Mitigating Delayed Ettringite Formation in Cementitious Mixtures Incorporating Ground Granulated Blast Furnace Slag (GGBFS)

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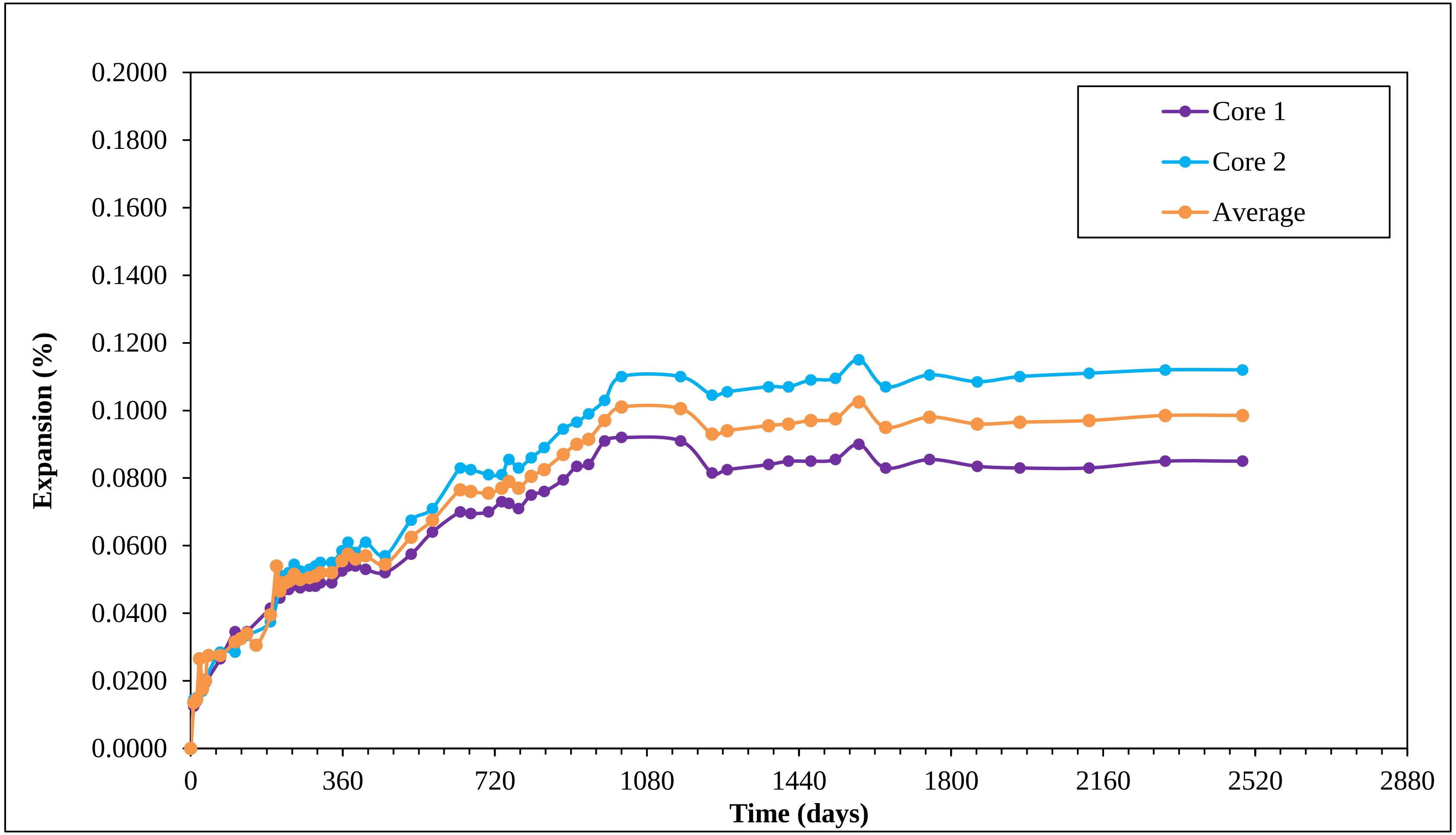
Maximum Concrete temperature, T	Prevention Required
T≤ 158°F (70°C)	No prevention required
158°F < T ≤ 185°F (70°C < T ≤ 85°C)	Use one of the following approaches to minimize the risk of expansion 1. Any ASTM C150/C 150M portland cement in combination with the following proportions of pozzolan or slag cement: (a) Greater than or equal to 25% fly ash meeting ASTM C618 for Class F fly ash (b) Greater than or equal to 35% fly ash meeting ASTM C618 for Class C fly ash (c) Greater than or equal to 35% slag cement meeting the requirements of ASTM C989/C989M (d) Greater than or equal to 5% silica fume (ASTM C1240) in combination with at least 25% slag cement (e) Greater than or equal to 5% silica fume (ASTM C1240) in combination with at least 20% Class F fly ash (f) Greater than or equal to 10% metakaolin meeting ASTM C618 2. An ASTM C595/C595M or ASTM C1157/C1157M blended hydraulic cement with the same pozzolan or slag cement content as listed in item 1
T> 185°F (85°C)	Internal Concrete temperature should not exceed 185°F (85°C) under any circumstances

