Physico-Chemical Characterization of Ground Bottom Ashes and Fluidized Bed Combustion Ashes and Evaluation of their Performance in Concrete Mixtures

ACI Spring 2023 Convention, San Francisco, CA

R. Tokpatayeva, A. Castillo, B. Zhaksybay and J. Olek

Purdue University

K. Jafari, J. Yoon, G. Kaladharan, M. Sharbaf and F. Rajabipour

Penn State University

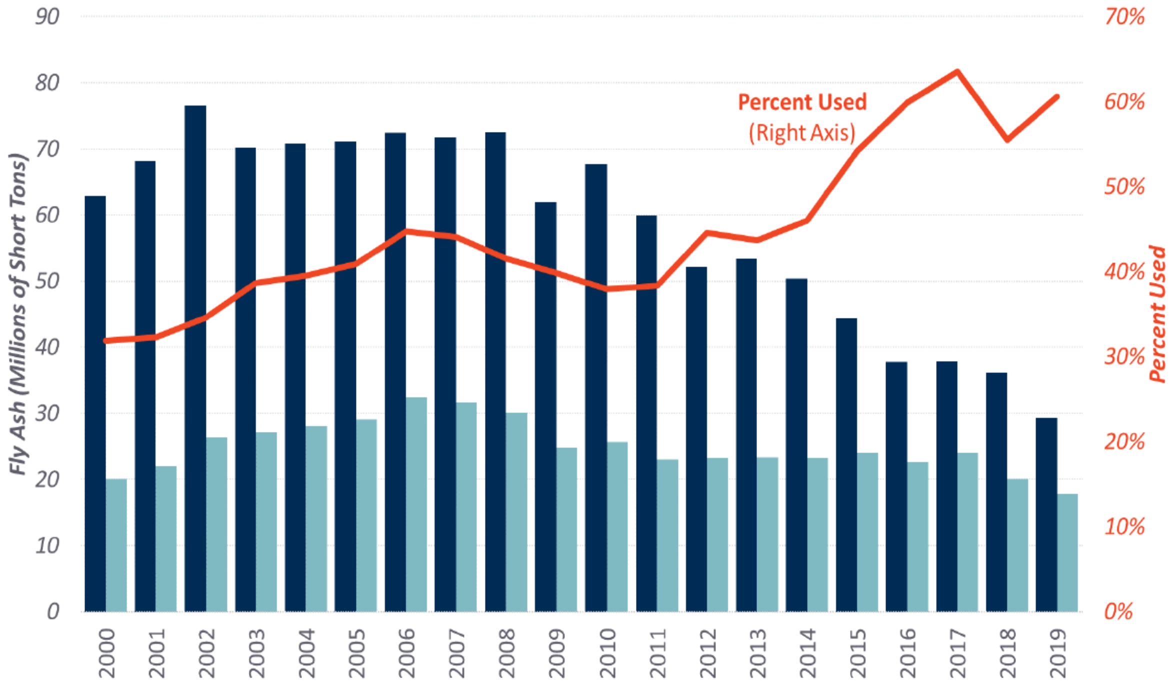
THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

Motivation

Shortage of traditional SCMs

- Any alternatives?
- How to make durable low-CO_2 concrete?

Source: ACAA



Potential non-traditional, off-spec and natural SCMs

- How good are they?

- suitable test methods
- specific peculiarities →modifications of the tests
- mix design

Outline of the presentation

- Characterization of the raw GBAs and FBCs
- Estimation of the pozzolanic reactivity of the GBAs and FBCs
- Evaluation of the performance of the GBAs and FBCs in cementitious systems

Ground Bottom Ashes (GBAs)

GBA1

CaO = 2.8%

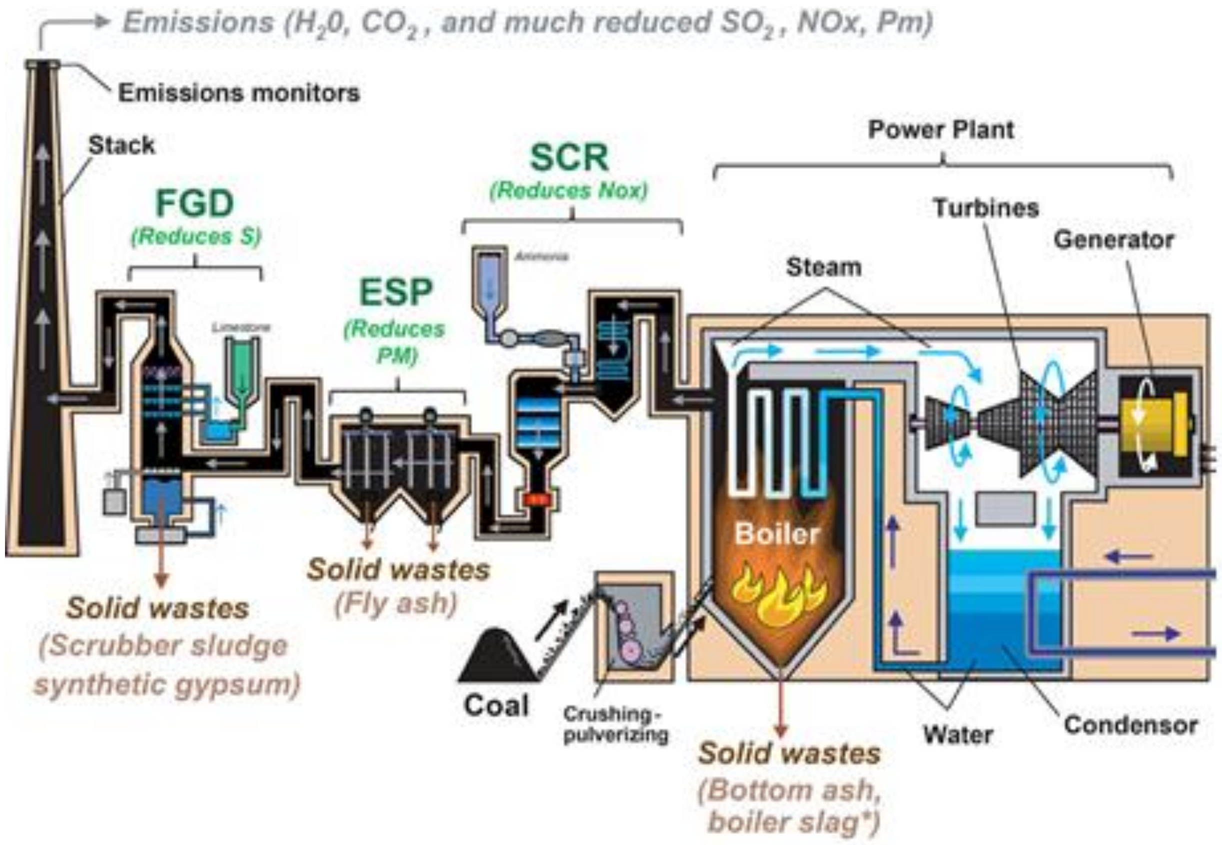
GBA2

CaO = 11.5%

GBA3

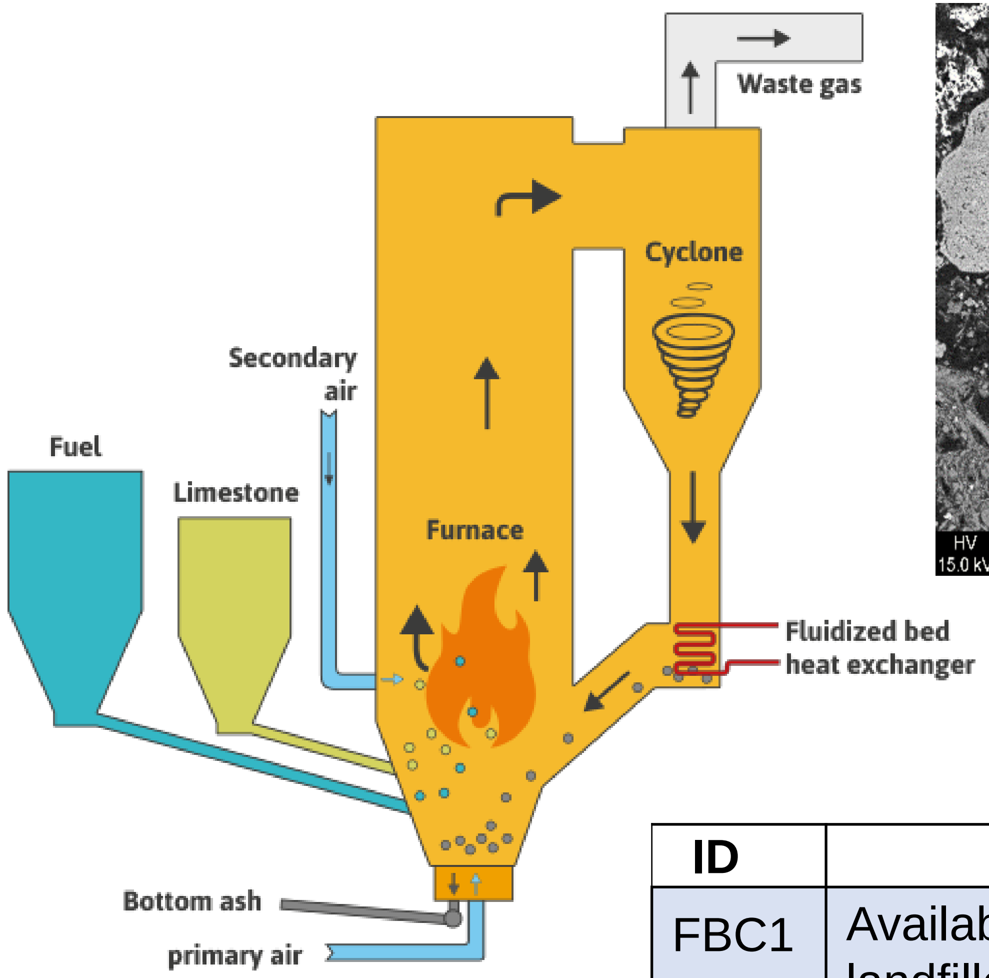
CaO = 23.0%

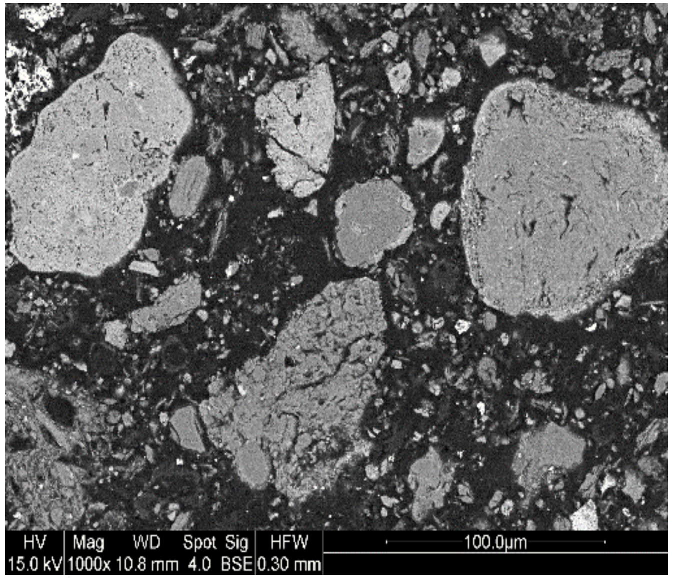
ID	Rationale for Selection
GBA1	Available nationwide. Currently landfilled, potential source of low-cost, nontraditional pozzolan
GBA2	
GBA3	



