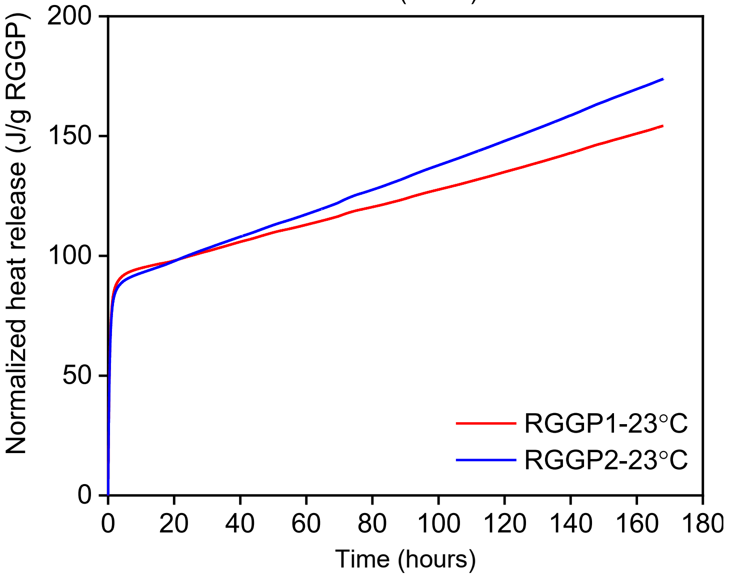
POZZOLANIC REACTIVITY OF RGGP1 AND RGGP2

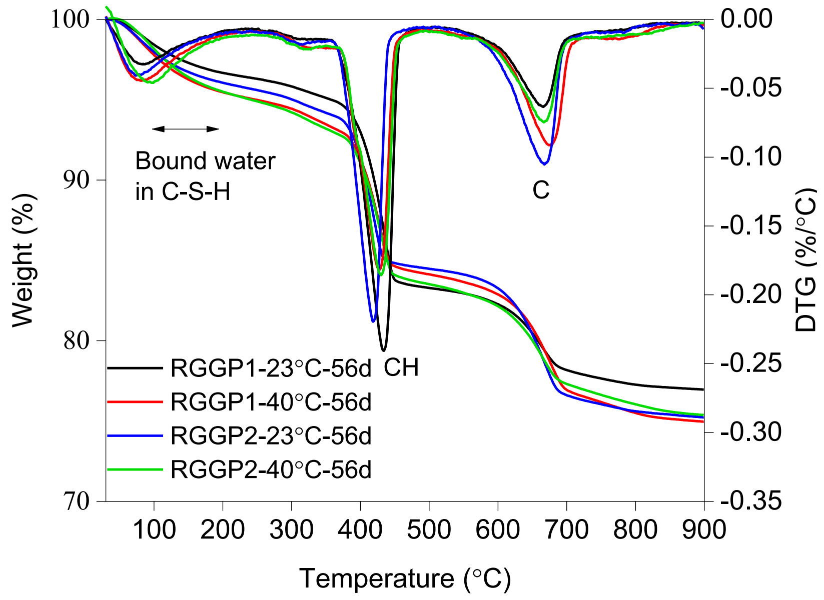
R3 Test (ASTM 1897) - Isothermal calorimetry & thermogravimetric analysis (TGA)