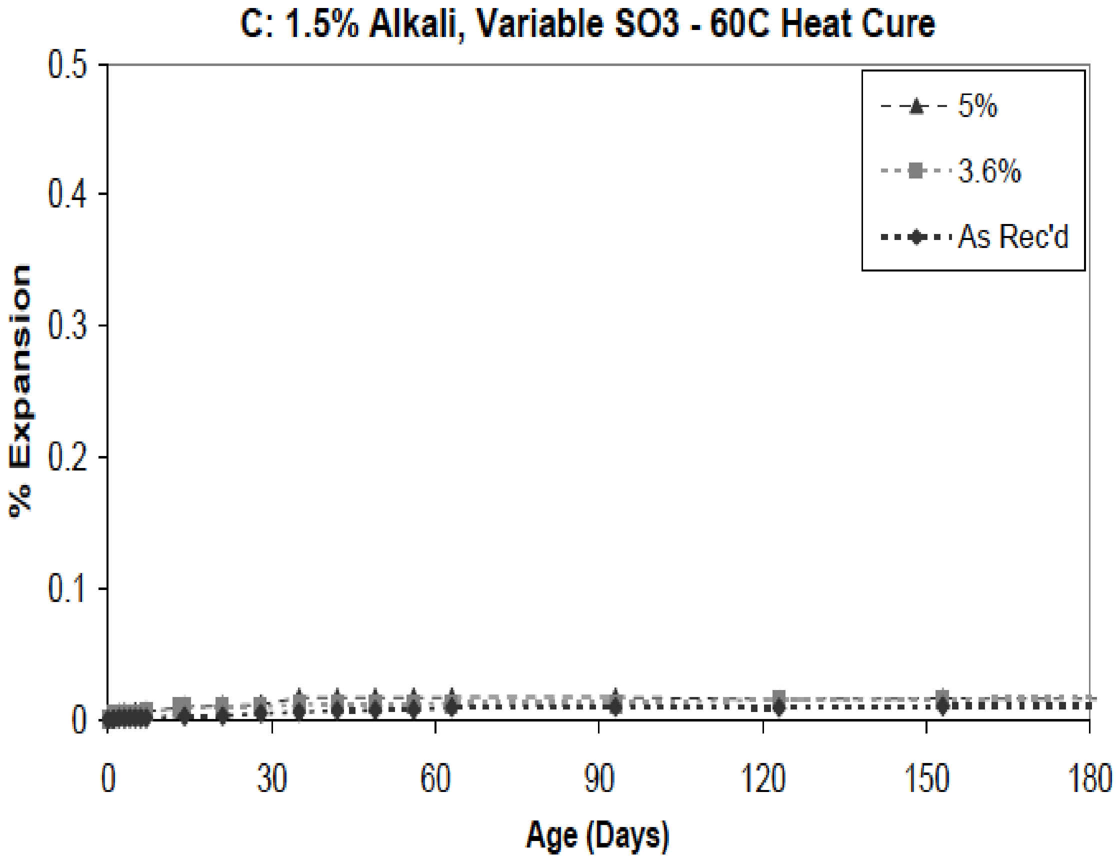
Ghorab et al. (1980), Ramlochan et al. (2003), Thomas (2001), Thomas et al. (2008b)

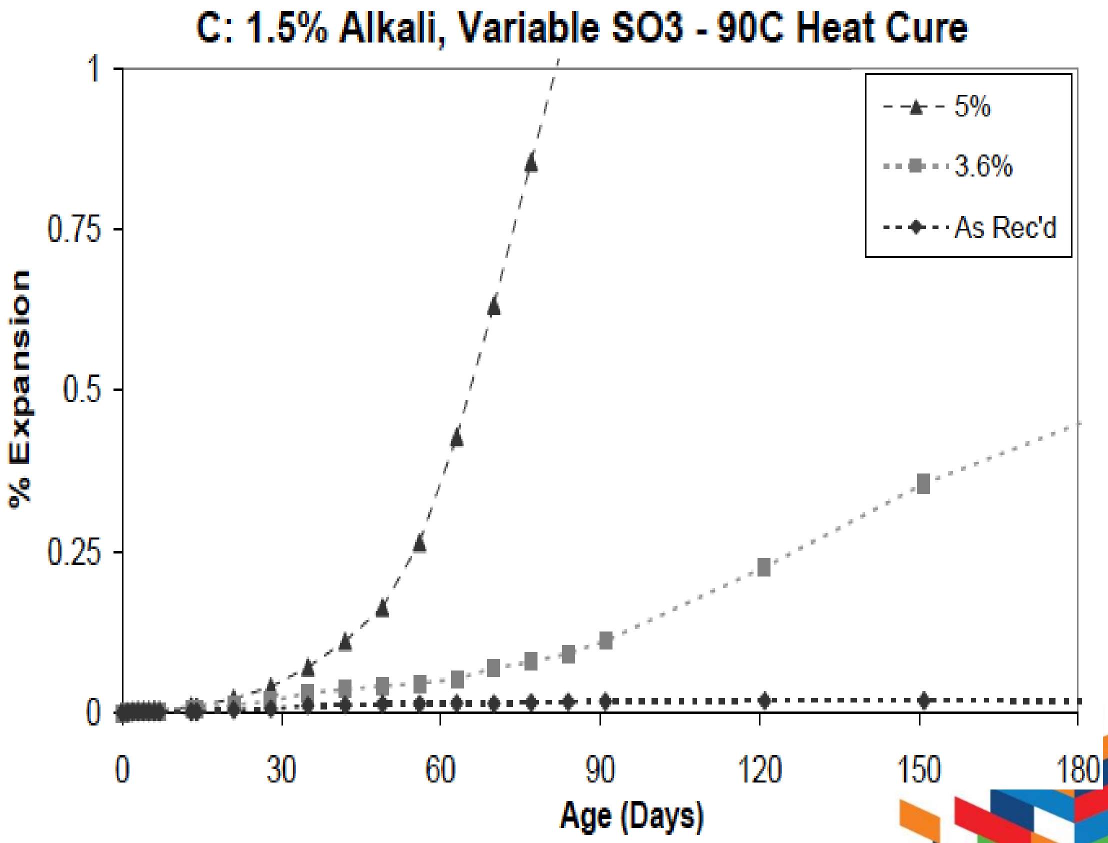
DEF assessment of field concrete (2016)



USF Construction Materials Group Zayed et al. (early 2000s)