- Similar bulk chemistry as conventional fly ash but coarser particle size (0.1 to 10mm)
- Traditionally used as sand but can be ground for use as SCM

Fluidized Bed Combustion Ashes (FBCs)





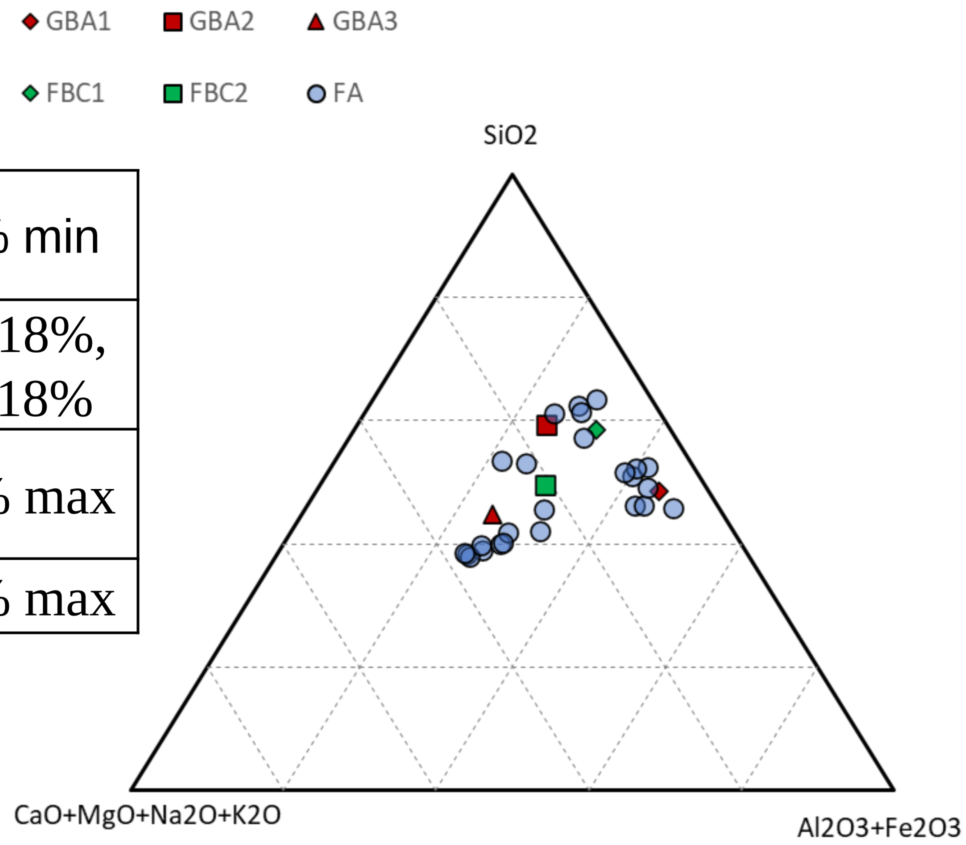
- Burns waste coal at up to 870°C (1600°F)
- Internal SO_3 scrubber via limestone powder injection → higher SO_3 in ash
- Angular, porous particles

FBC1 FBC2

ID	Rationale for Selection
FBC1	Available mainly in Eastern US. Currently landfilled, potential source of low-cost, nontraditional pozzolan
FBC2	Available mainly in Eastern US. Currently landfilled, potential source of low-cost, nontraditional pozzolan

Characteristics of GBAs and FBCs

Chemical properties	GBA series			FBC series		
	GBA1	GBA2	GBA3	FBC1	FBC2	
$SiO_2+Al_2O_3+Fe_2O_3$	91.8%	80.7%	67.0%	81.4%	68.6%	*70% min
CaO	2.8%	11.5%	23.0%	4.3%	14.4%	*F: <18%, C: >18%
SO_3	0.1%	1.2%	0.4%	1.2%	8.0%	*4.0% max
LOI	0.0%	1.1%	1.4%	6.0%	3.4%	*5.0% max
Carbon	0.7%	0.7%	0.8%	5.8%	2.9%	
Na_2O_{eq}	2.01%	0.97%	1.29%	2.57%	1.74%	
Amorphous	58.9%	63.4%	48.4%	18.8%	50.7%	
Inert	41.0%	36.2%	51.7%	48.0%	29.6%	

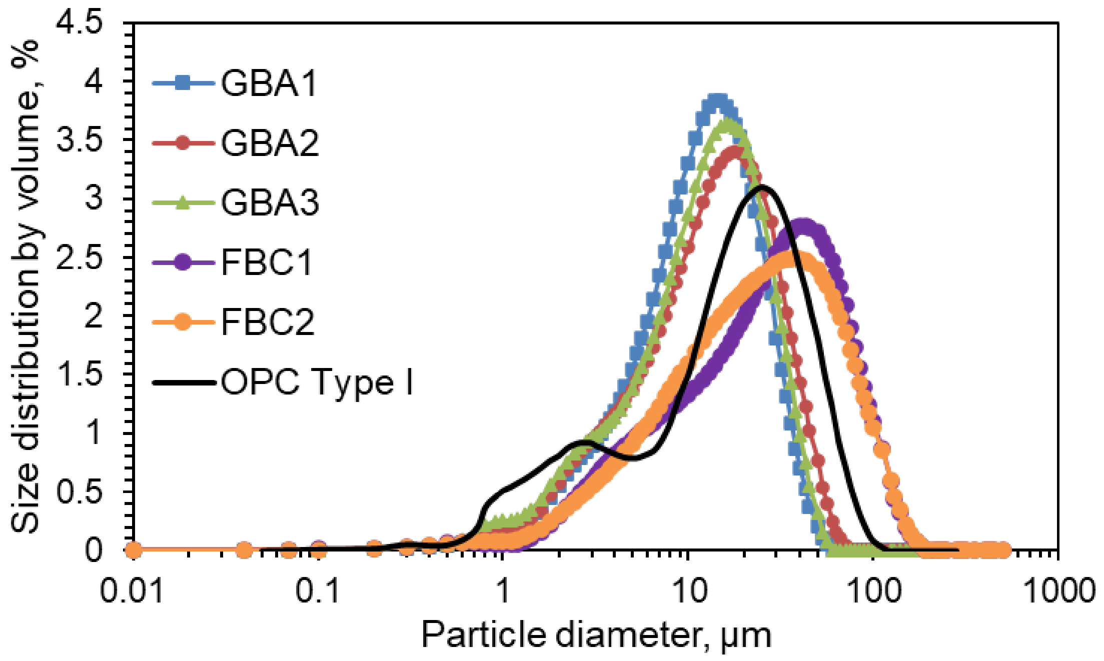


* - ASTM C618 limits

Characteristics of GBAs and FBCs

Physical properties		GBA series			FBC series		
		GBA1	GBA2	GBA3	FBC1	FBC2	
PSD [μm]	d_{10}	4.4	4.0	3.8	5.8	5.5	
	d_{50}	11.4	12.8	11.8	37.9	37.3	
	d_{90}	25.4	41.1	34.3	106.0	115.0	
Density [g/cc]		2.893	2.689	3.001	2.681	2.671	
Fineness (wt.>45 μm)		0%	0%	0%	32%	33%	*34% max
SAI	7 d	88%	86%	89%	88%	86%	*75% min
	28 d	87%	82%	96%	86%	91%	
	56 d	84%	105%	92%	82%	84%	
Water requirement		101%	101%	101%	107%	109%	*105% max
Soundness		-0.02%	-0.02%	0%	-0.03%	-0.03%	*0.8% max

* - ASTM C618 limits



Pozzolanic reactivity: R3 test (ASTM C1897)

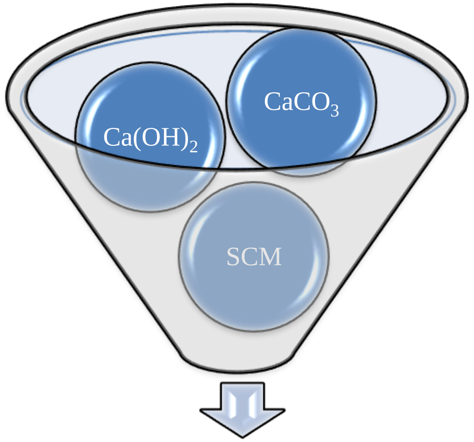
Bound water

Isoth. Calorimetry at 40°C

TGA (CH consumed)

Acid dissolution
(% GBA reacted)

Mix design for R3 paste, gr			
SCM	$Ca(OH)_2$	$CaCO_3$	*Alkaline solution
10	30	5	54

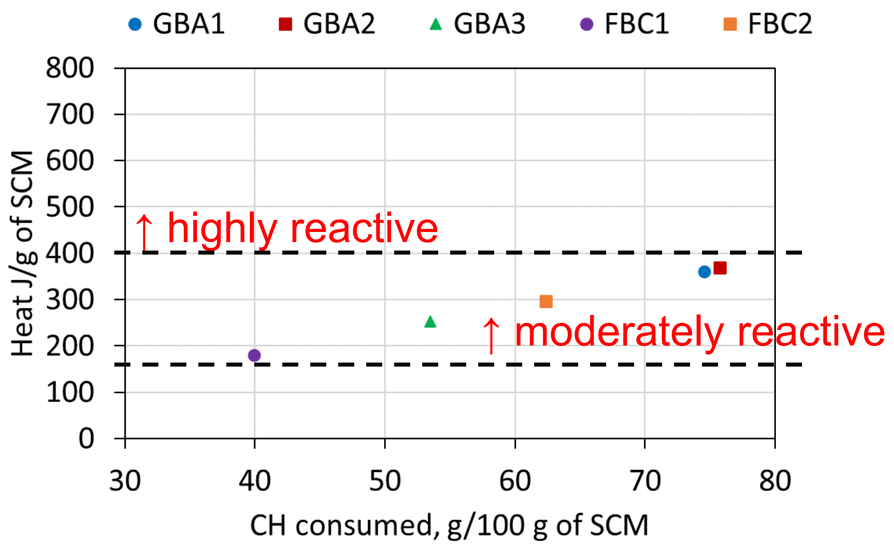


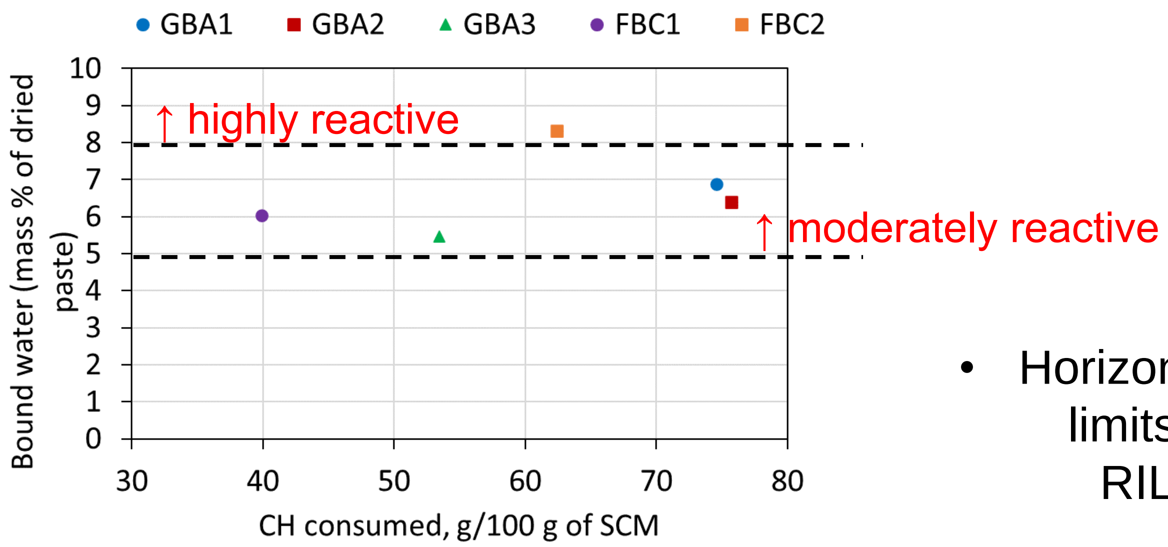
Mixed for 4 mins and sealed cured at 40°C

- R3 paste was ground and mixed with 1M HCl solution (1 g paste : 50 mL acid solution).
- After stirring for 20 mins, the slurry was vacuum filtered.
- The solid part was washed with de-ionized water and dried for 24 hr at 40°C.
- Dried solid was weighed.