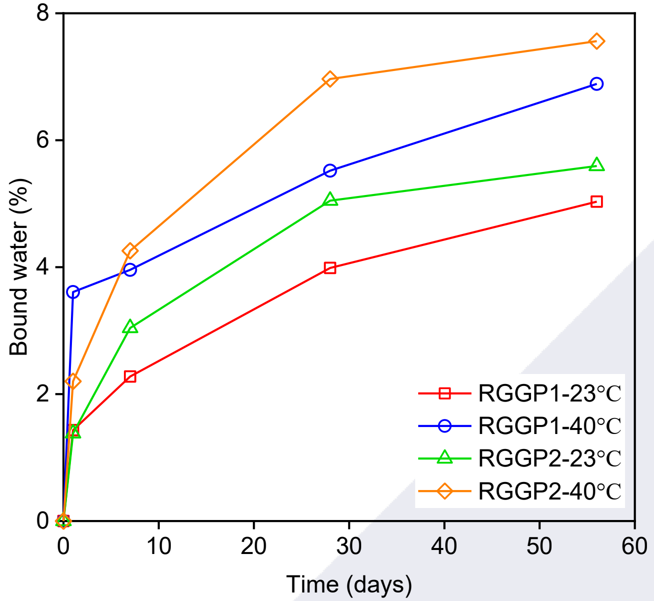








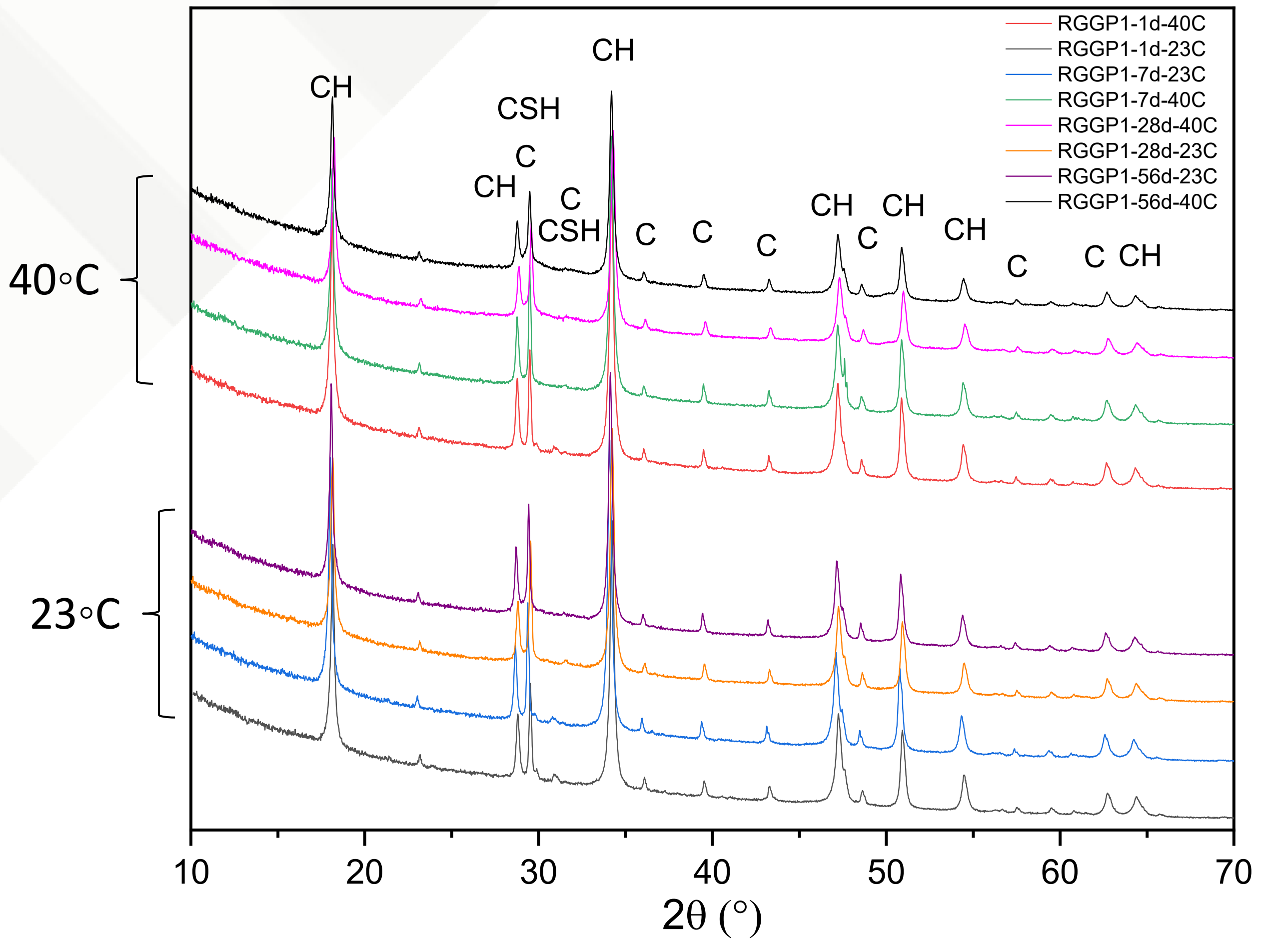




POZZOLANIC REACTIVITY OF RGGP1 AND RGGP2

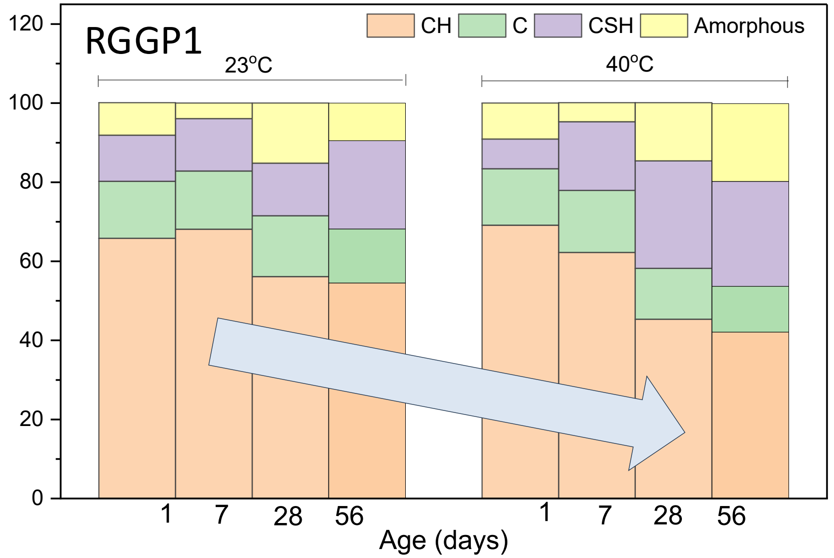
R3 Test (ASTM 1897)-XRD

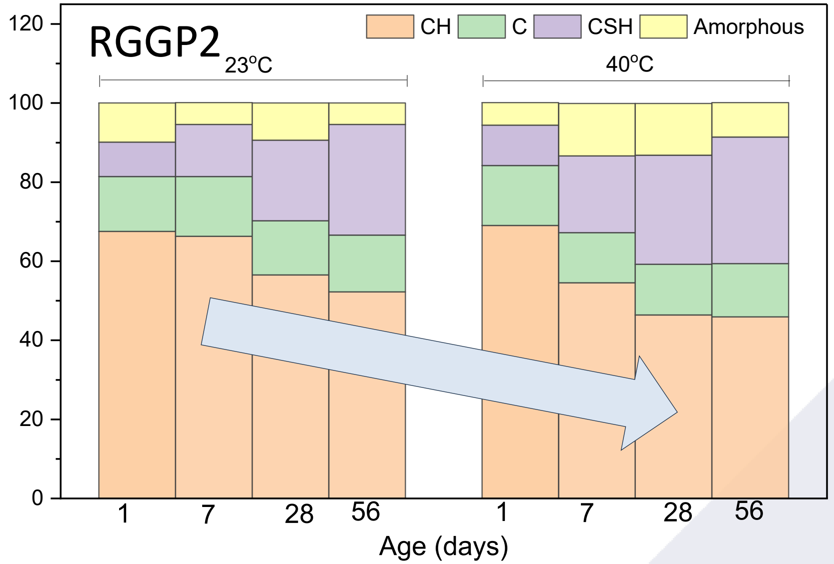
XRD patterns of RGGP1



CH-calcium hydroxide, C- Calcium carbonate, CSH- Calcium silicate hydrate

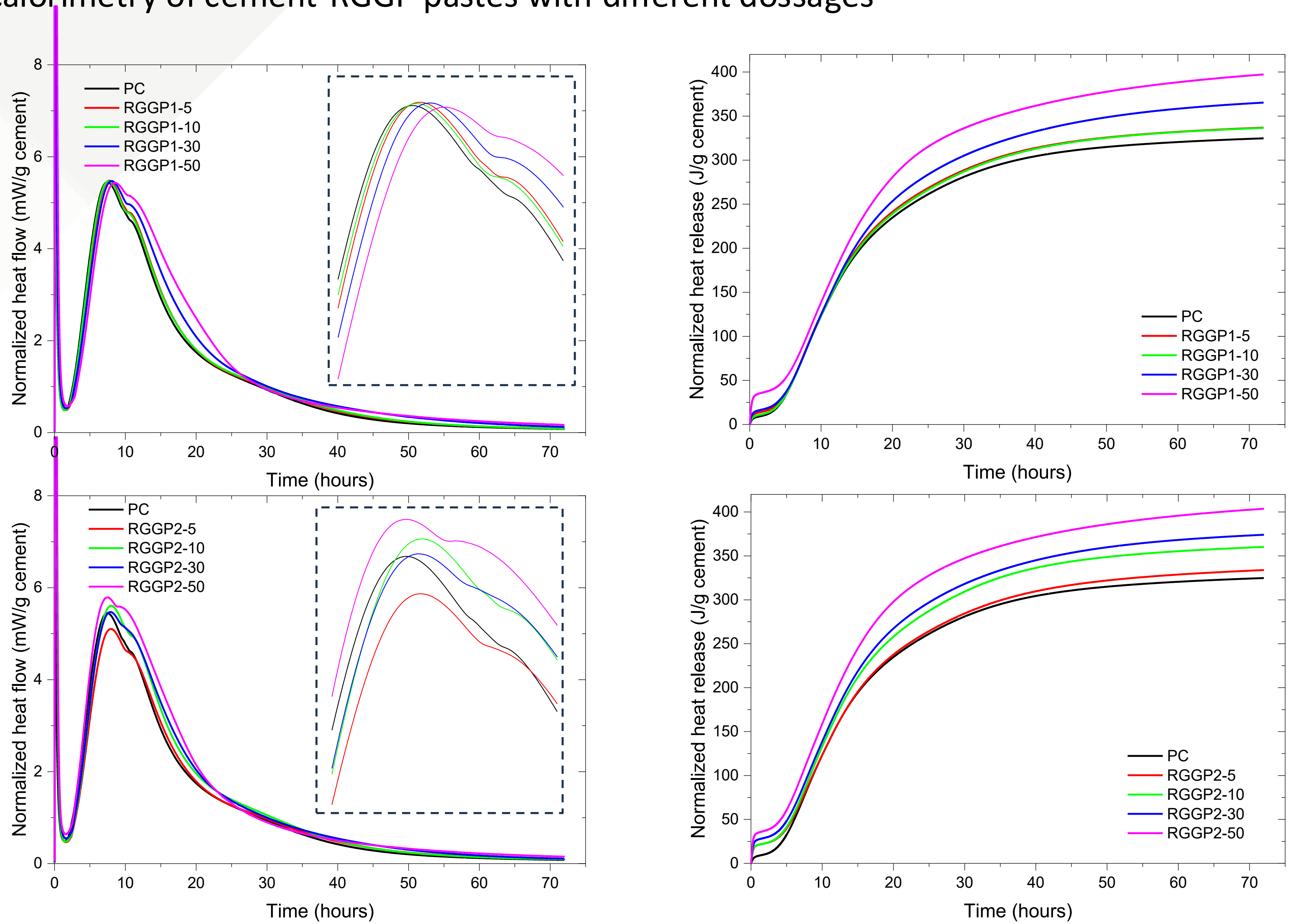
Rietveld refinement quantification





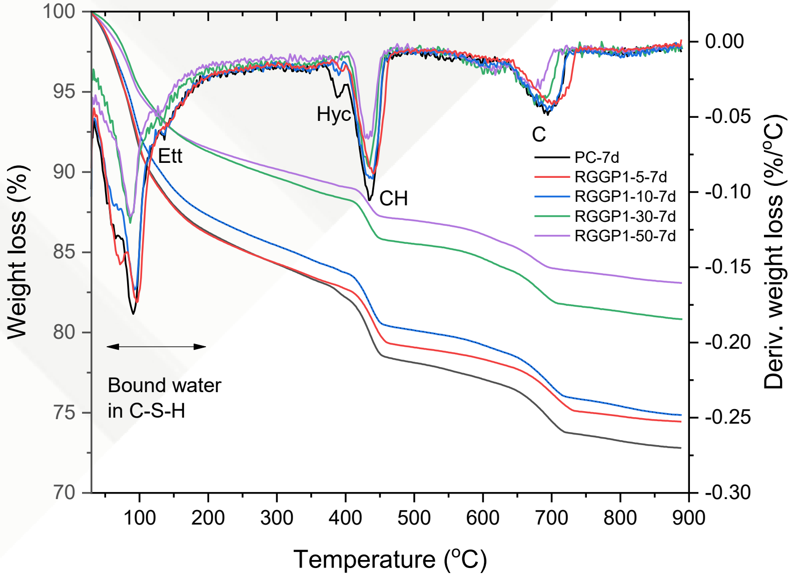
INFLUENCE ON CEMENT HYDRATION BEHAVIOR

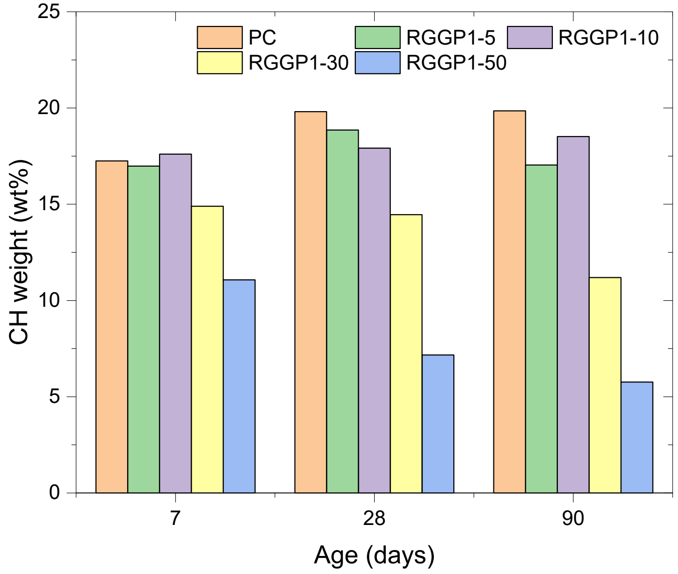
Isothermal calorimetry of cement-RGGP pastes with different dossages

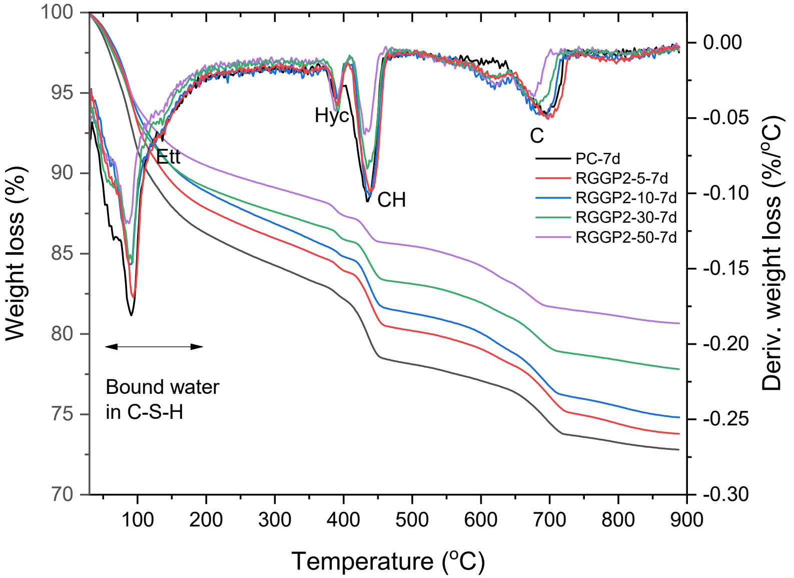


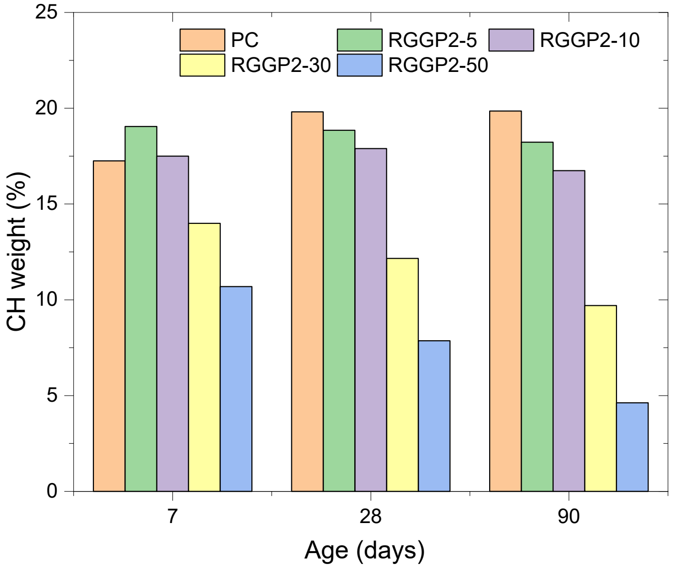
PHASE EVOLUTION OF RGGPS AT DIFFERENT DOSAGES

TGA and quantification of CH in cement-RGGP pastes







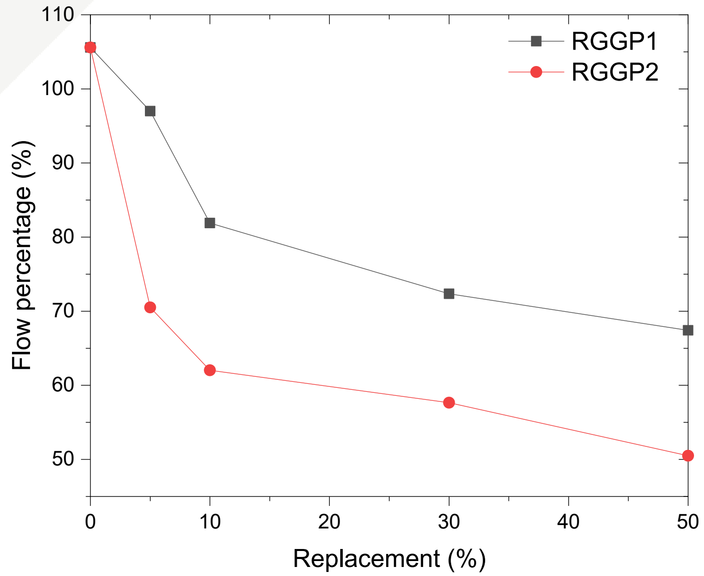


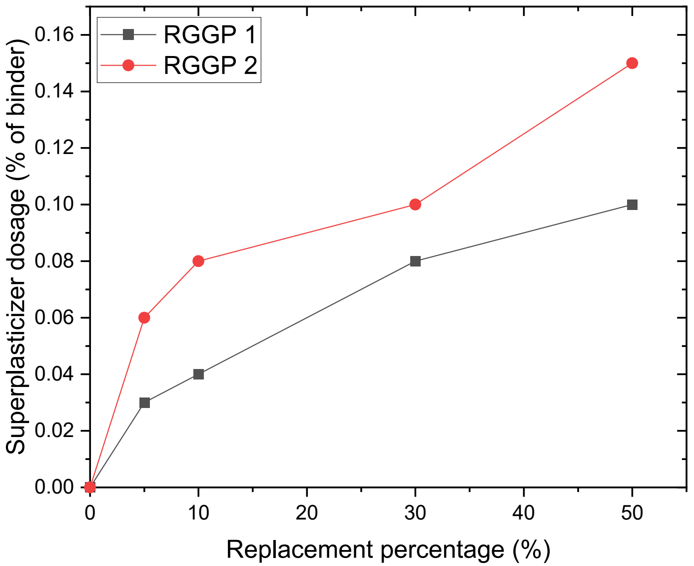
- Up to a RGGP dosage of 10%, early-age CH formation exceeds consumption
- After 90 days, CH consumption increased with RGGP dosage due to pozzolanic reaction
- RGGP2 showed greater CH consumption than RGGP1 after 90 days