Effect of Temperature on DEF



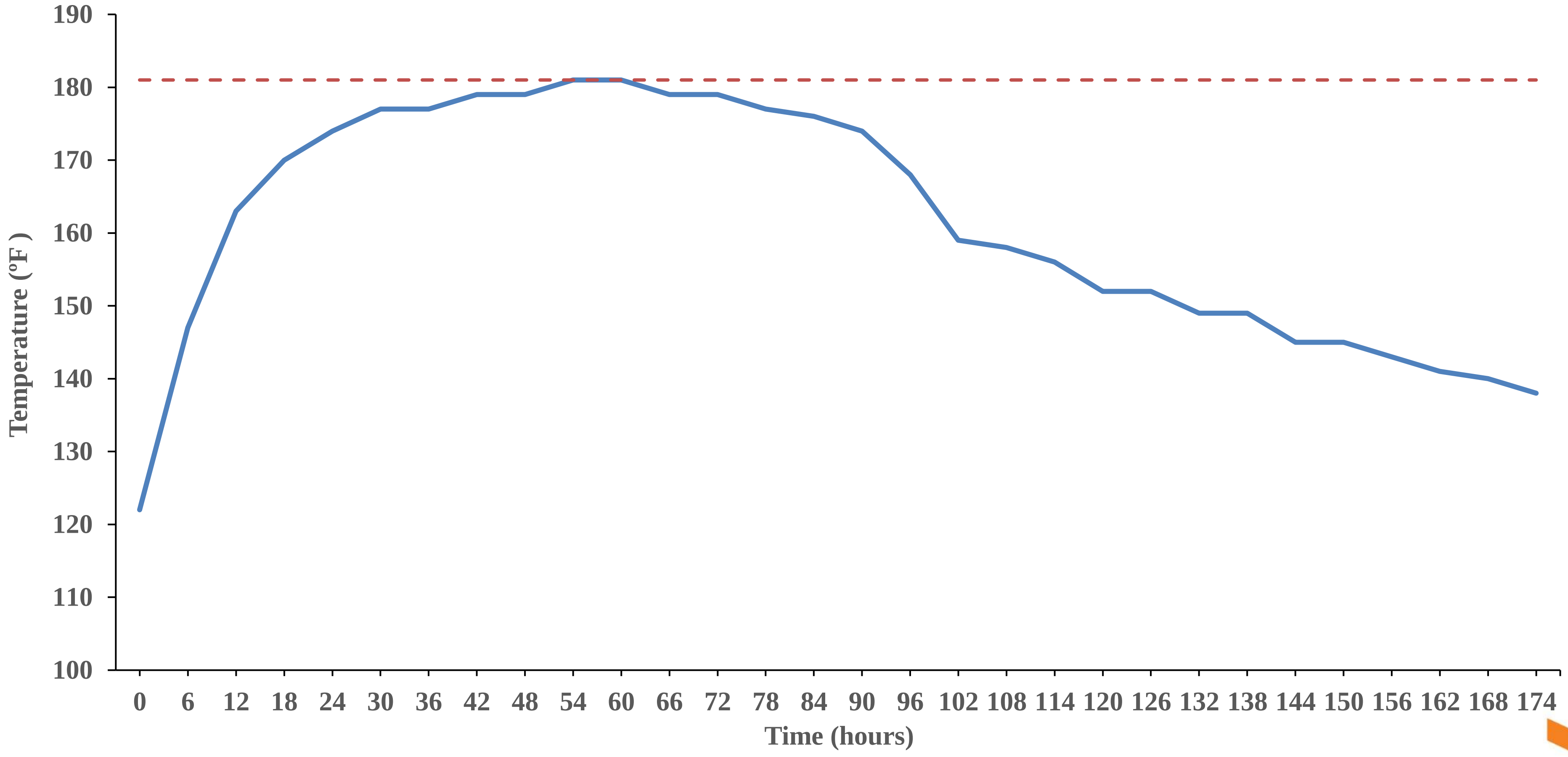


USF Structures Research Group Mullins et al. (2016 – current)

- Thermal integrity tests of 662 FDOT drilled shafts
  - 3 to 9ft diameter.
  - Temperatures measured at the cage (6in from edge)
  - Time of temperature measurement 24 to 60hrs after casting; rarely at peak time
  - Slag/portland cement or fly ash/portland cement mixtures
- 13.6% cage temperatures exceeded 158°F (90 shafts)
- New cage to core temperature prediction method
- 61% had predicted core temperature >> 158°F (403 shafts)
- 98% had predicted differential temperature > 35°F (all but 13 shafts)

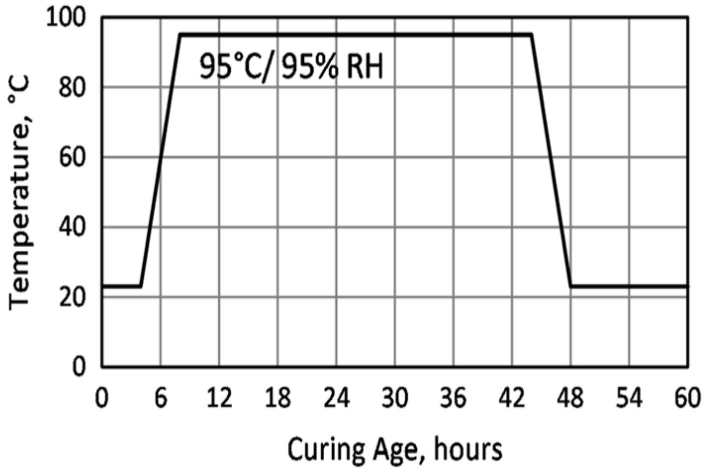
- Many shafts excluded from Mass Concrete Control Plan