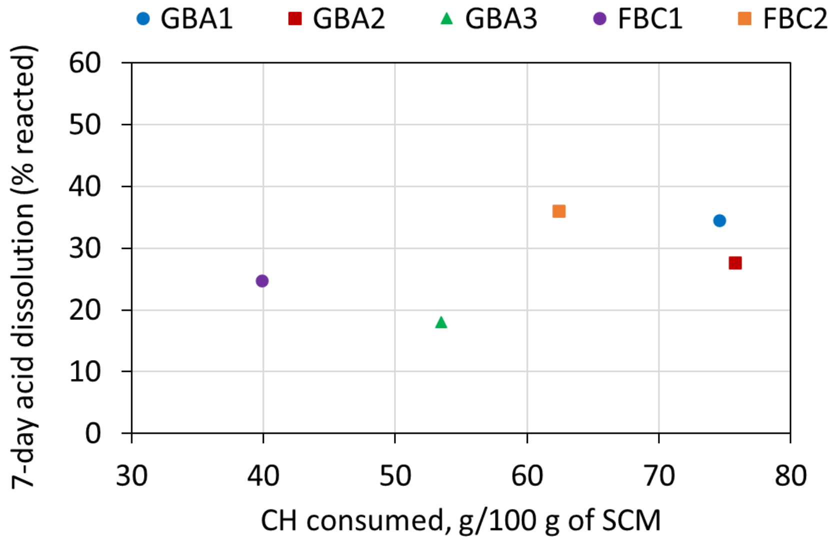
*Alkaline solution:
4 g KOH and 20 g K_2SO_4 dissolved in 1L of de-ionized water.

Pozzolanic reactivity: R3 test (ASTM C1897)



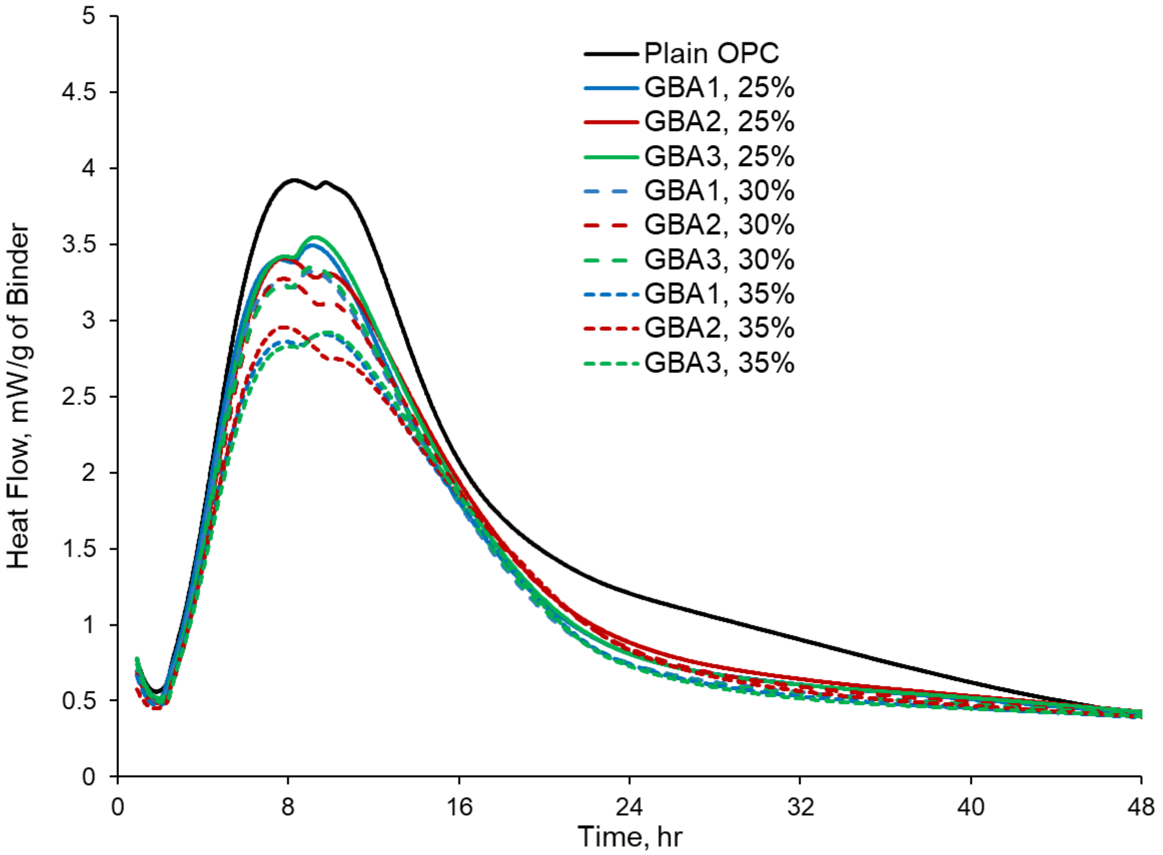


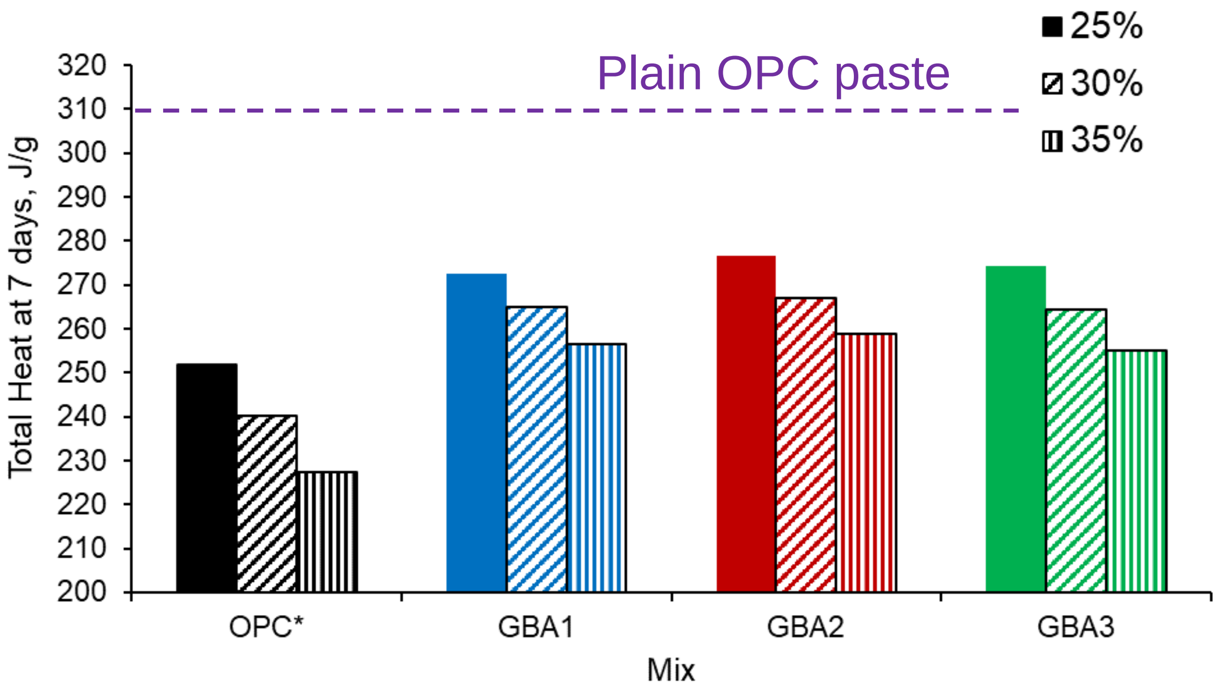
- Horizontal lines indicate limits suggested by RILEM 267TRM



GBA1, GBA2 and FBC2 showed higher % of dissolved material.

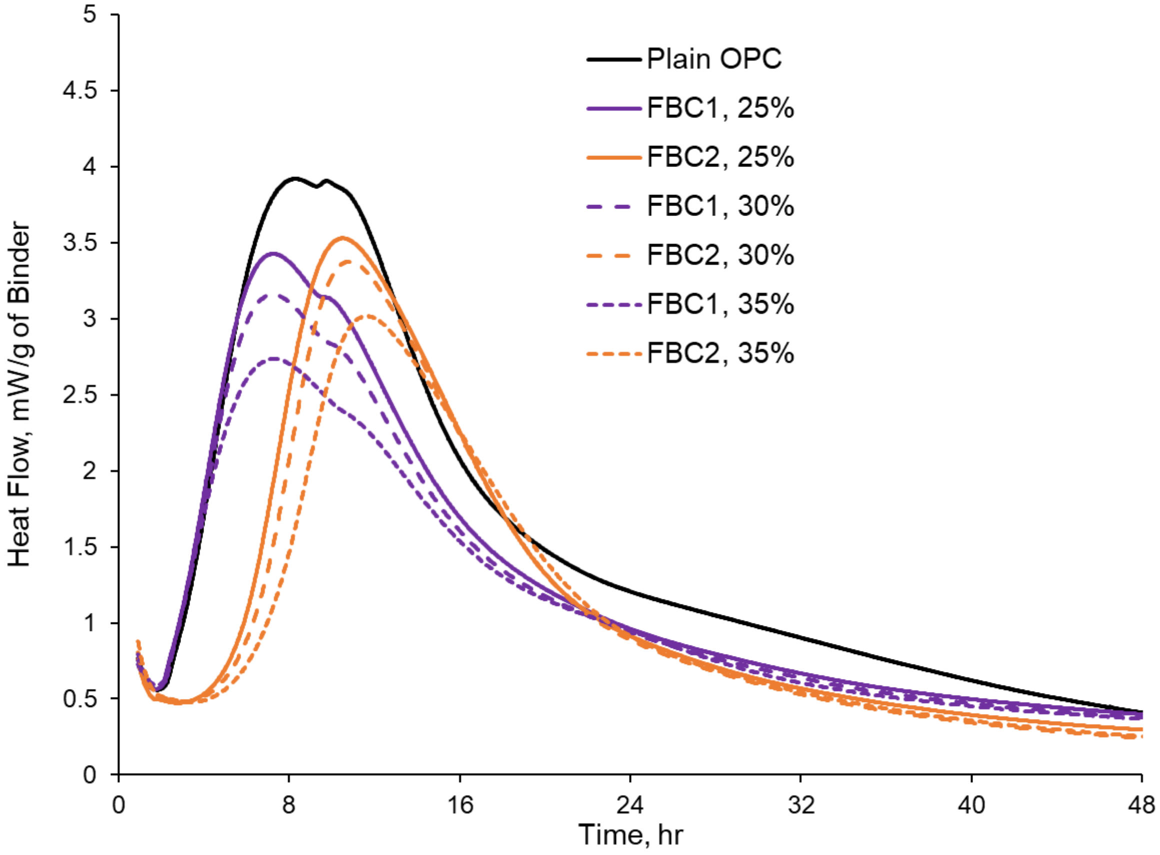
Heat of Hydration (Isothermal Calorimeter test)