CH-calcium hydroxide,
C- Calcium carbonate,
CSH- Calcium silicate hydrate
Hyc-Hydrotalcite
Ett-Ettringite

FRESH PROPERTIES – FLOW PERCENTAGE RGGP MORTAR MIX

Flow table test of cement-RGGP composites





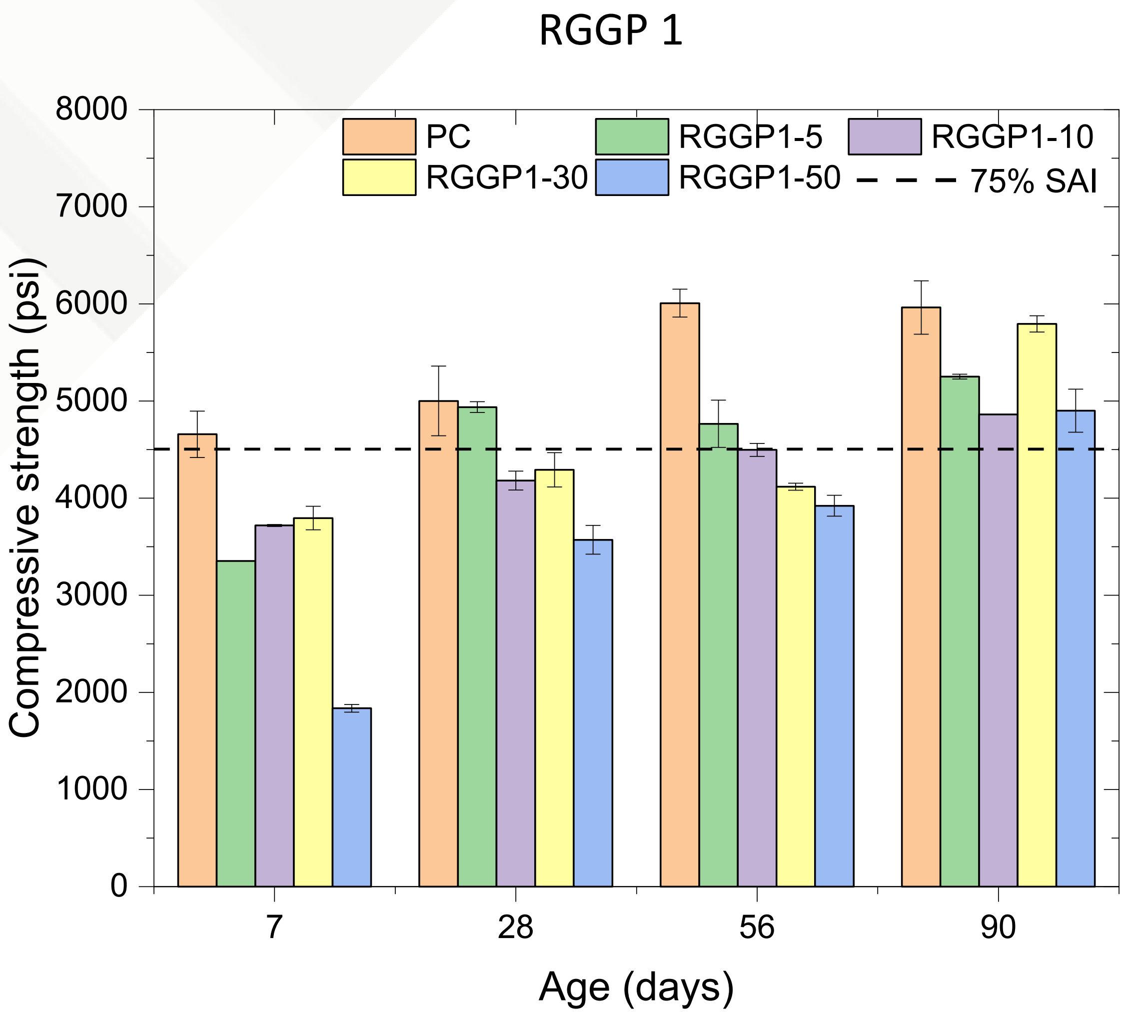
Flow percentage and HRWR dosage in cement-RGGP composites

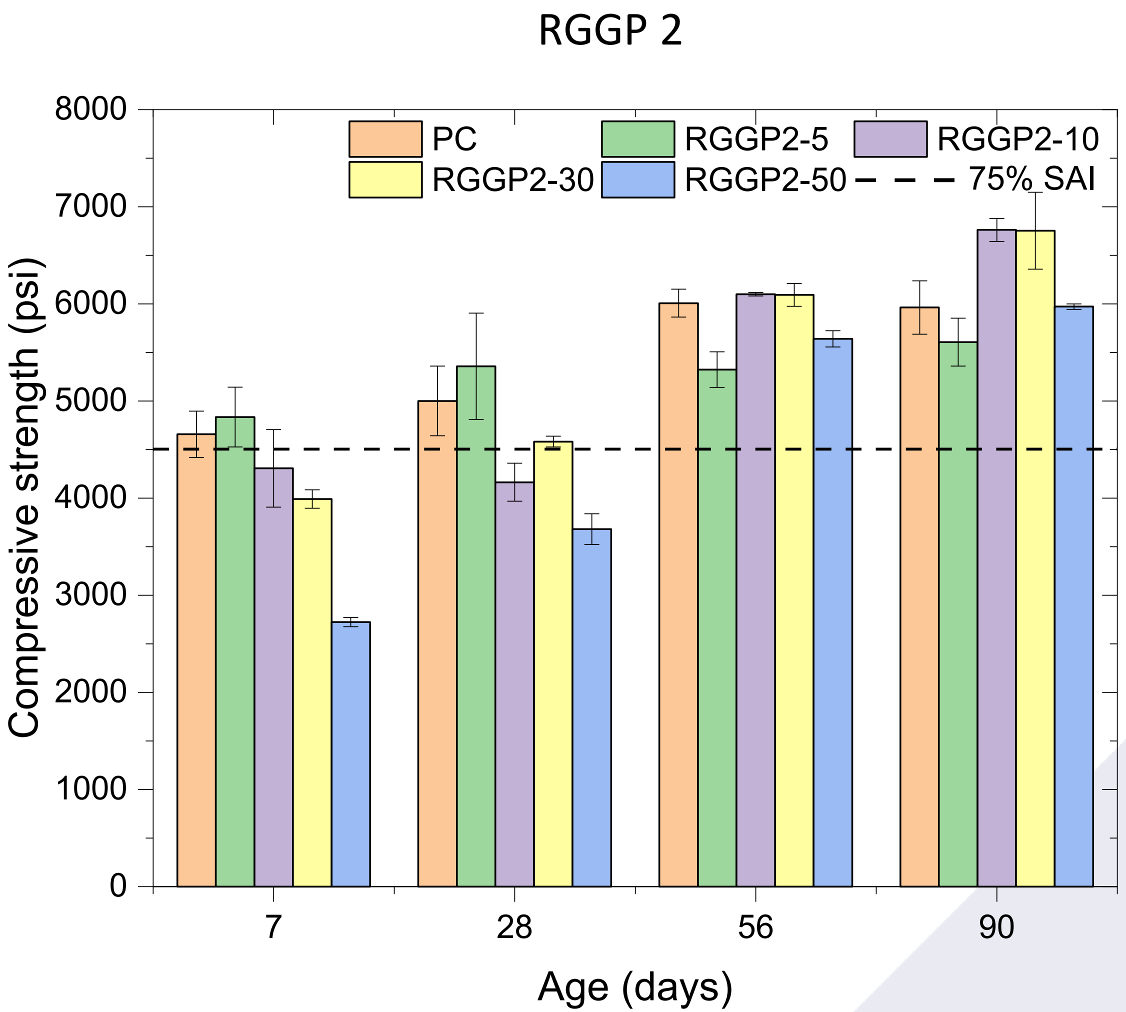
RGGP1 Replacement	Flow (%)	Dosage of HRWR (%)	Flow after HRWR (%)
0	105.58	0	105.58
5	97.00	0.03	105.62
10	81.89	0.04	105.33
30	72.35	0.08	105.97
50	67.42	0.10	108.14

RGGP2 Replacement	Flow (%)	Dosage of HRWR (%)	Flow after HRWR (%)
0	105.58	0%	105.58
5	70.52	0.06%	105.62
10	62.04	0.08%	106.19
30	57.65	0.10%	105.82
50	50.51	0.15%	106.53

STRENGTH DEVELOPMENT OF RGGP MORTARS

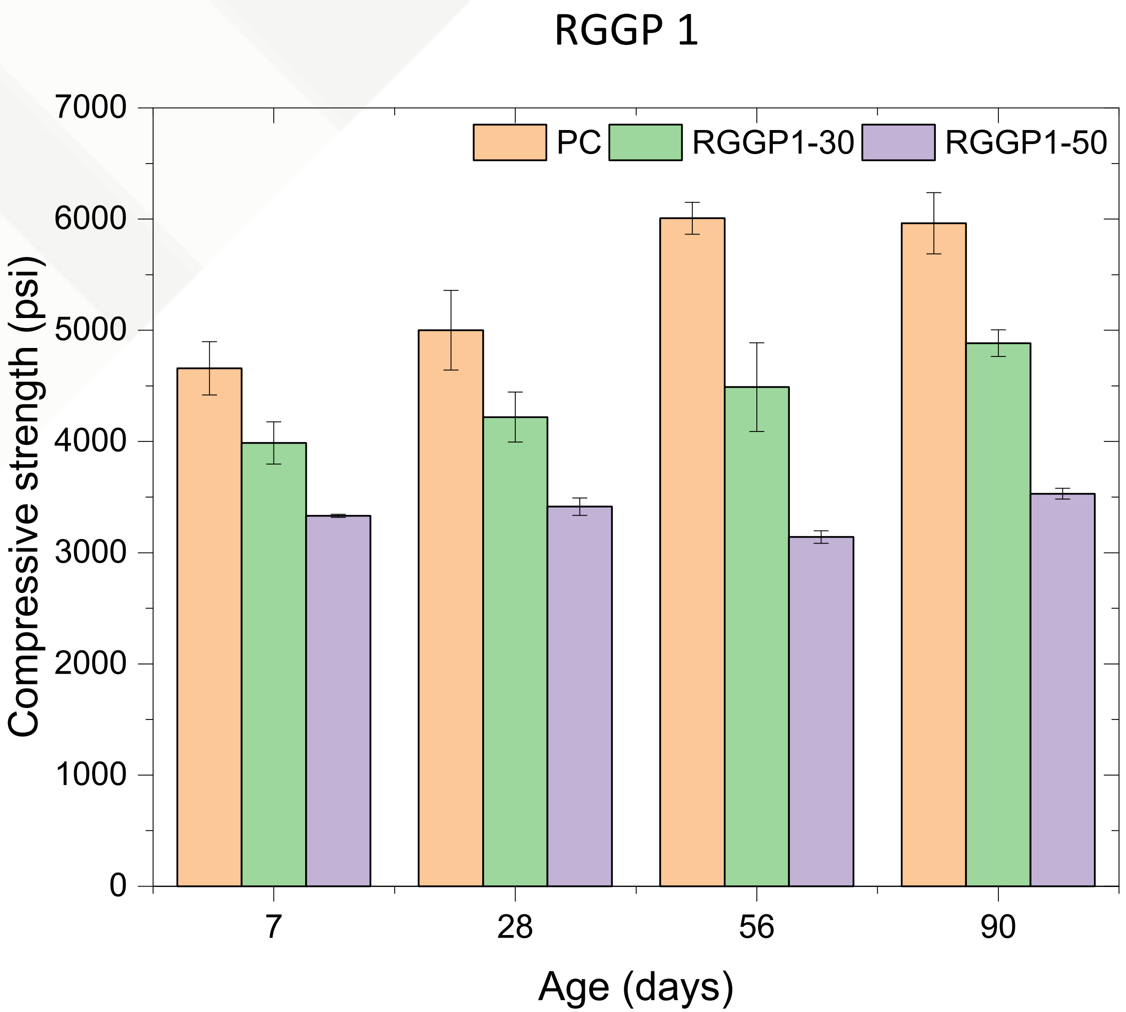
Development of compressive strength of mortar (regular lime water curing)