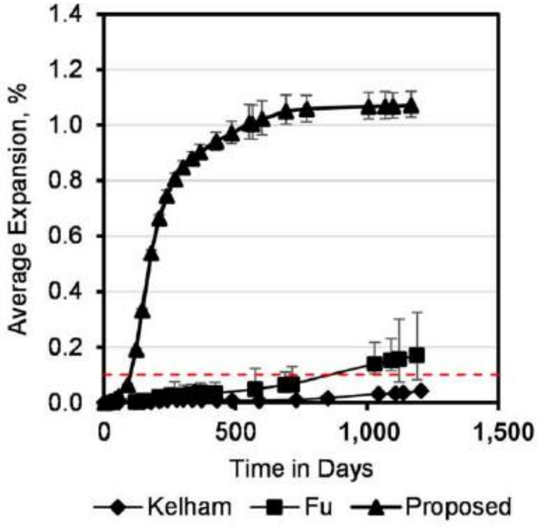
Field Data - temperature vs. time (2016)



UF Ferraro et al. Research Group (2017- current)

- The time/temperature curves of existing DEF methods (Kelham and Fu) do not replicate the mass concrete
- The use of an extended soak time (at elevated temperature) is more representative of mass concrete
- Shortens time to failure (0.1% expansion):
  - under 100 under days using “Ferraro Method”
  - 825 days using Fu Method
  - 1,000 days using Kelham Method
- “Sulfate resisting cements” Type II and Type V are more likely to expand than OPC due to the relatively high sulfate to aluminate ratio in sulfate resisting cements (external sulfate attack)
- The previously published Table 6.2.2.2 of ACI 201.2-R16 allowing the use of Type II or Type V cements without use of a pozzolan (notes 1 & 2) was not conservative





Paris, et al.. (2022) ACEM 11(1): 81–93
Ferraro (2018) EPRI Final report 3002007577

Research Question

Can any ASTM C150/150M portland cement with 35% GGBFS suppress DEF?

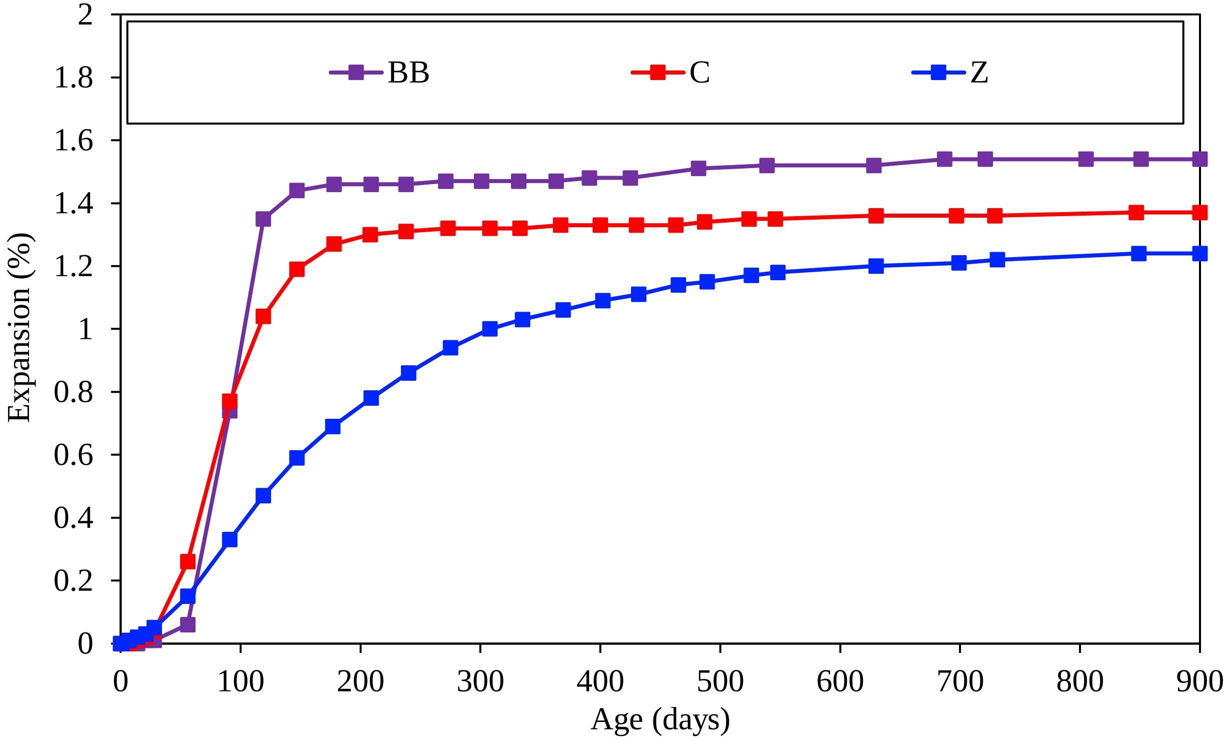
Portland Cements and GGBFS Chemical Composition

Analyte	Cements					Slags	
	BB	C	Z	TIL (10)	THIL (14)	S14B	S17
SiO_2	19.53	19.00	19.41	19.16	19.14	33.39	30.47
Al_2O_3	5.51	5.90	4.64	4.61	4.52	13.80	17.07
Fe_2O_3	1.79	2.80	3.06	3.74	3.54	0.84	0.46
CaO	64.27	60.80	62.77	62.40	62.11	42.00	35.49
MgO	1.05	2.50	3.01	1.12	1.08	5.60	10.96
Total SO_3	3.93	4.00	3.25	2.47	2.44	3.10	2.87
SO_3 as Sulfate	-	-	-	-	-	1.22	1.39
Na_2O	0.11	0.32	0.02	0.17	0.17	0.23	0.48
K_2O	0.41	1.10	0.95	0.32	0.29	0.28	0.30
L.O.I. (950°C)	2.60	2.40	2.53	5.35	5.99	0.09	0.17
Total	99.84	99.82	100.21	99.98	99.91	100.17	100.39
Na_2O_{eq}	0.38	1.05	0.65	0.38	0.36	0.41	0.68