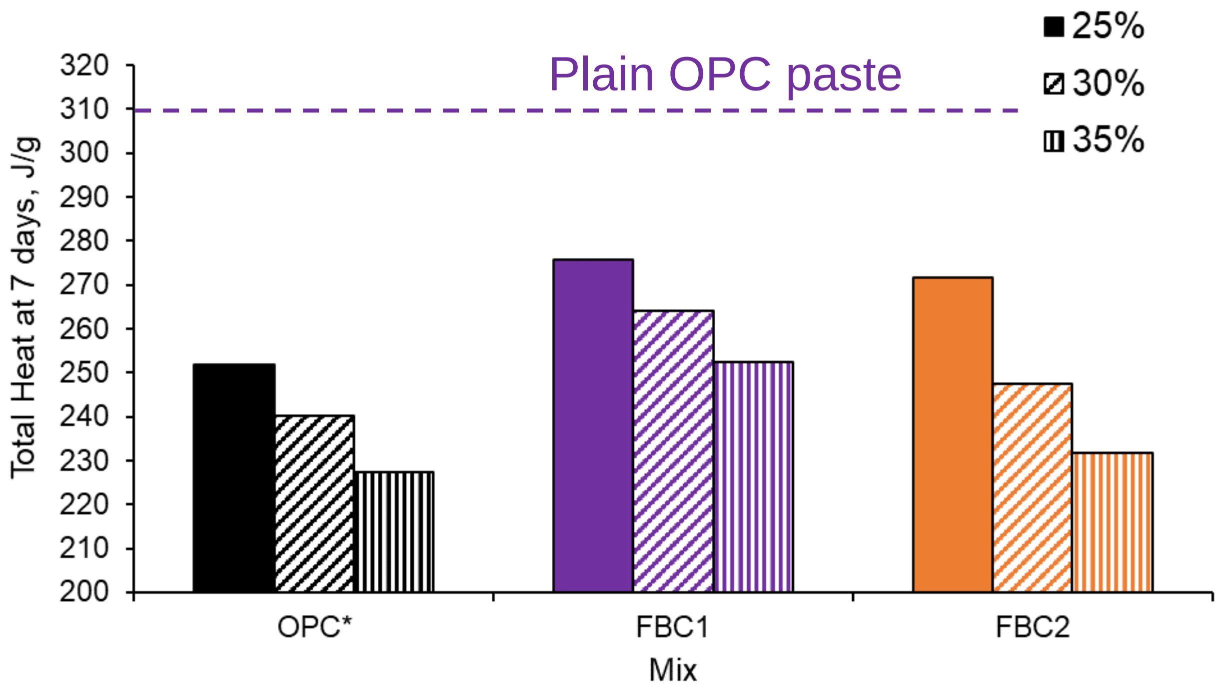




- The paste samples were prepared with w/cm = 0.42 and 25, 30 and 35% replacement levels.
- OPC* paste samples were prepared with inert filler (ground Ottawa sand).

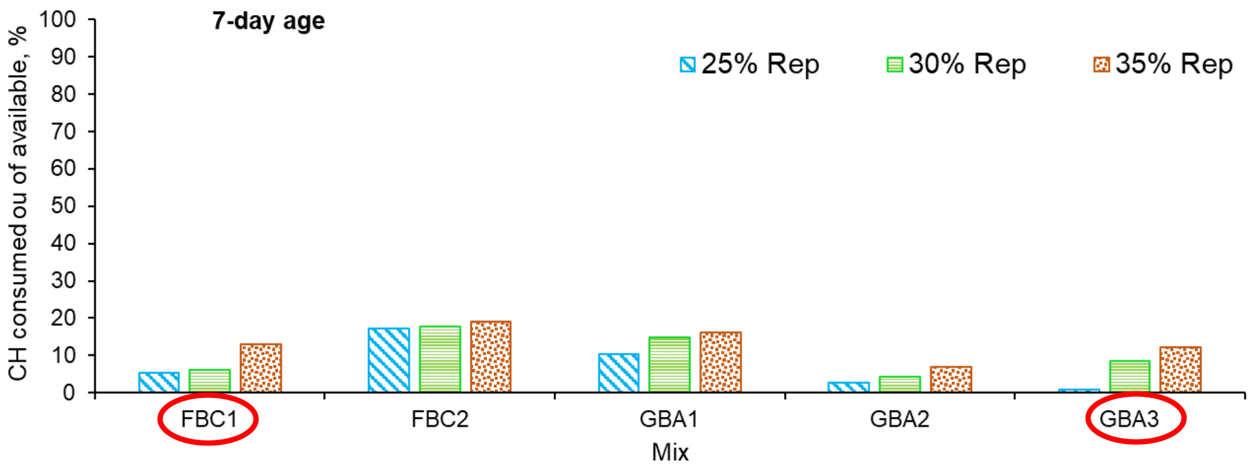
Heat of Hydration (Isothermal Calorimeter test)

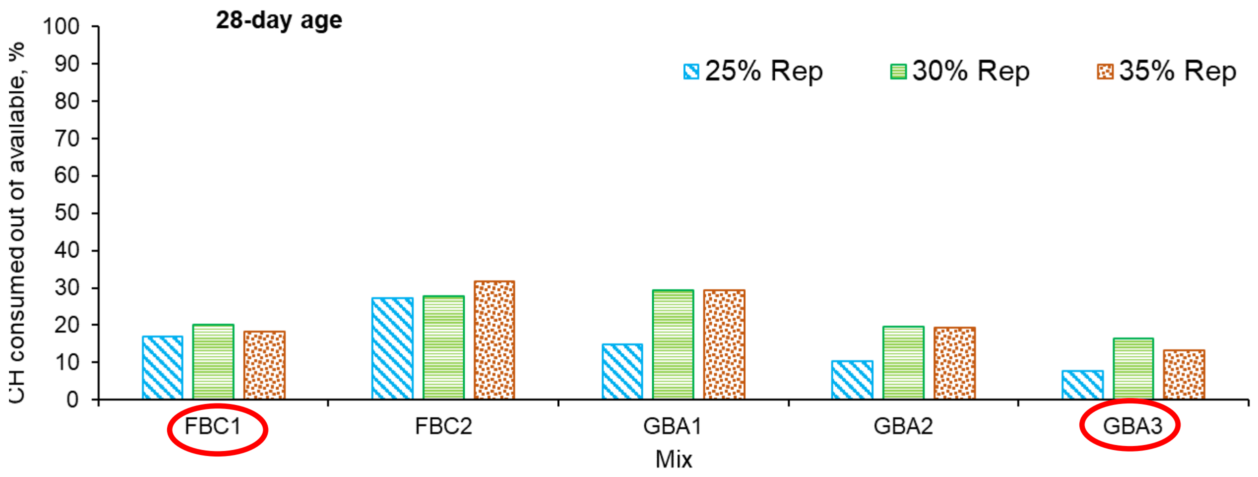


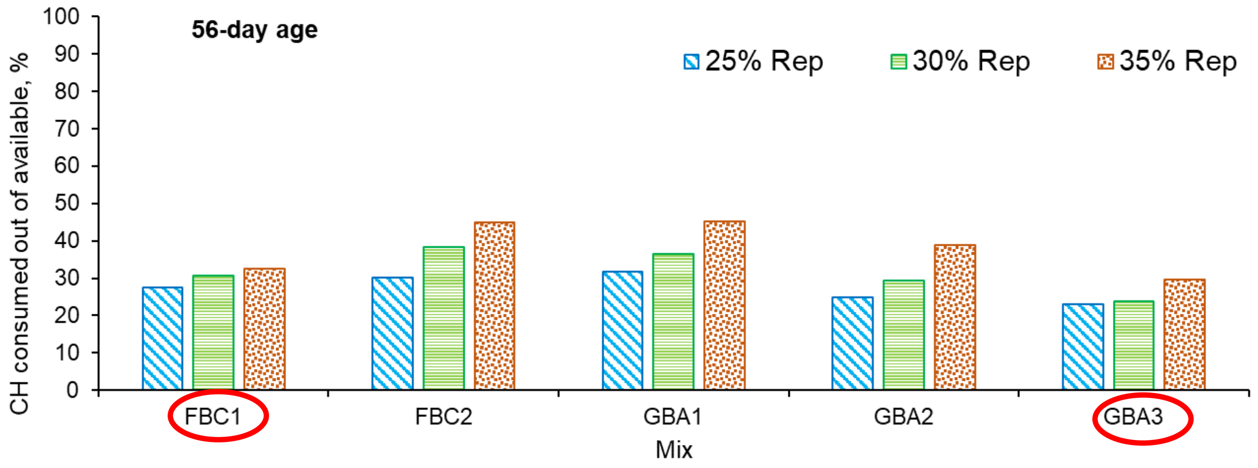


- The paste samples were prepared with w/cm = 0.42 and 25, 30 and 35% replacement levels.
- OPC* paste samples were prepared with inert filler (ground Ottawa sand).