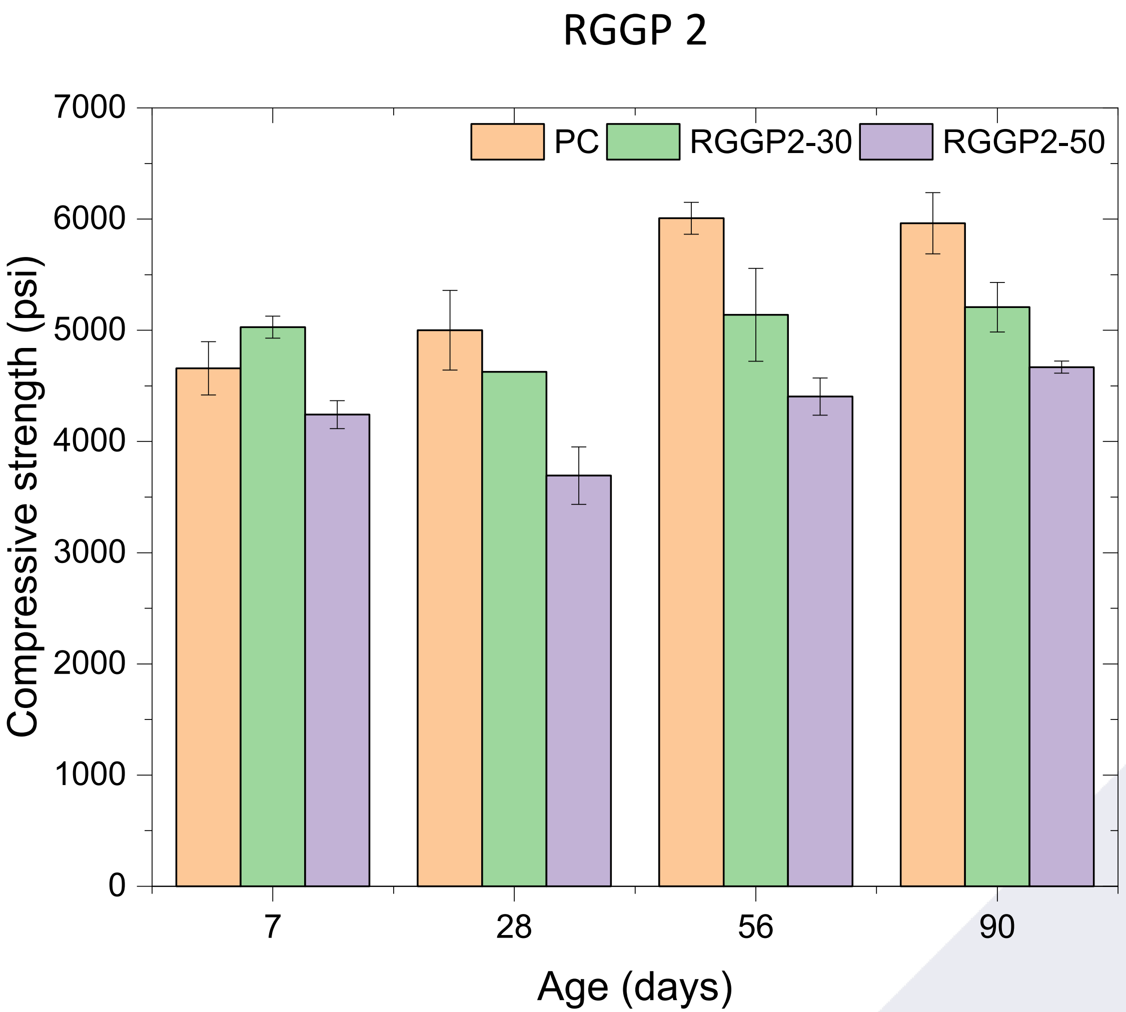




STRENGTH DEVELOPMENT OF RGGP MORTARS

Development of compressive strength of mortar (steam curing)





RGGP CONCRETE MIX PERFORMANCE

GENERAL CONCRETE MIX DESIGN (UMASS AMHERST)

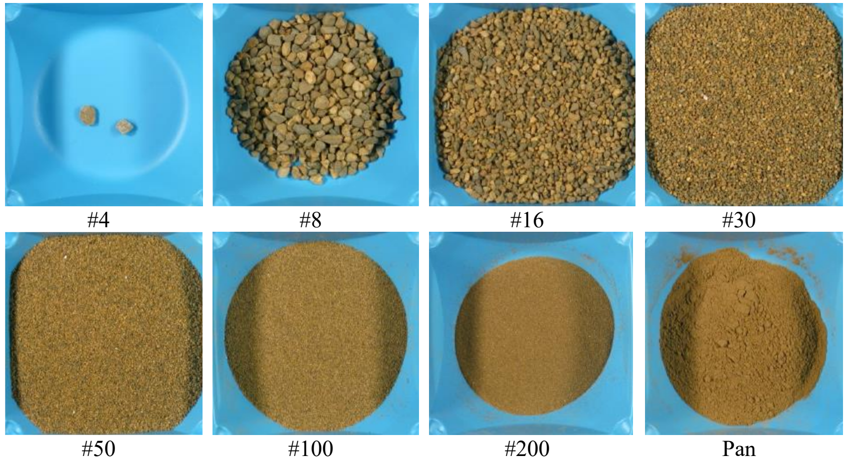
Constituent Material	Description	Source	Quantity	Unit
Fine Aggregate	Normal Weight/M6	Delta Sand and Gravel	1,230	(lbs./yd^3)
Coarse Aggregate	Normal Weight67/M80	J S Lane	1,830	(lbs./yd^3)
Total Cementitious Material	Type IL Cement	HOLCIM	660	(lbs./yd^3)
	POZZOTIVE Ground Glass (RGGP1)	Urban Mining Industries		
Water	Potable Water	Amherst, MA Municipal Supply	264	(lbs./yd^3)
Air Entraining Admixture	MasterAir AE 200	Master Builders Solution	2.00	(oz./yd^3)
Workability Retaining Admixture	MasterSure Z 60	Master Builders Solution	13.2	(oz./yd^3)
High Range Water Reducing Admixture	MasterGlenium 7500	Master Builders Solution	46.2	(oz./yd^3)
Water Reducing and Retarding Admixture	MasterSet R 100	Master Builders Solution	29.7	(oz./yd^3)
Corrosion Inhibiting Admixture	MasterLife CI 30	Master Builders Solution	384.0	(oz./yd^3)

w/cm=0.40

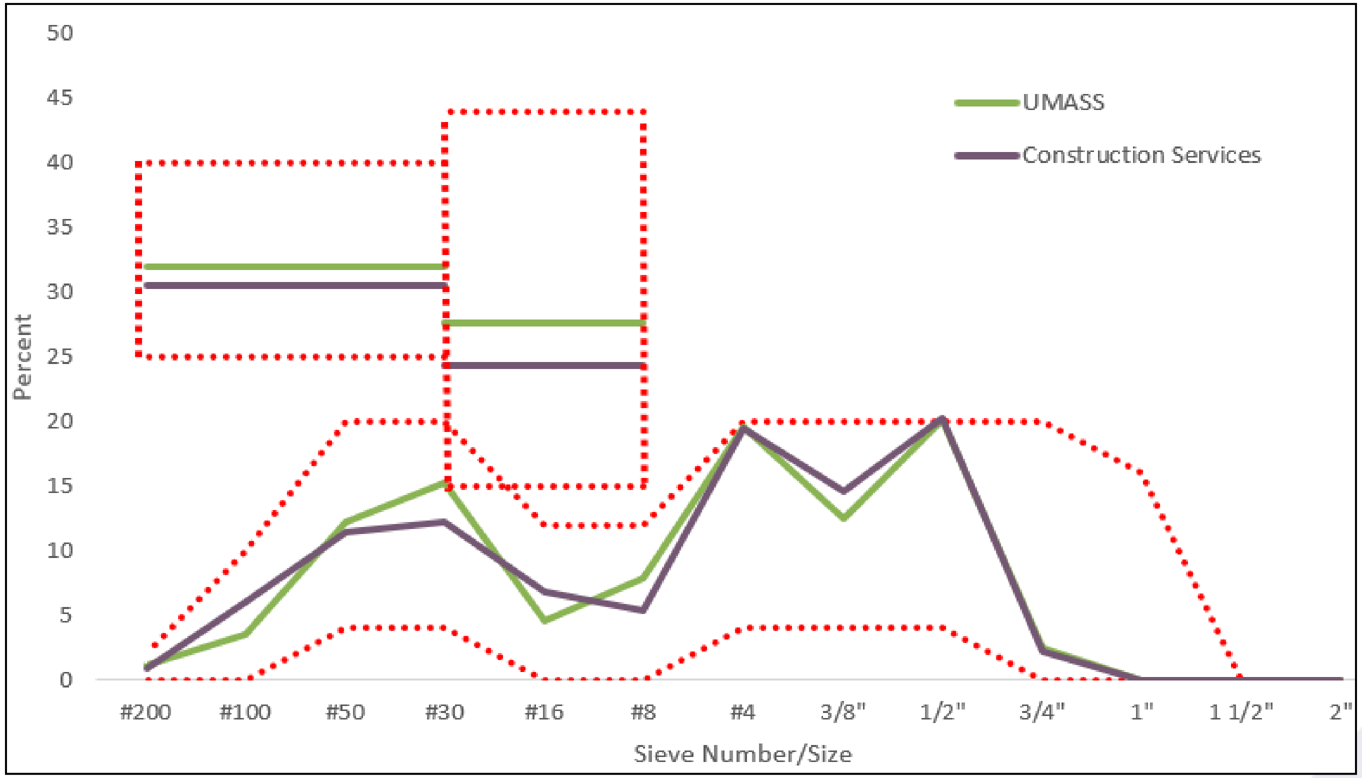
% RGGP varied from 0 to 30% in 5% increments