Mineralogical Composition and Physical Properties

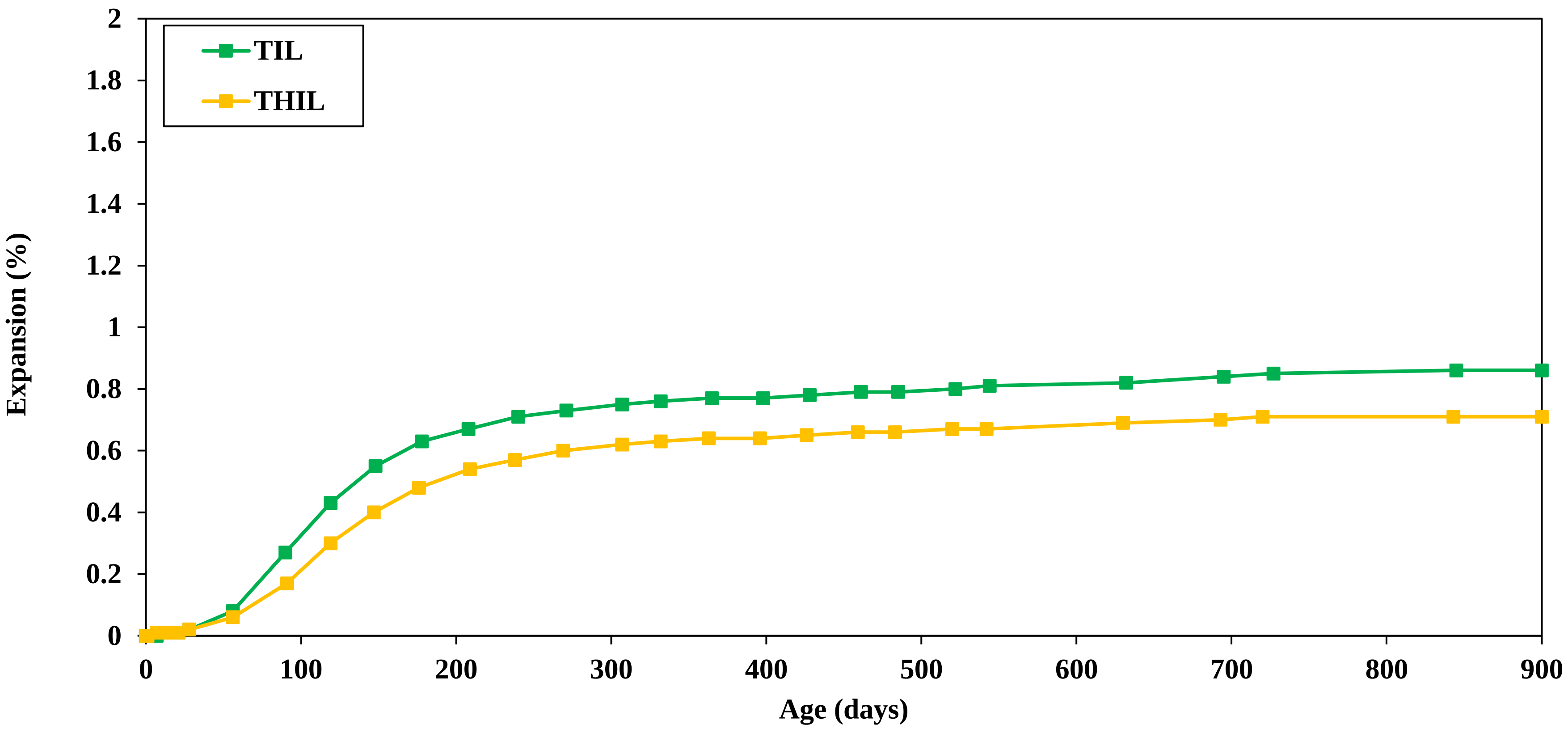
Analyte	Cements					Slags	
	BB	C	Z	TIL(10)	THIL(14)	S14B	S17
C_3S	49.1	49.5	53.8	44.5	40.3	-	-
C_2S	15.6	13.7	7.7	16.1	16.9	-	-
C_3A	8.6	8.3	5.6	2.3	2.9	-	-
C_4AF	4.2	7.5	7.6	11.8	10.8	-	-
Calcite	0.2	1.8	3.5	8.8	11.4	1.4	0.2
Gypsum	5.7	3.8	0.3	1.5	1.5	2.0	2.6
Hemihydrate	0.2	1.7	2.5	1.4	2	-	-
Anhydrite	0.1	-	-	-	-	-	-
Portlandite	1.1	0.2	-	-	-	-	-
Quartz	-	0.2	0.2	1.2	1.4	-	0.1
Dolomite	-	1.3	0.5	-	-	-	-
Periclase	0.1	1.3	1.8	-	-	-	-
Syngenite	0.5	0.9	1.1	-	-	-	-
Aphthitalite	0.3	0.6	-	-	-	-	-
Melilite	-	-	-	-	-	0.3	1.4
Merwinite	-	-	-	-	-	0.1	-
Amorphous/ unidentified	14.2	9.4	15.5	12.5	12.8	96.1	95.7
MPS (µm)	14.03	16.50	13.46	10.80	12.75	12.55	9.79
SG (g/cm^3)	3.04	3.15	3.08	3.11	3.13	2.89	2.92
BF (m^2/kg)	356	436	412	483	488	553	510