Consumption of calcium hydroxide (CH) (TGA test)



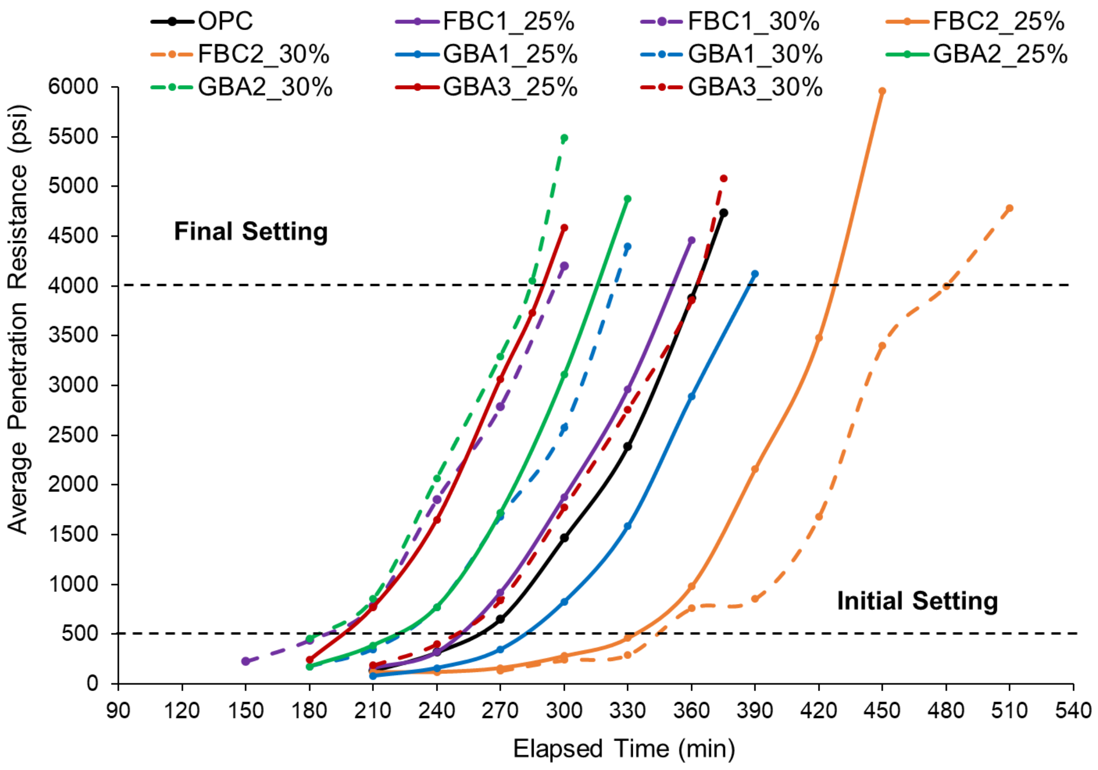


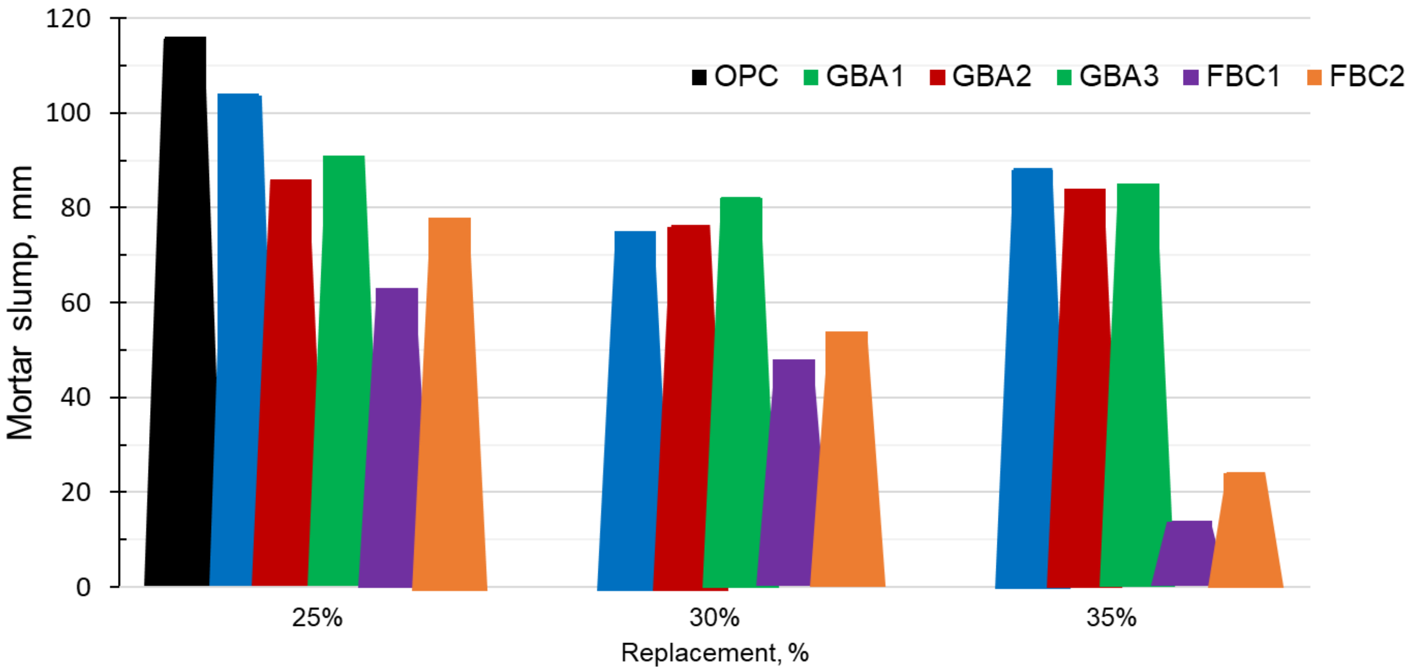


$$CH\ consumed, \%\ available = \frac{CH_{i,inert} - CH_{i,GBA}}{CH_{i,inert}} \times 100\%$$

- The paste samples were prepared at w/cm = 0.42 and 25, 30, 35, 40 and 45% replacement levels.
- Reference paste samples were prepared with inert filler (ground Ottawa sand).

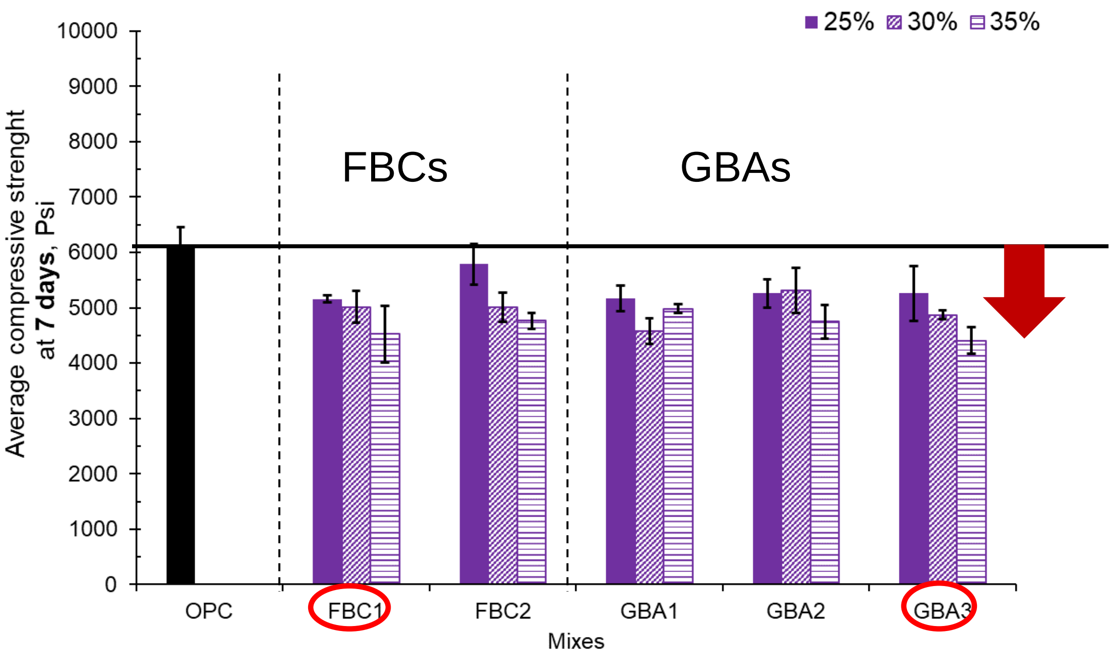
Setting time (penetrometer mortar test)

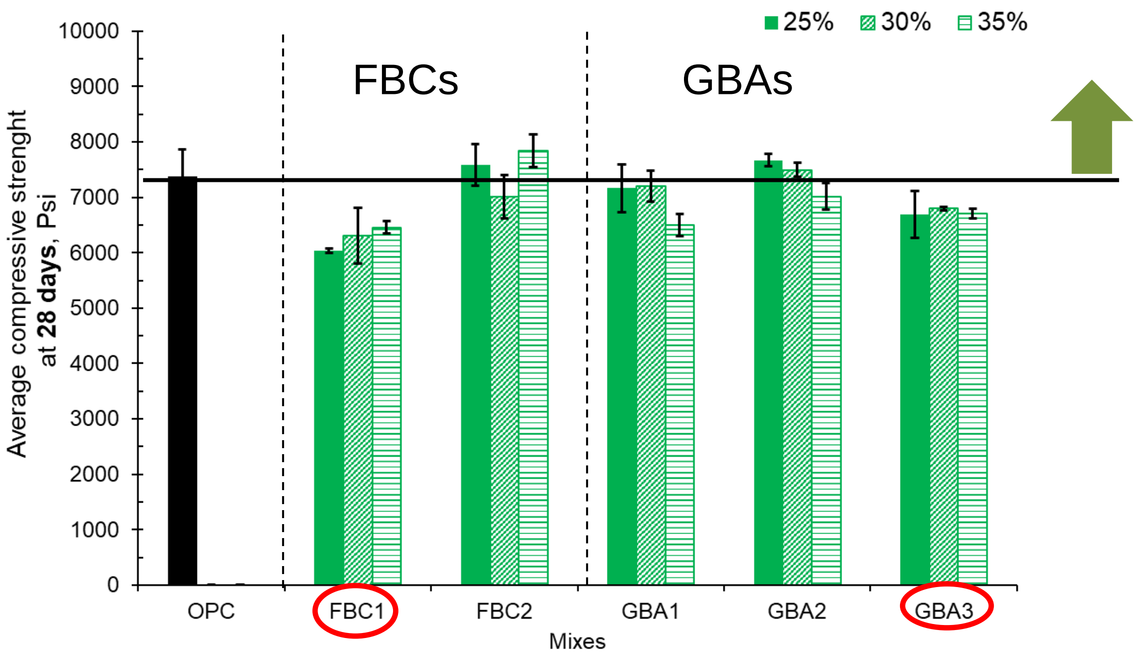




- The mortar samples were prepared with w/cm = 0.42 and 25, 30 and 35% replacement levels.
- The cement-to-sand ratio was 1.7.
- Reference mortar sample was plain OPC (w/c = 0.42, cement-to-sand of 1.7).

Mechanical Properties of Mortars: Compressive Strength





- Overall, when cured for longer period of time, most mortars containing 25% of the ashes performed similarly (or better) than the OPC mortars.
- Considering 7 and 28 days compressive strength results of all mortars containing ashes, the lowest performing were **FBC1** and **GBA3** from each respective group.