AGGREGATE SIZE DISTRIBUTION (UMASS AMHERST)

Coarse Aggregate – J S Lane

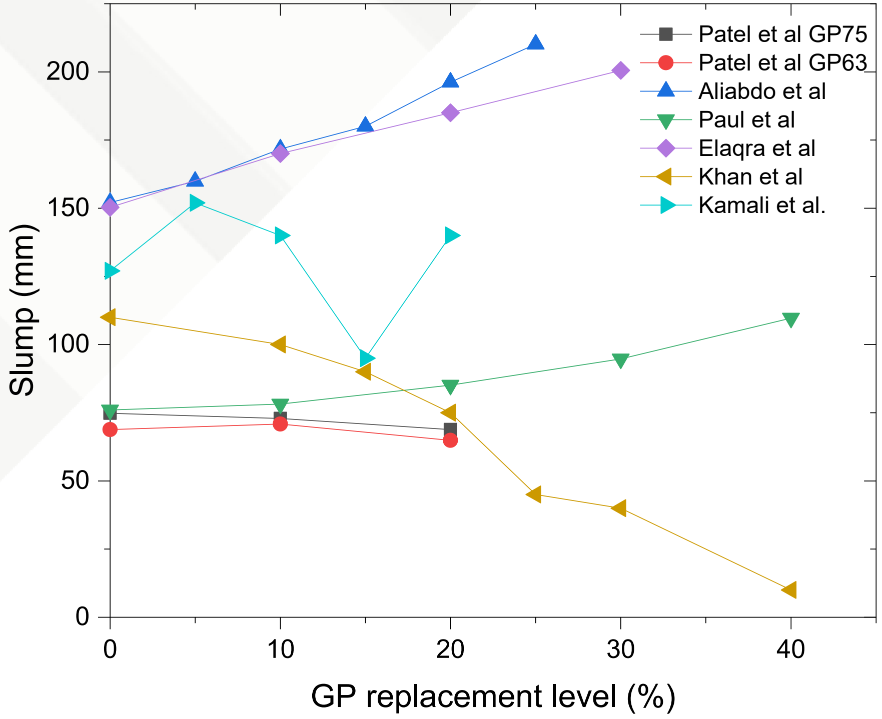


Fine Aggregate – Delta Sand and Gravel

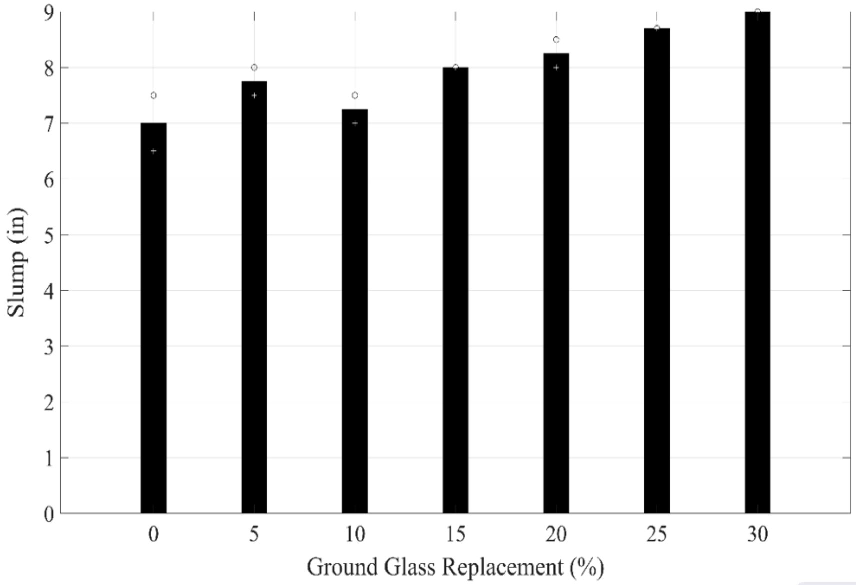


Tarantula Curve

SLUMP FOR DIFFERENT PERCENTAGES OF RGGP1

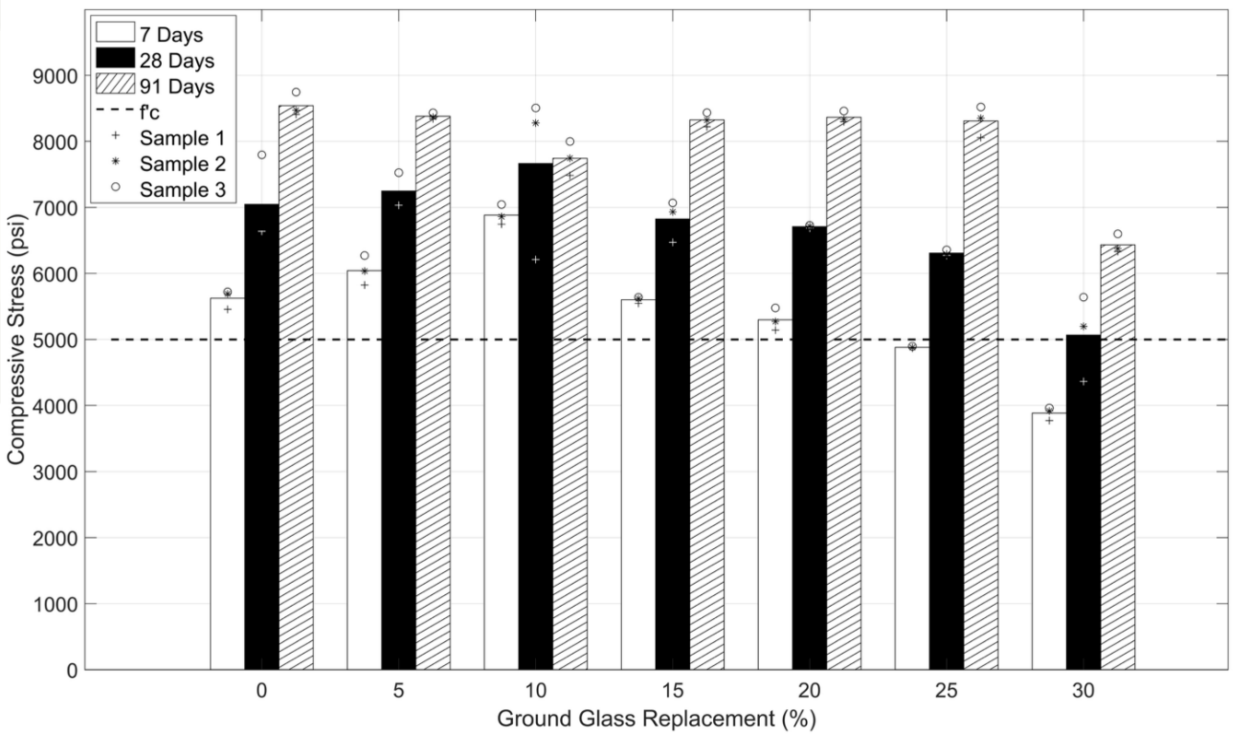


Slump variation attributed to RGGP particle size

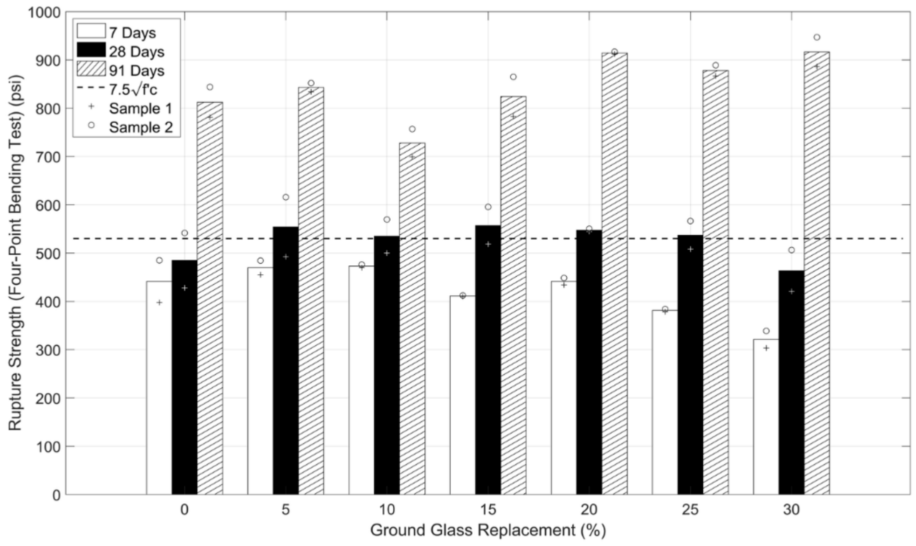


Variation of slump as a function of RGGP percentage

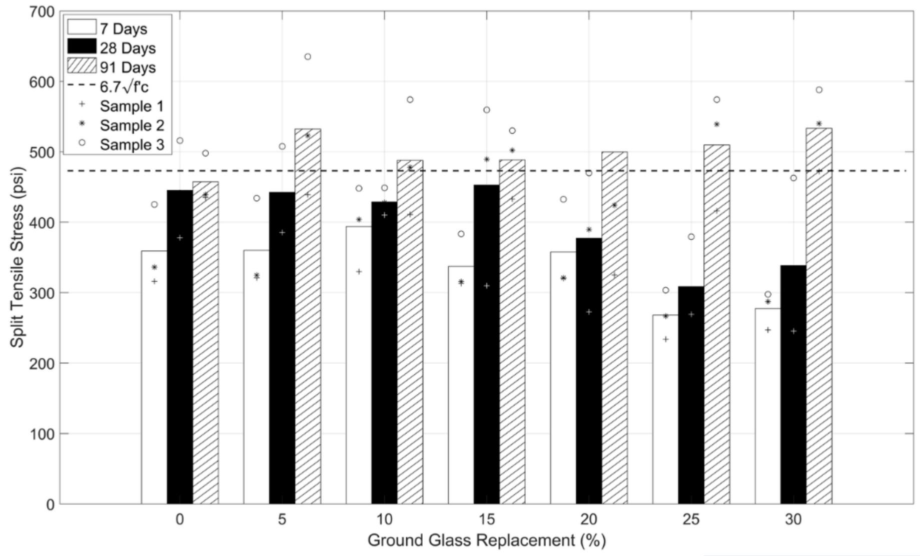
STRENGTH TESTING FOR DIFFERENT PERCENTAGES OF RGGP REPLACEMENT



Compression strength (4 x 8 in. cylinders)



Modulus of rupture (6 x 6 in. beams)



Splitting tensile strength (4 x 8 in. cylinders)