ASTM C150/150M Portland Cements



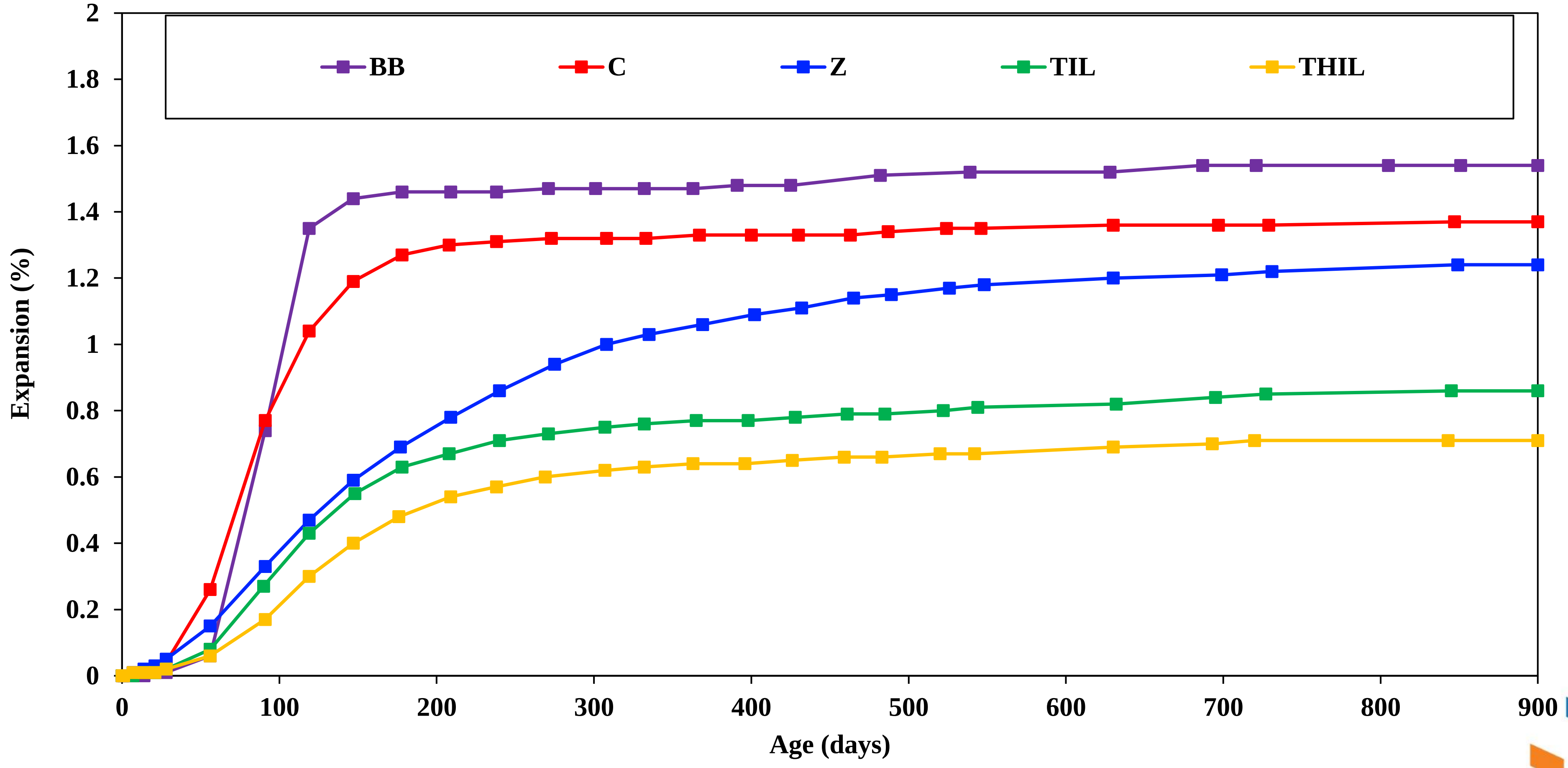
Analyte	BB	C	Z
Al_2O_3	5.51	5.90	4.64
SO_3	3.93	4.00	3.25
SO_3/Al_2O_3	0.71	**0.68**	0.70
Na_2O_{eq}	0.38	**1.05**	0.65
C_3A (Bogue)	11.58	10.90	7.12
BF [m^2/kg]	356	436	412
DEF Index (Zhang [34])	0.87	**1.32**	0.75