Tests Performed on Concrete and Mortar Specimens

Characterization tests performed on paste and mortars

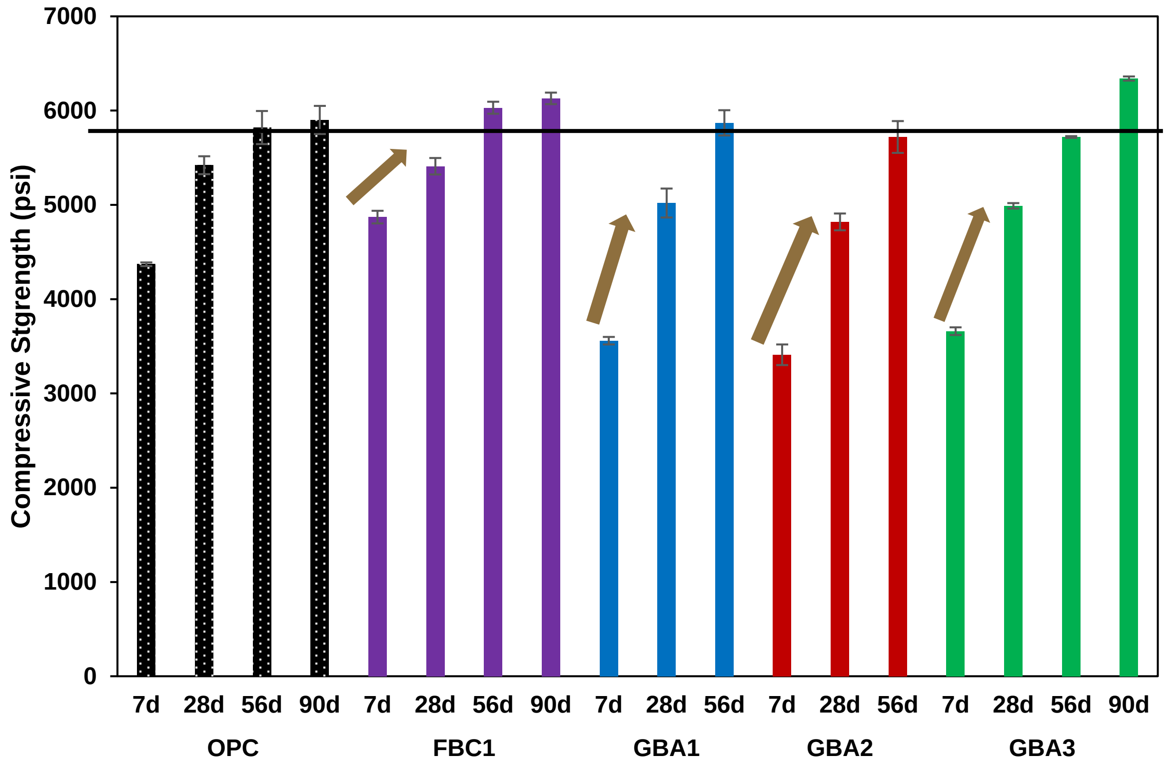
Materials evaluated in concrete

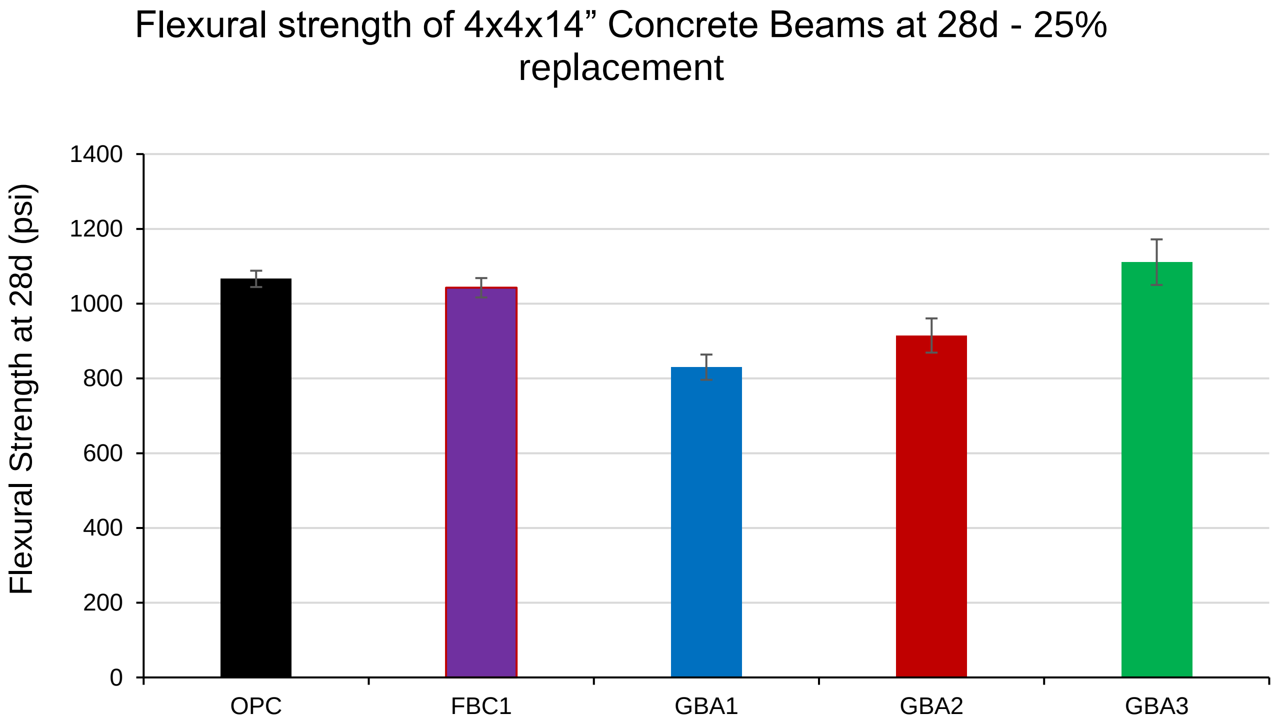
FBC1 and all GBAs at **25% replacement level**

- Compressive Strength (AASHTO T22).
- Flexural Strength (ASTM C78).
- Drying Shrinkage (Modified version of ASTM C596).
- Rate of Water Absorption (Modified version of ASTM C1585).
- Bulk Resistivity (AASHTO TP 119).
- Formation Factor (AASHTO PP84).
- *Scaling Resistance (ASTM C672)
- Oxychloride Formation (AASHTO T365).

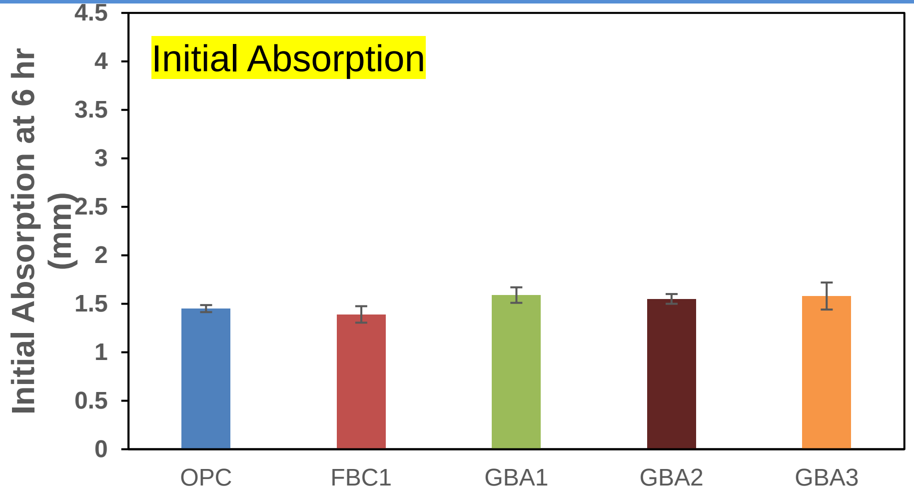
- Concrete mixtures designs were developed based on section 502 of the 2020 Indiana Department of Transportation (INDOT) specifications for portland cement concrete pavements but with a slight adjustment to the maximum replacement percentage of bottom ashes (increase from 20% to 25%).
- The w/cm for all mixtures was 0.44 using 564 total cementitious content.

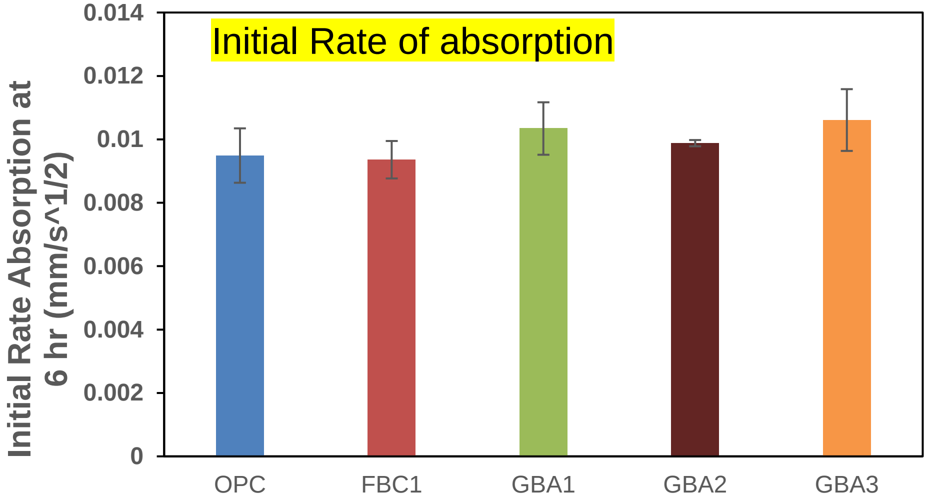
Mechanical Properties of Concrete Mixes

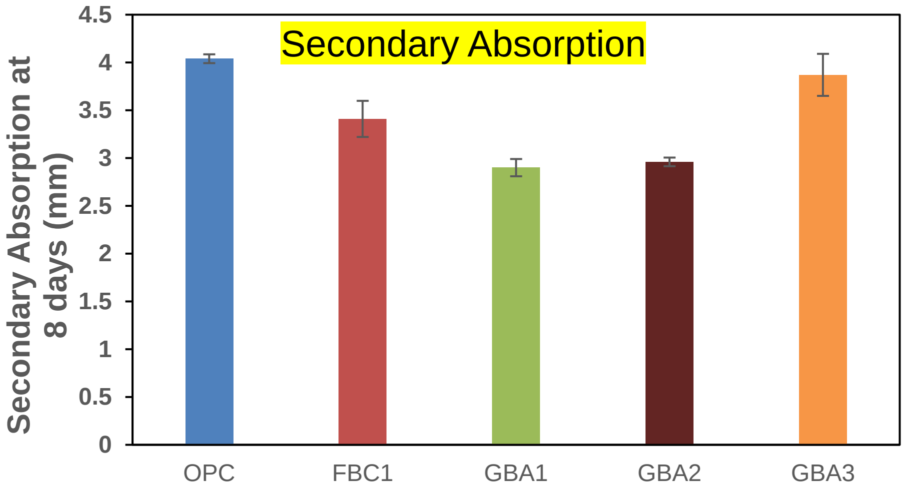


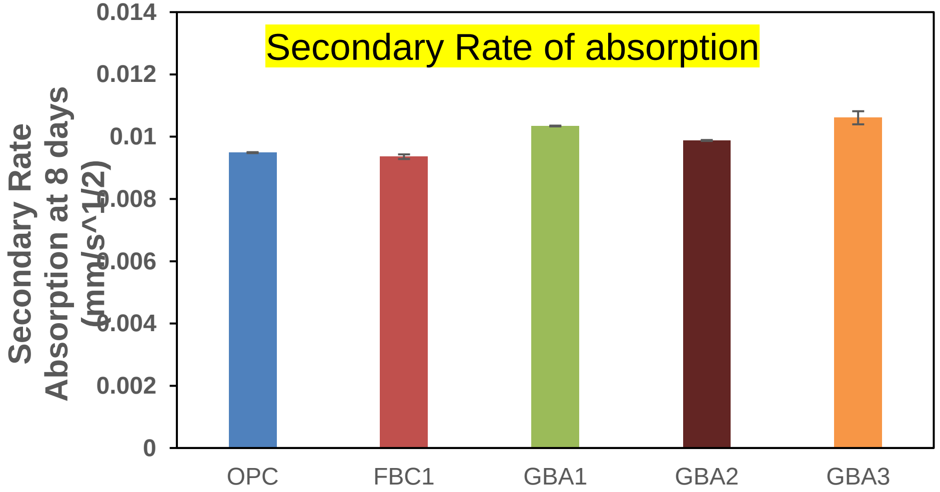


Water Absorption of the Concrete samples (25% replacement)