FIELD PLACEMENT OF 25% RGGP MIX

DURABILITY OF CONCRETE

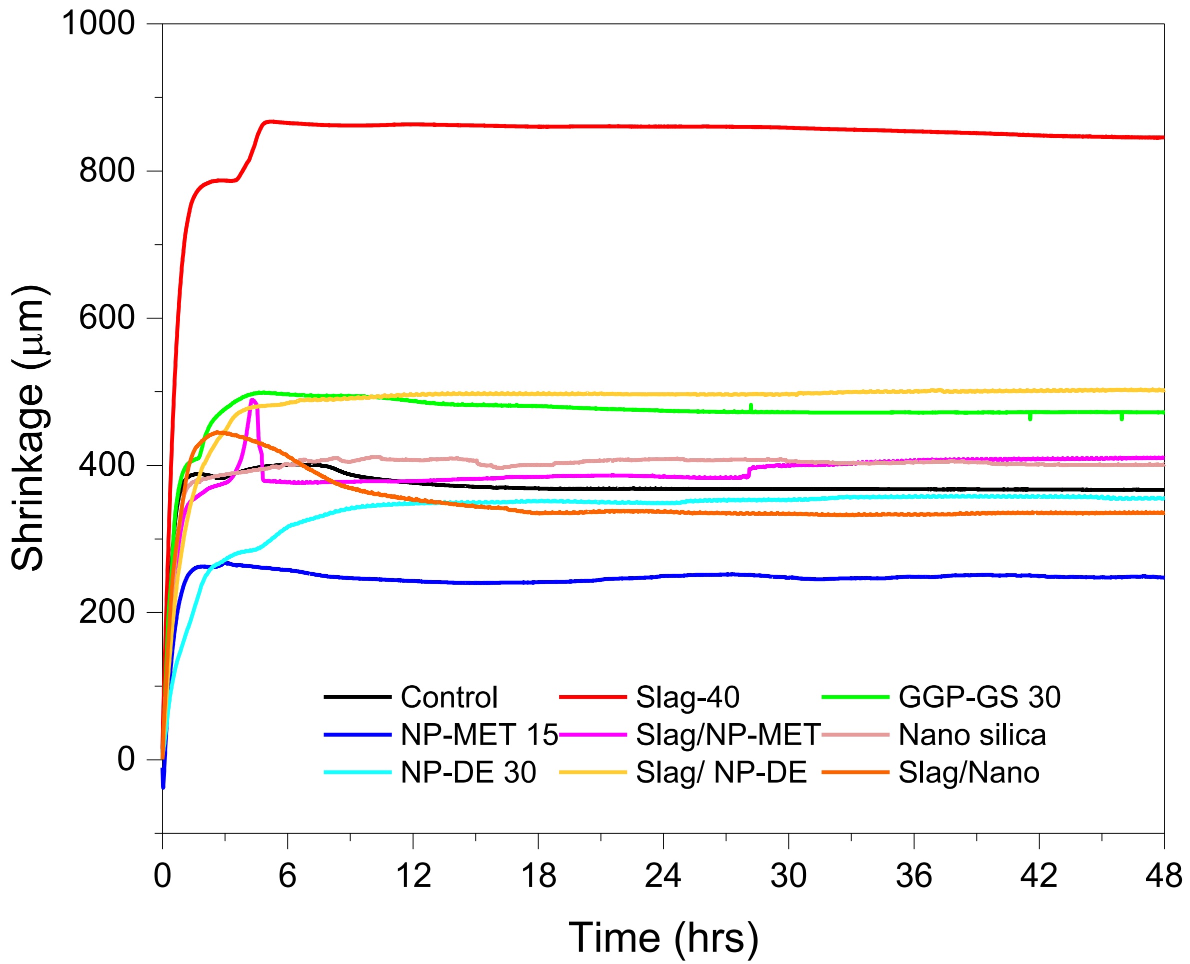
9 groups with different SCMs and combinations

Group index	Details of concrete binder
Control	Plain cement binder with no SCM
Slag-40	40% cement replaced with slag
GGP-GS30	30% cement replaced with RGGP
NP-MET15	15% cement replaced with metakaolin
Slag/NP-MET	40% cement replaced with slag
NP-DE30	30% cement replaced with diatomaceous earth
Nano silica	Plain cement binder with 49 oz/yd^3 liquid fly ash and 24 oz/yd^3 internal cure admixtures
Slag/NP-DE	25% cement replaced with slag (20%) and diatomaceous earth (5%)
Slag/Nano	40% cement replaced with slag plus 49.2 oz/yd^3 liquid fly ash and 24.6 oz/yd^3 internal cure admixtures

DURABILITY OF CONCRETE – VARIOUS SCMS

Early-age autogenesis shrinkage

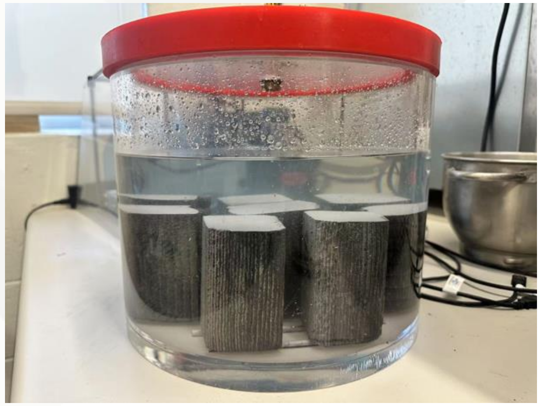
Laser-based shrinkage cone

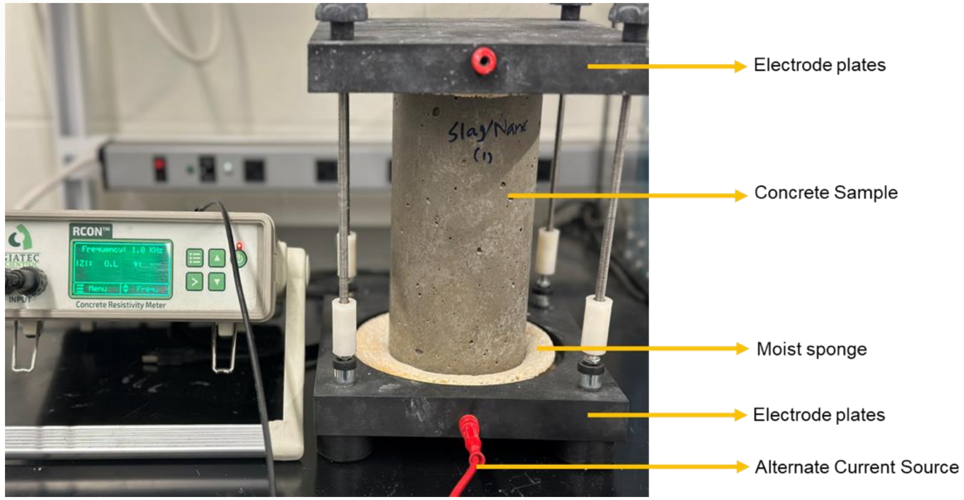


- Slag-40 showed the highest shrinkage (~865 µm), significantly exceeding all other mixtures.
- NP-MET 15 exhibited the lowest shrinkage (~260 µm), followed by NP-DE 30 at (~350 µm), indicating strong shrinkage control.
- Ternary blends like Slag/NP-DE & Slag/Nano showed lower shrinkage than Slag-40 alone, indicating better performance through the combination.

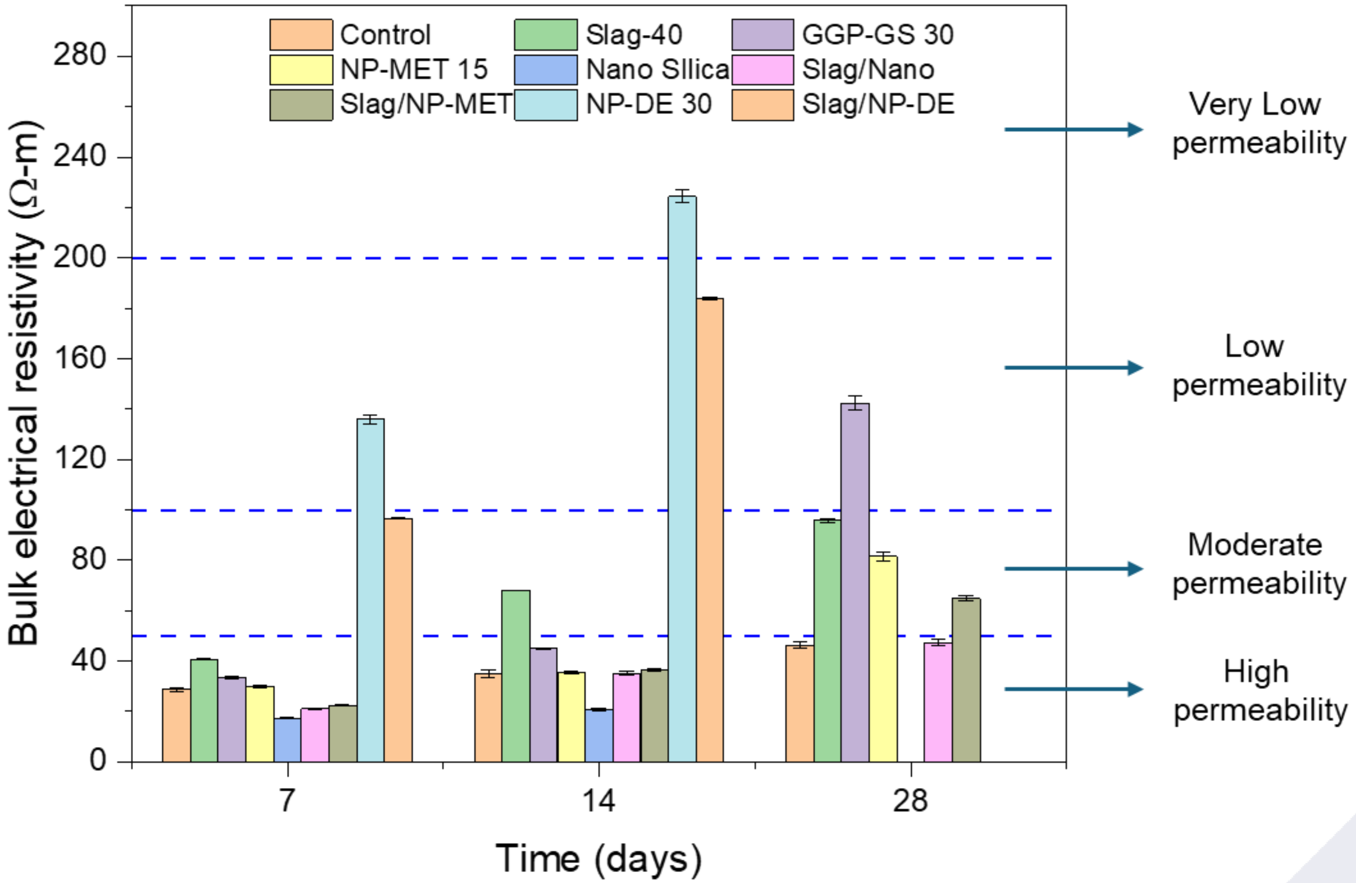
DURABILITY OF CONCRETE WITH VARIOUS SCMS