IL Portland Cements

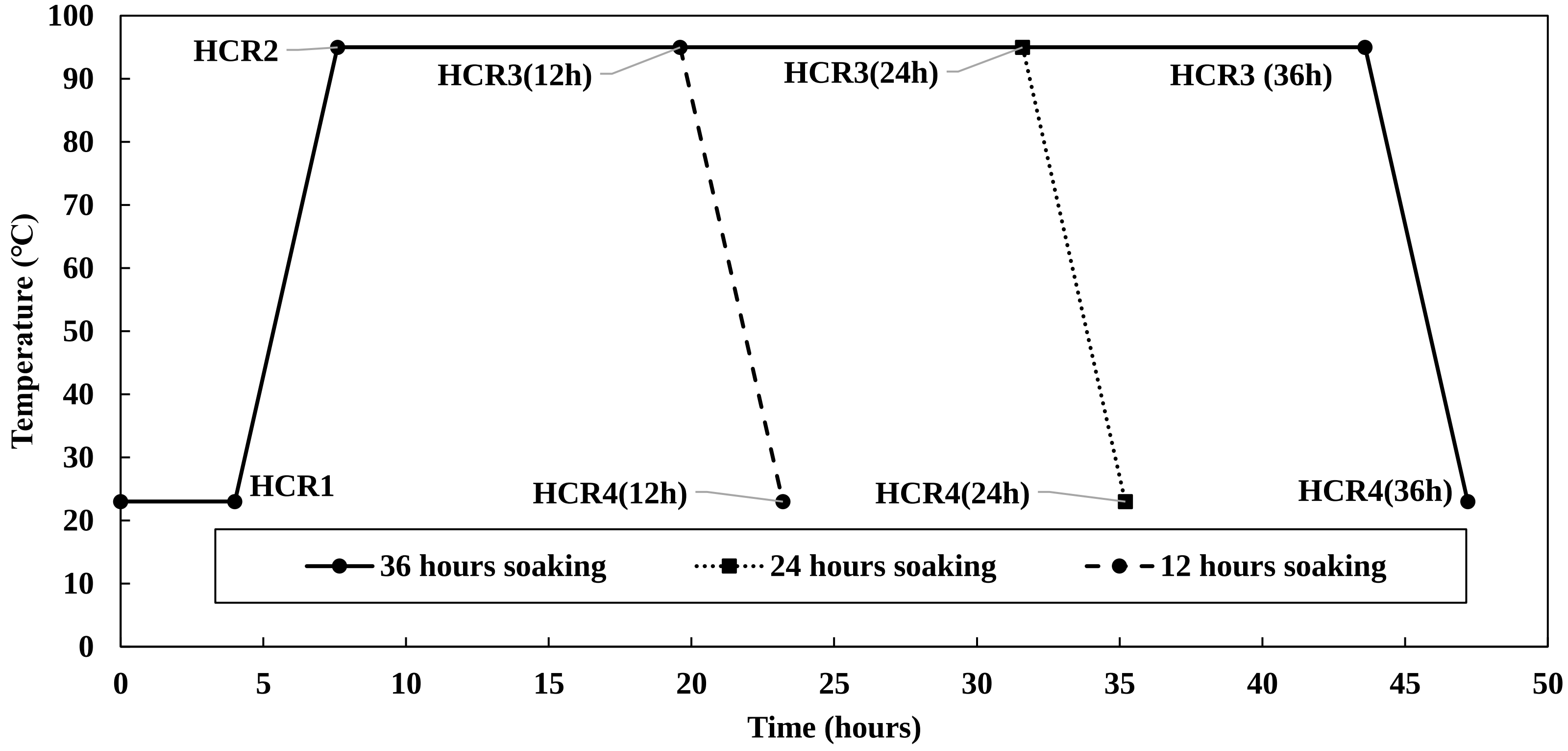


TIL= 8.8% Calcite
THIL= 11.4% Calcite

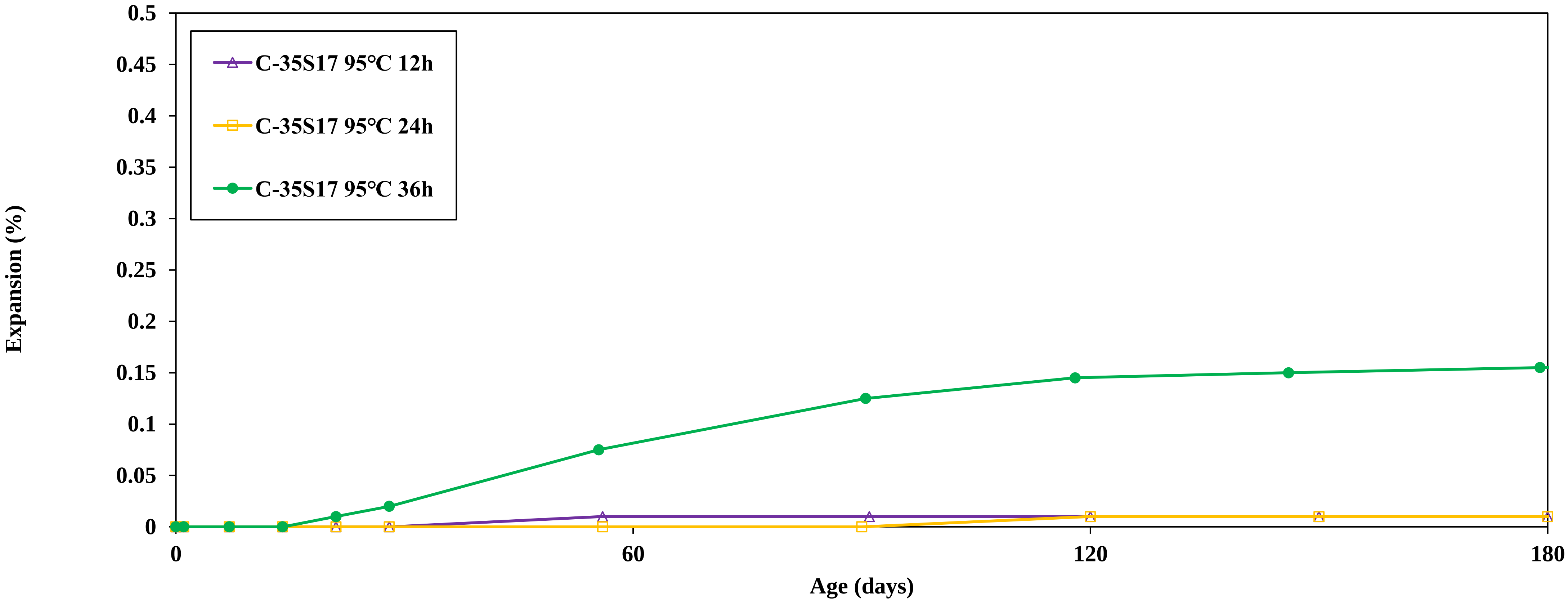
ASTM C150 and C595 cements



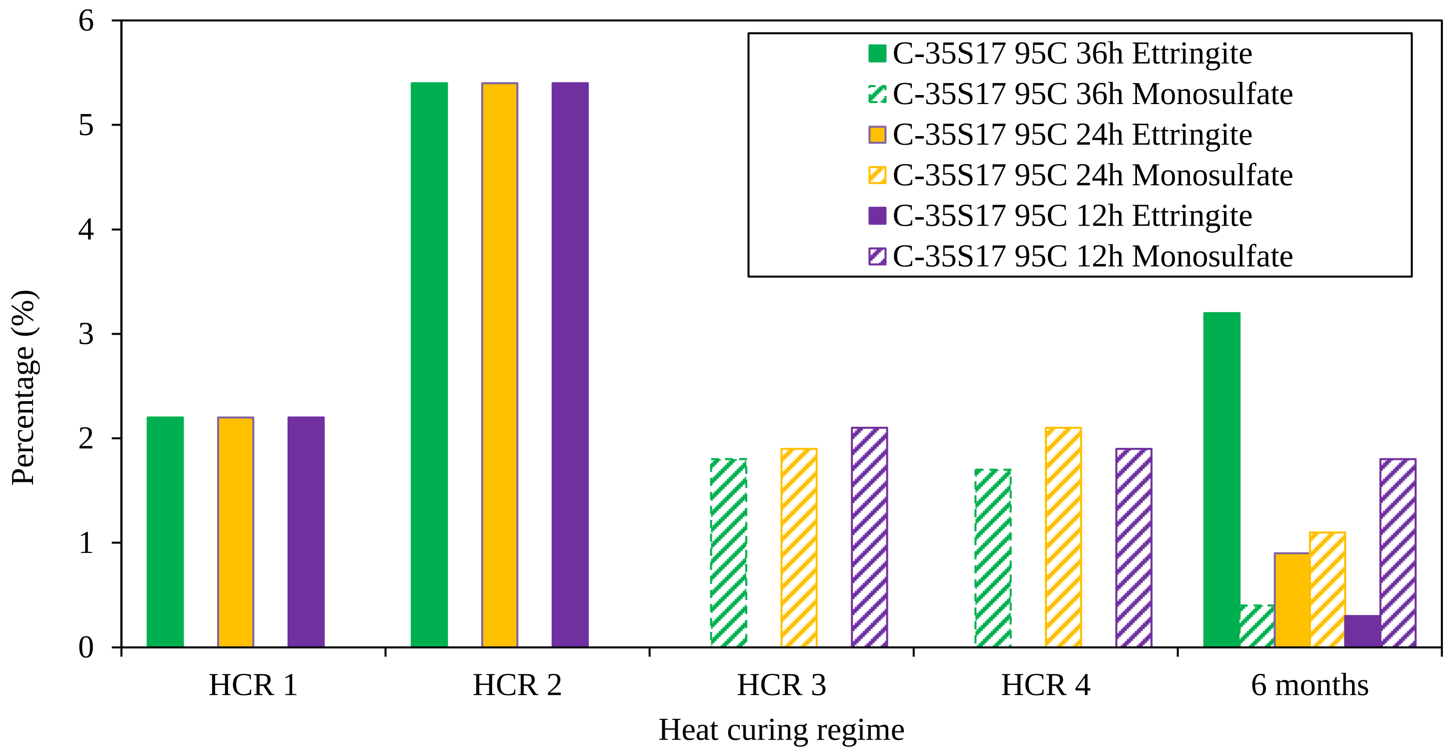