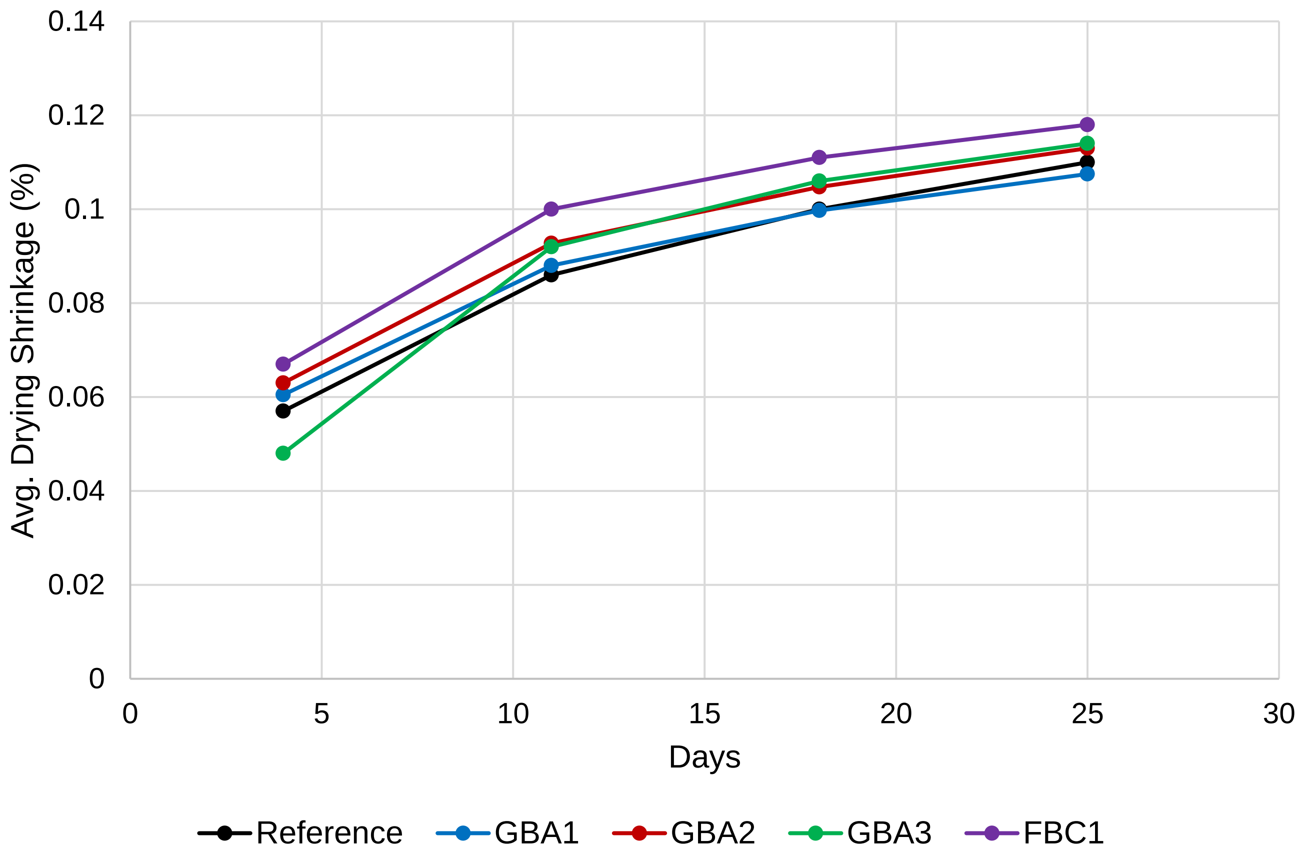






***Instead of placing the specimens in an oven at 50 °C and RH 80 % for 3 days like ASTM C1585 suggests, the specimens were placed in an oven at 60 °C until a daily mass change of less than 0.2% was achieved (DIN 52617).

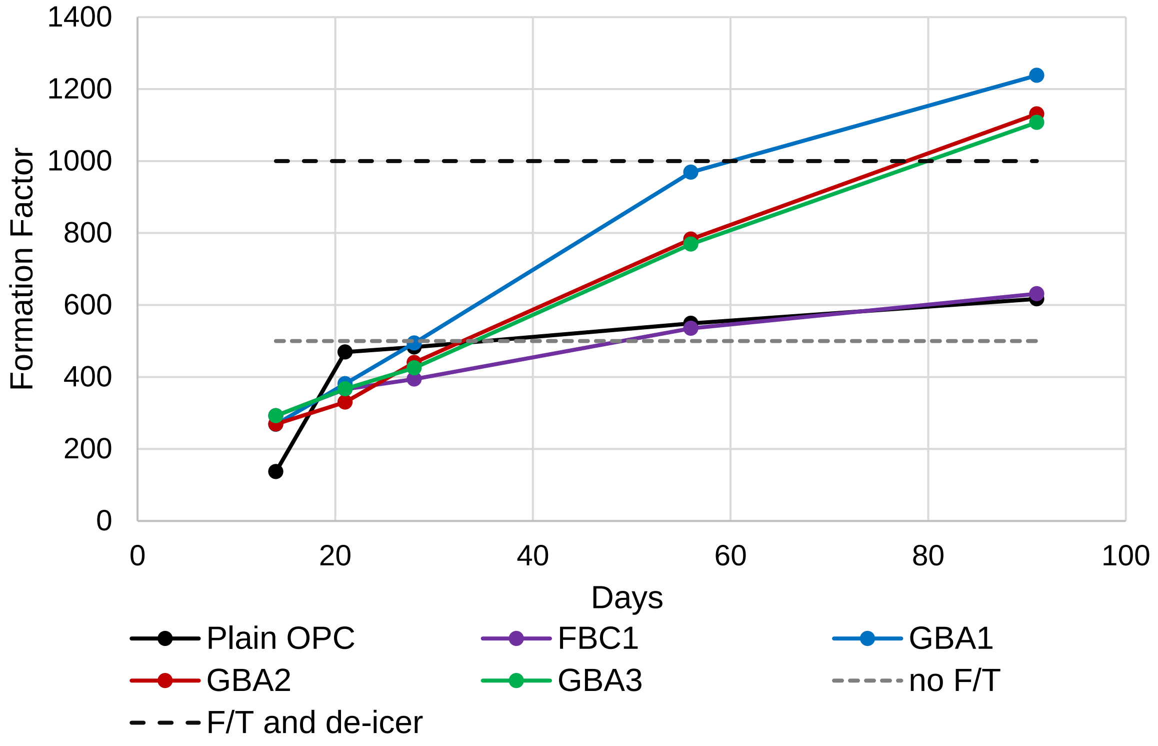
Drying Shrinkage Results of Mortars (25% replacement)



- Tested according to ASTM C596

w/cm kept at 0.44 - to match the value used in concretes

Formation Factor Results of Concretes (25% replacement)



- Based on AASHTO TP84-20, concrete not subjected to freezing and thawing or deicer application: saturated F factor greater than 500 (6.6.1.2.1.)
- Concrete subjected to freezing and thawing or deicer application: saturated F Factor greater or equal to 1000 (6.6.1.2.2.)
- Specimens were conditioned using option A of AASHTO TP119-21 (calcium hydroxide saturated, simulated pore solution)

Scaling Results: Surface of concrete slabs (25% NNP replacement), 0 FT cycles

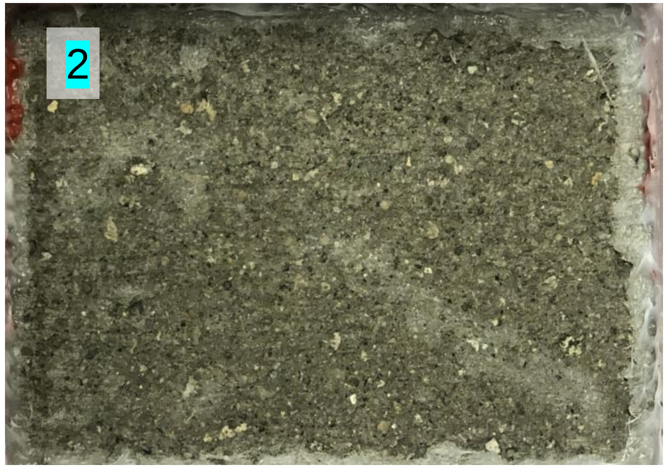
Reference

FBC1

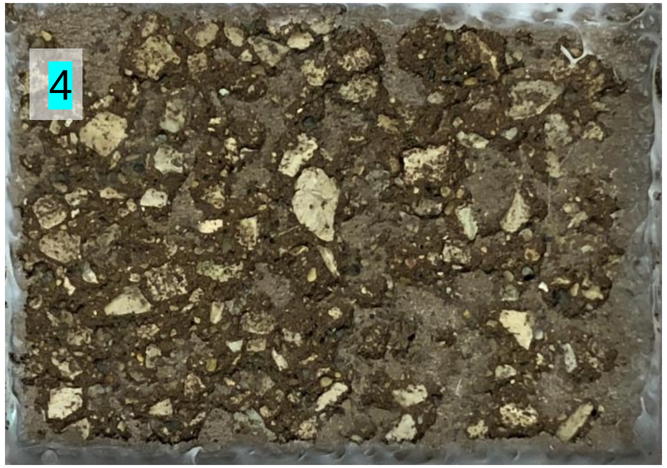
GBA3

Rating	Condition of Surface (based on C672)
0	No scaling
1	Very slight scaling (1/8 in. depth, max, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse agg. Visible)
4	Moderate to severe scaling
5	Severe scaling (coarse agg visible over entire surface)

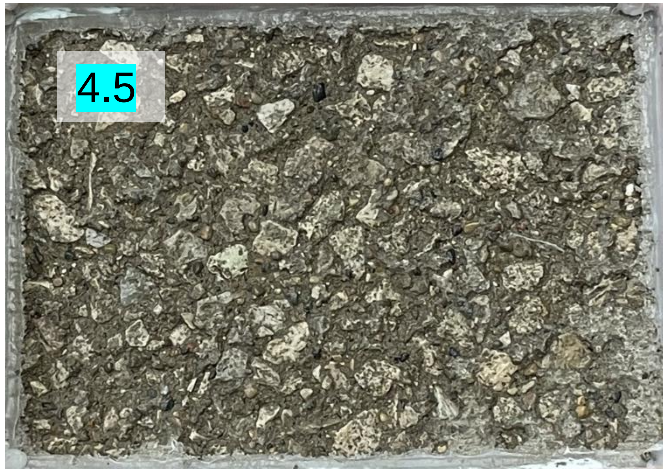
Scaling Results: Surface of concrete slabs (25% NNPs replacement) after 50 FT cycles



Reference



FBC1



GBA3

Mix	Air Content (%)	Total Mass Loss (%)	Avg. Visual Rating
Ref.	6.4	0.19	2
FBC1	5.5	1.55	4
GBA3	5.8	1.79	4.5

Scaling Results: Surfaces of concrete slabs (30% FA replacement) after 50 FT cycles