Permeability





Bulk resistivity test per AASHTO T402

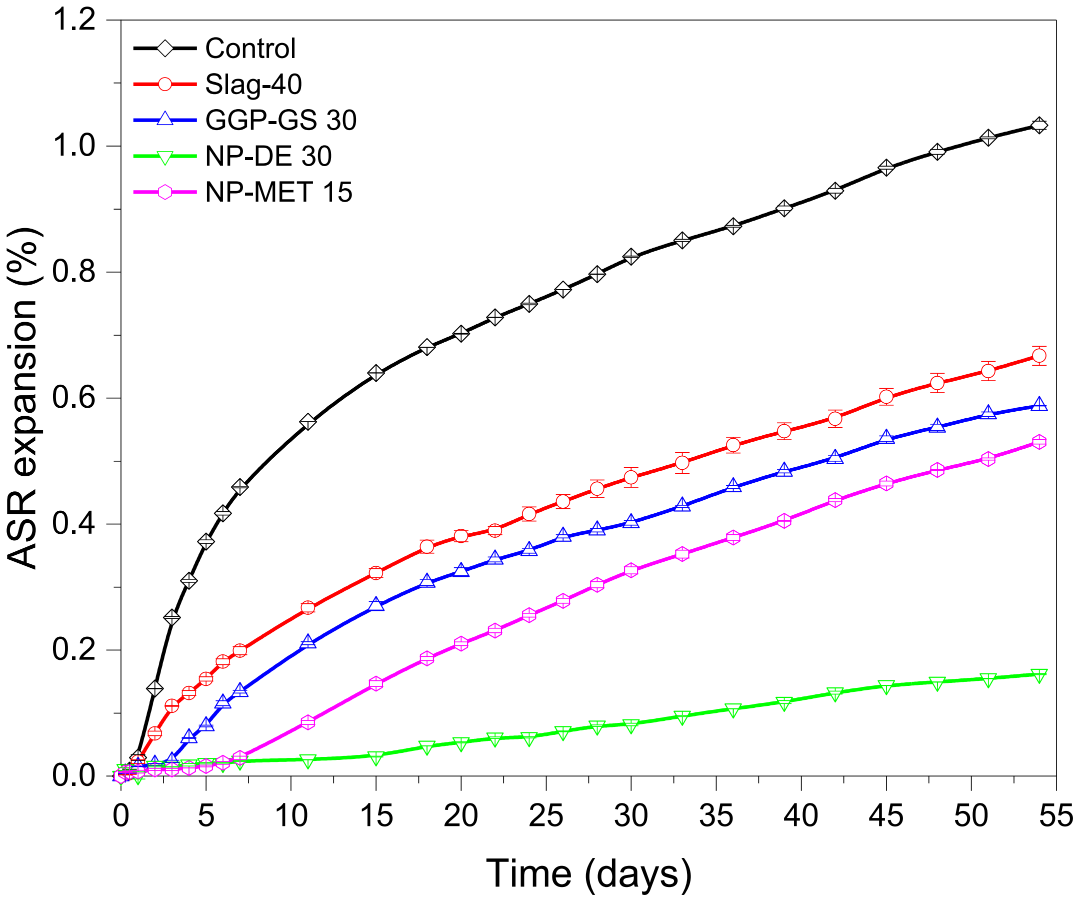


- NP-DE 30 showed a significant 372.6% and 543.2% increase in resistivity at 7 and 14 days compared to control group, indicating a significant decrease in permeability.
- Slag/NP-DE and GGP-GS 30 also exhibited high resistivity values, both exceeding 120 Ω-m at 14 days and falling within the "low permeability" range.

MORTAR BAR EXPANSION – REACTIVE SAND (TX)

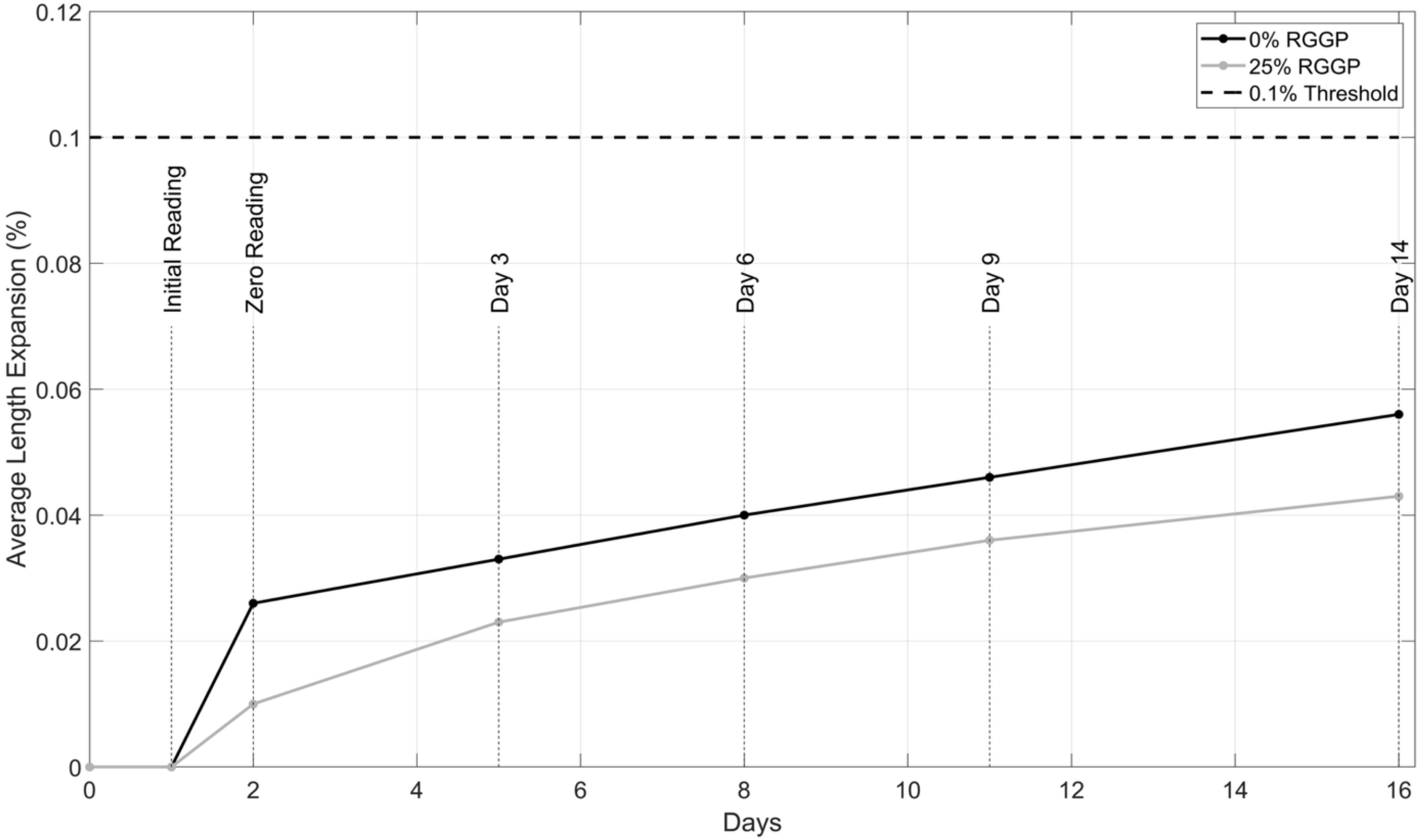
ASR test 1

Mortar bar method per ASTM C1260
(Alkali reactivity of aggregates)



- ASR expansion was measured as per ASTM C1260 using mortar bars (25.4 mm x 25.4 mm x 285.85 mm) submerged in 1N NaOH at 80°C.
- The control group expanded severely due to ASR and exhibited an expansion of >1% at 75 days.
- Slag-40 and GGP-GS 30 showed a 30.70% and 40.35% reduction in ASR expansion compared to the control group at 75 days, indicating a partial ASR mitigation.
- Replacing 30% cement with DE exhibited the lowest expansion of (0.22%) at 75 days, which is ~81% lower than that of the control group.

MORTAR BAR EXPANSION – WESTERN MASS AGGREGATE

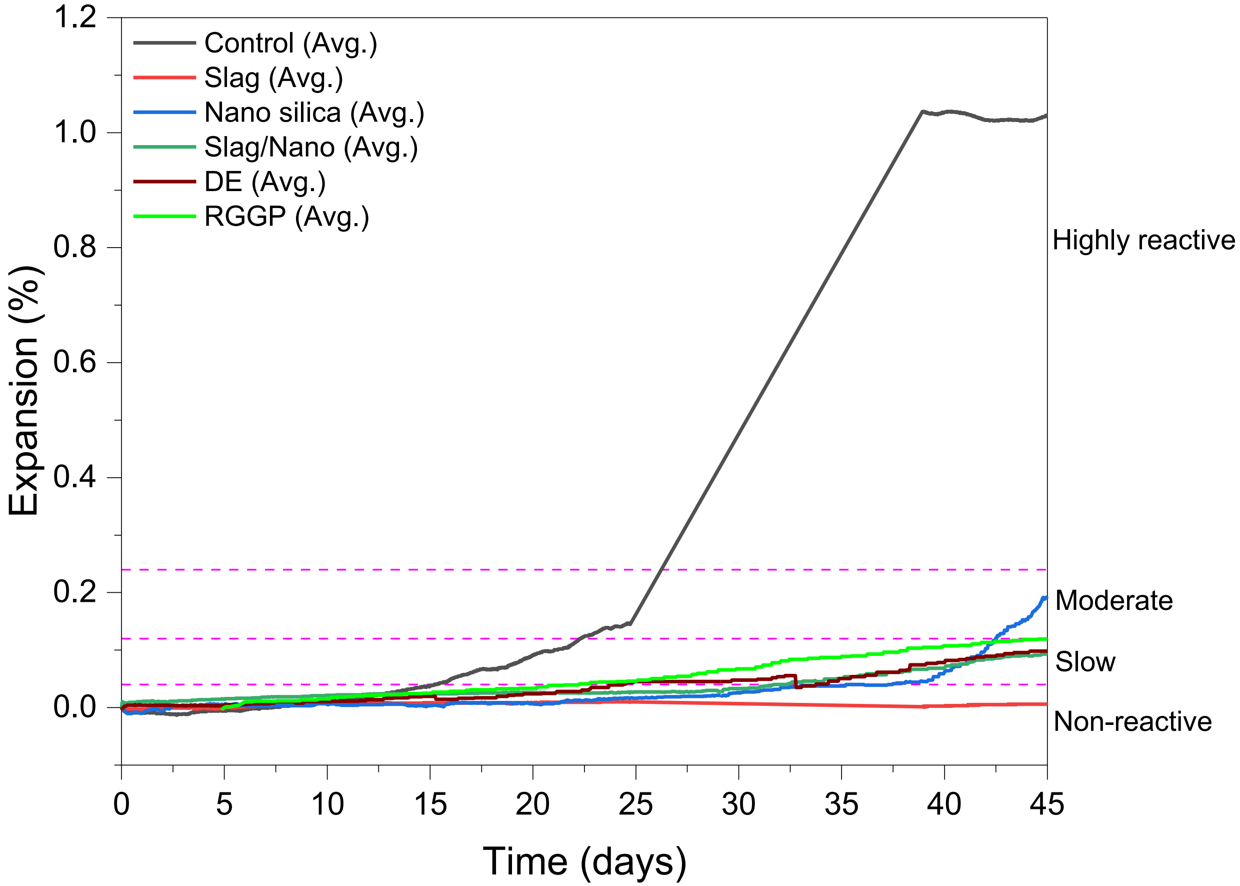


Accelerated mortar bar method per ASTM C1567
(ASR of combinations cementitious materials and aggregate)

DURABILITY OF CONCRETE WITH VARIOUS SCMS

ASR test 2

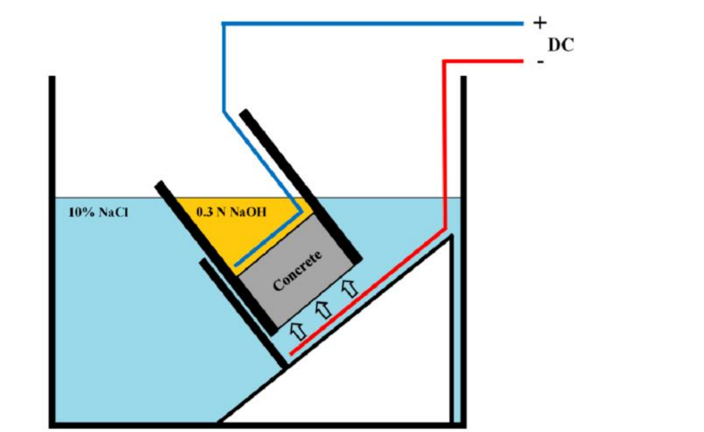
Accelerated Concrete Cylinder Test per AASHTO TP 142