Reference

P1
w/c=0.42
0% of FA

P2
w/c=0.45
0% of FA

Fly Ash

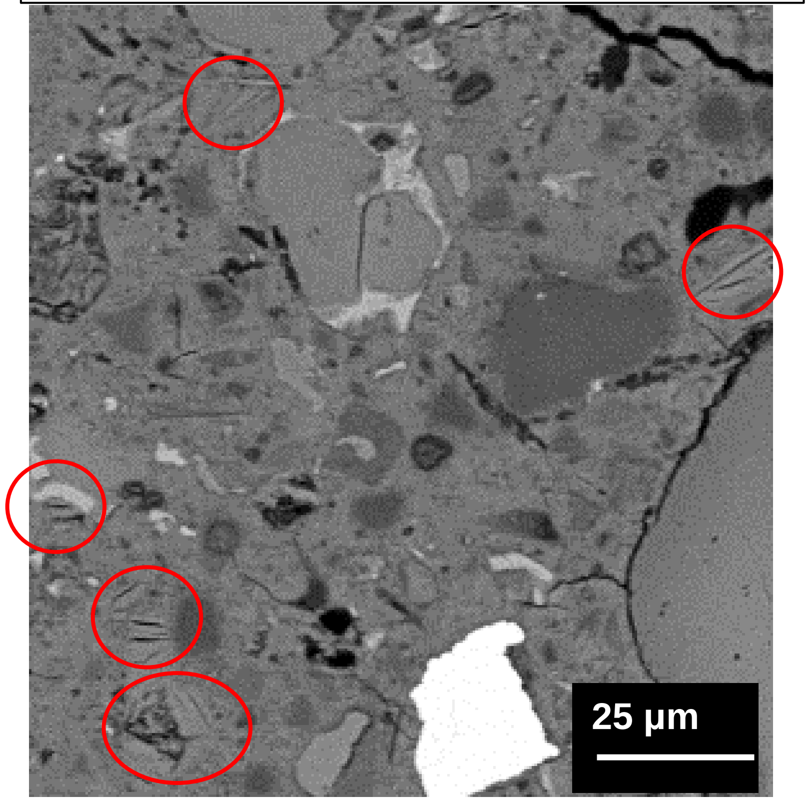
F1
w/cm=0.42
30% of FA

F2
w/cm=0.45
30% of FA

Interaction of the ash mixes with chlorides

Binding of the chlorides into non-harmful phases: **Friedel's salt** ($C_3A \cdot CaCl_2 \cdot 10H_2O$)

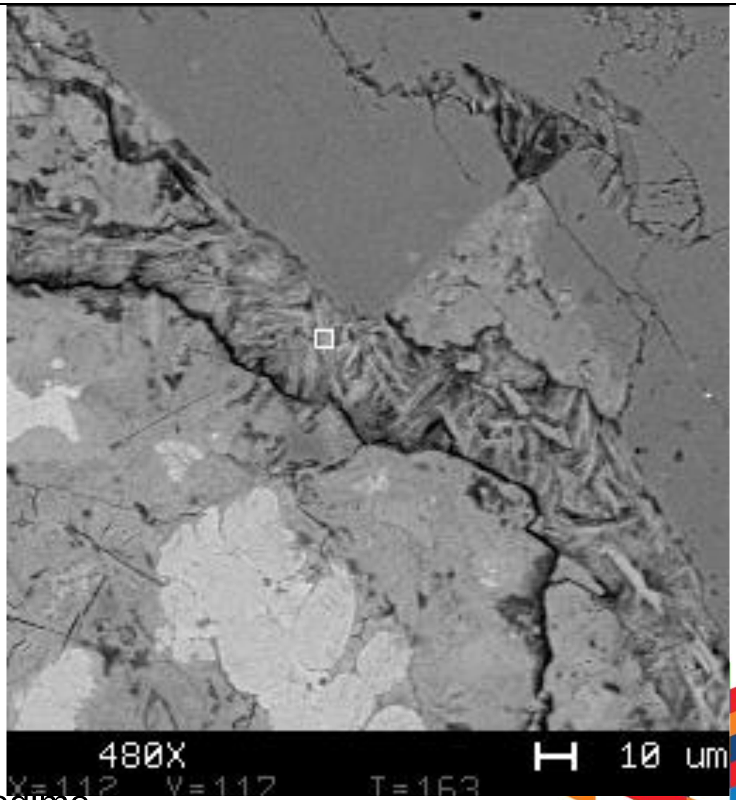
Role of the reactive aluminates



- Specimen exposed to the ASTM C672 scaling test temperature regime (up to 50 temperature cycles of -20°C to + 20°C).

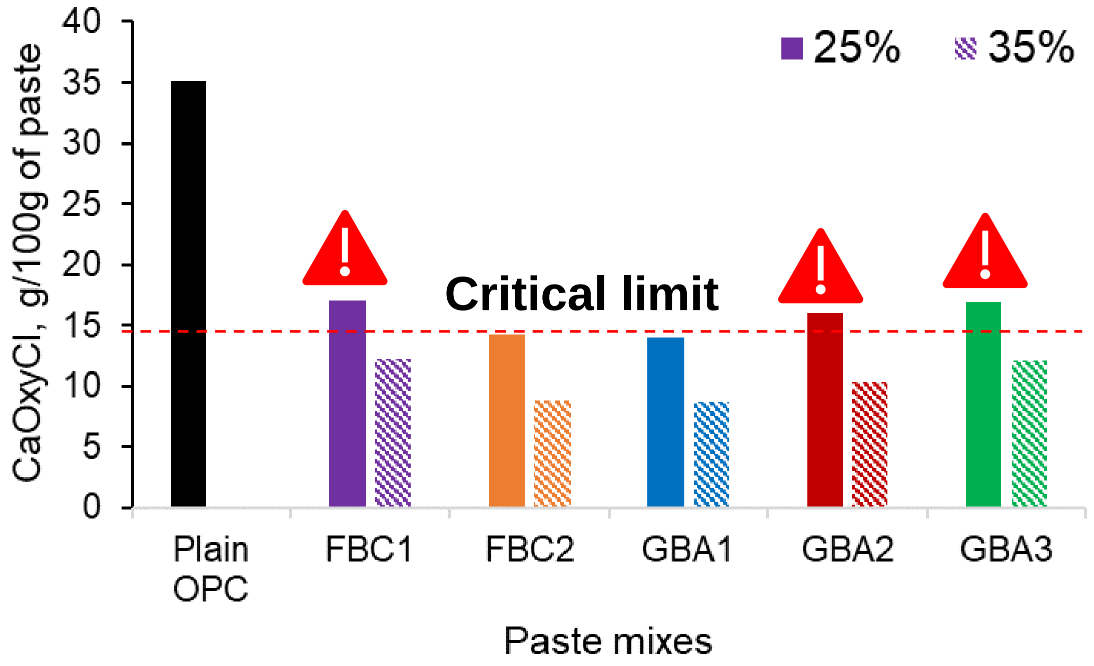
Formation of destructive phases: **Calcium-Oxychloride** ($3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O$)

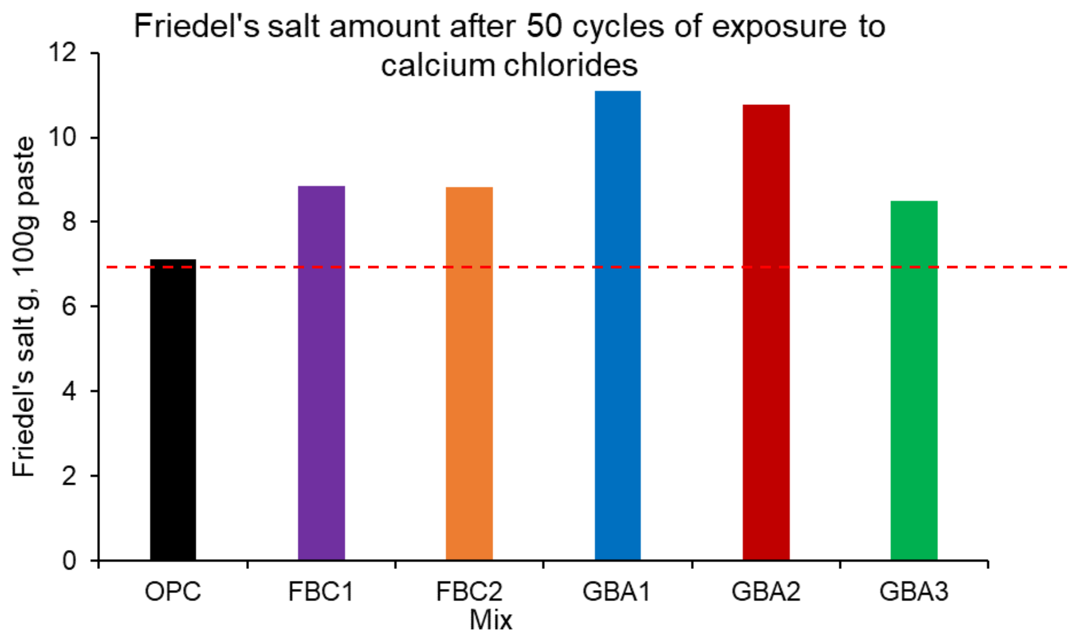
Role of the $Ca(OH)_2$ in the mix

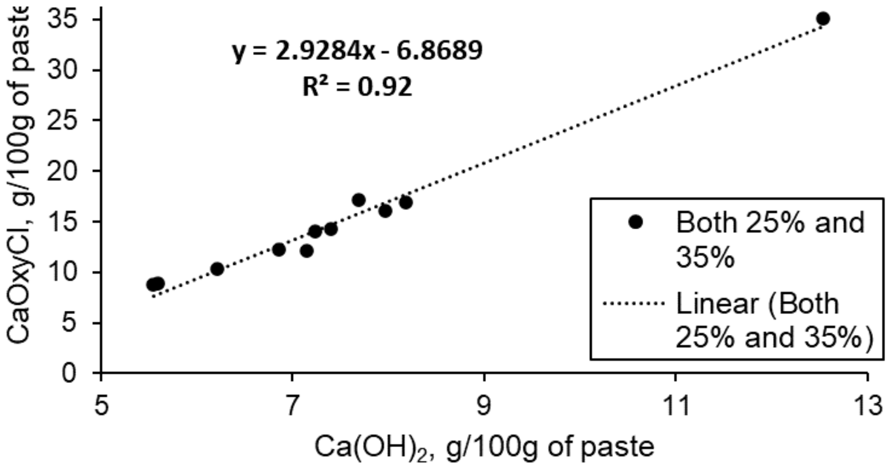


- The exposure regime followed the AASHTO T365-20 methodology.

Interaction of the ash mixes with chlorides







Summary

- All GBA and FBC ashes used in the study met requirements of ASTM C 618 except for the sum of alumina, silica and ferrite for GBA3 (it was slightly (3%) lower than the specified min. value of 70%) and high SO3 in FBC2.
- The reactivity tests indicated that all GBAs and FBCs can be classified as moderately reactive with reactivity comparable to that of traditional fly ashes.
- However, among all ashes studied, GBA3 and FBC1 were observed to be the least reactive.
- Compared to the OPC mixtures the slump of the GBAs mixtures was slightly reduced and the degree of reduction increased with the increase in the % replacement. This was significantly prominent in case of FBC ashes.
- All ash mixtures showed increase in $Ca(OH)_2$ consumption with the increase in curing time.
- Concretes with 25% of ashes performed similar or better than OPC concrete in almost all tests (with the exception of scaling resistance).

Thank you!