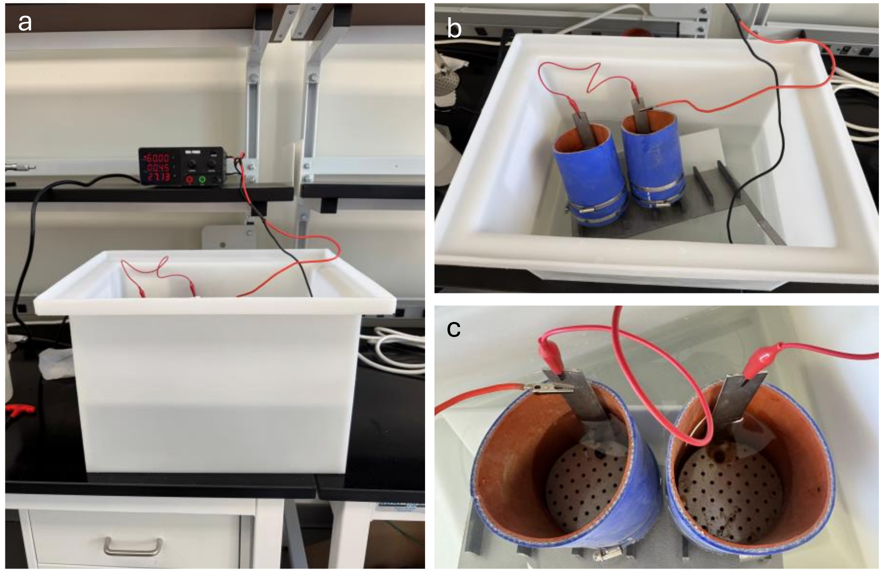


- The control mix showed a steady expansion over time, reaching a maximum of 1.10%.
- Slag-40 mix exhibited minimal expansion throughout the test, remaining well below the 0.04-inch threshold.
- The divergence in expansion trends between the two mixes began to emerge clearly after ~10 days and widened significantly after 20 days.

DURABILITY OF CONCRETE

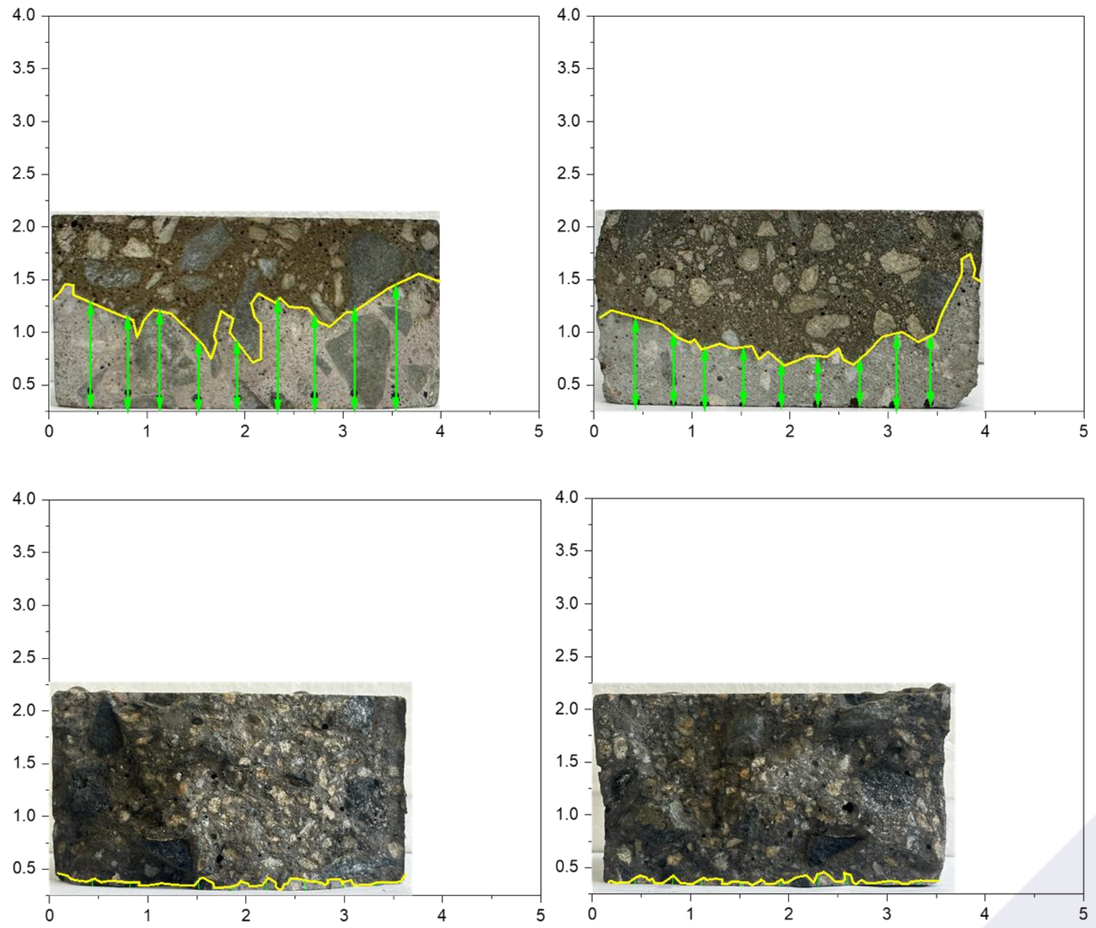
Rapid chloride migration test





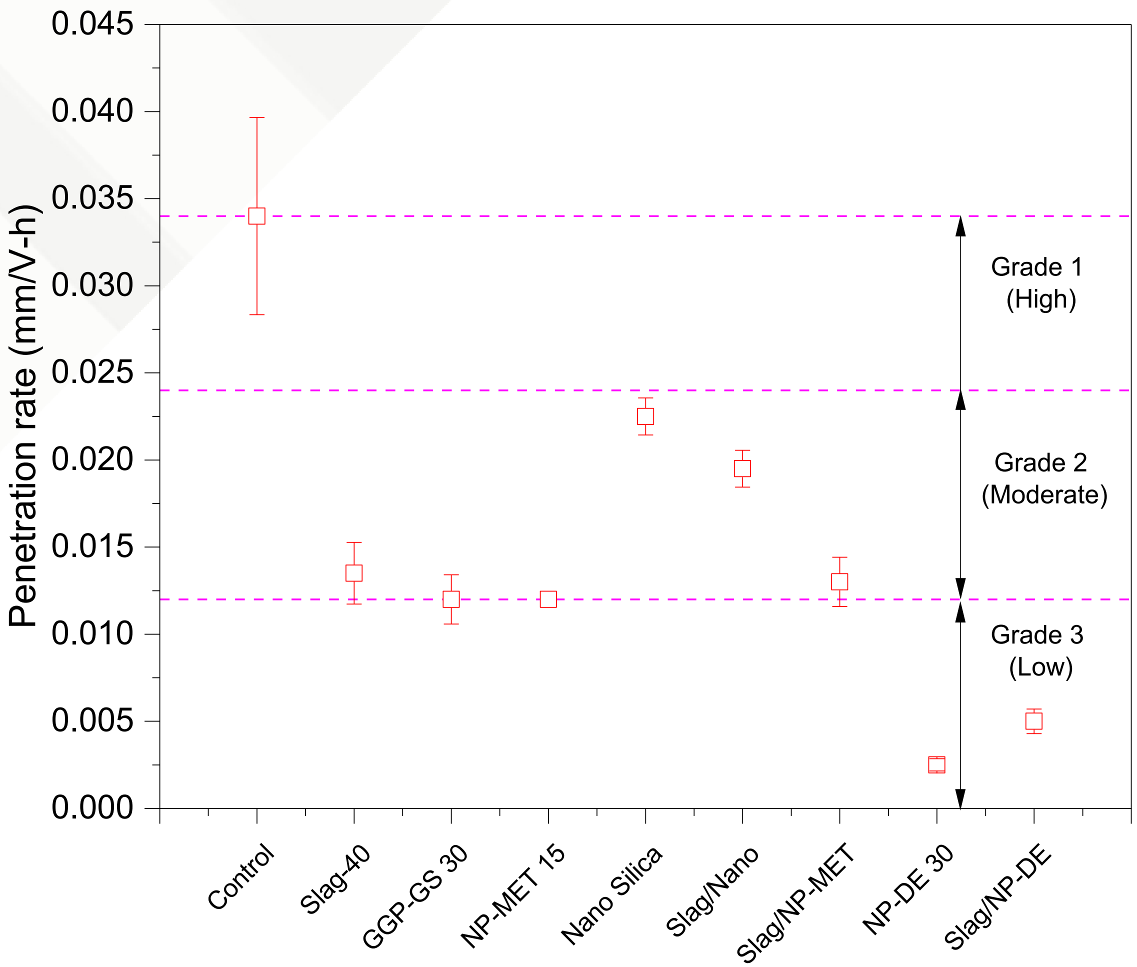
Rapid Chloride Migration Test per AASHTO T357

Selected measurements of chloride penetration depth



DURABILITY OF CONCRETE

Rapid chloride migration test



- Compared with the control group, all the SCM-modified mixtures displayed lower chloride penetration rates.
- GGP-GS 30 and NP-MET 15 showed 65% better chloride resistance and fell under the low chloride penetration region, which shows good agreement with the ASR expansion and bulk resistivity data.
- An interesting finding lies in the penetration rate of nano-silica group. The bulk resistivity results after 7 to 56 days showed a high chloride penetration rate, while the nano-silica group showed only a 33% improvement over the control group, which makes it in the moderate penetration rate range.
- The mismatch between the bulk resistivity and rapid chloride migration results might be due to the conductive nature of the nano-silica admixture.
- The combined use of slag and liquid fly ash improve the chloride resistivity further by 13% compared to the nano silica group.
- The DE-30 and Slag/DE groups exhibited similar trends, like their bulk resistivity, and demonstrated a 92% and 85% reduction in chloride ingress compared to the control group, respectively.

CONCLUSIONS

- The incorporation of RGGP resulted in increases in hydration heat of cement, indicating enhanced cement hydration due to pozzolanic reactions.

- The phase evolution shows increased consumption of calcium hydroxide (CH) with RGGP dosage. RGGP2 showed a greater CH consumption capacity than RGGP1 along, with the formation of C-S-H and amorphous contents.

- Promising potential of RGGP in increasing concrete strength was observed. The 90-day strength of RGGP2-10% and RGGP2-30% surpassed the that of control group by 13.3% and 13.2%, respectively.

- The permeability results, assessed via bulk electrical resistivity, show that all SCMs can improve concrete durability to varying degrees. The addition of 15% metakaolin and 30% RGGP decreased the concrete permeability by ~193% and 442%, respectively. The lowest permeability was abstained from the concrete containing 30% DE.

CONCLUSIONS

- In line with the permeability data, the mixture with 30% cement replacement with DE achieved the greatest resistance against chloride penetration, with a 92% reduction in chloride depth. Replacing cement with 20% RGGP or 15% metakaolin also performed well, each reducing chloride penetration by 65%, placing them in the low permeability category.

- Interestingly, a mismatch between the permeability and chloride migration testing results was observed from the group with nano-silica admixtures. While it yielded a high permeability performance, a moderate chloride penetration rate was found. This might be due to the conductive nature of the nano-silica admixture.

- The results from both the mortar bar test and the ACCT test demonstrate the effectiveness of various SCMs in mitigating ASR expansion. Among the SCMs, the group replacing 30% cement with diatomaceous earth performed best, reducing expansion by ~81%, followed by 15% metakaolin, which outperformed 40% slag and 30% RGGP.

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Thank You!
Questions?