Effect of residence time at elevated temperature on DEF

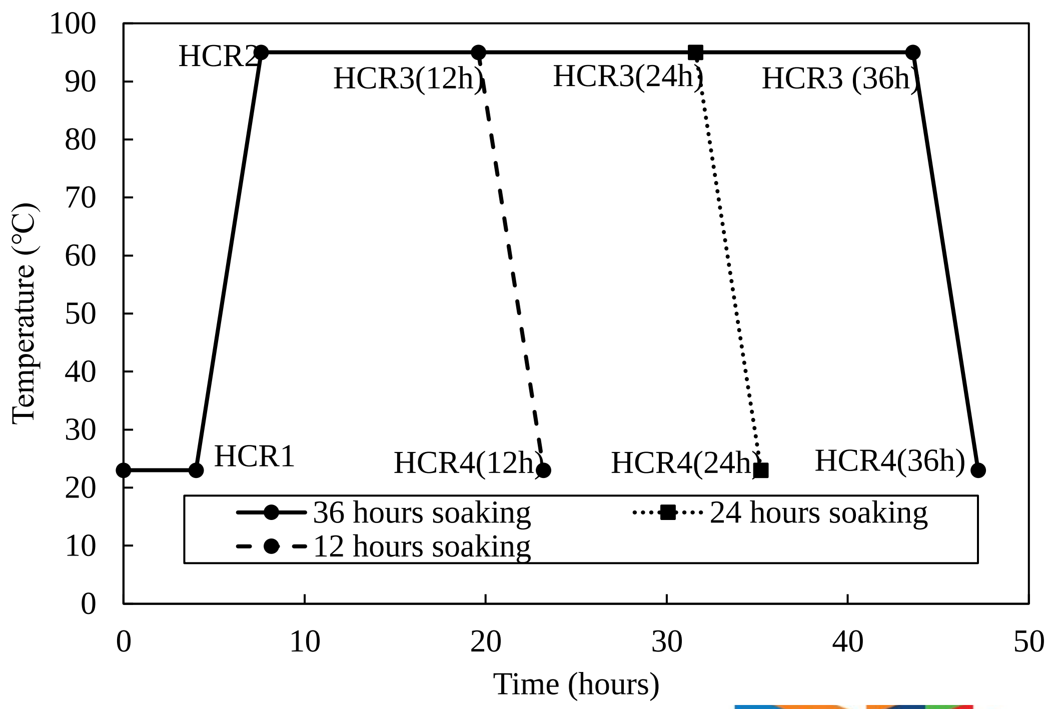


Slag blended cementitious mixtures at 35% replacement (Variable residence time at 95C)

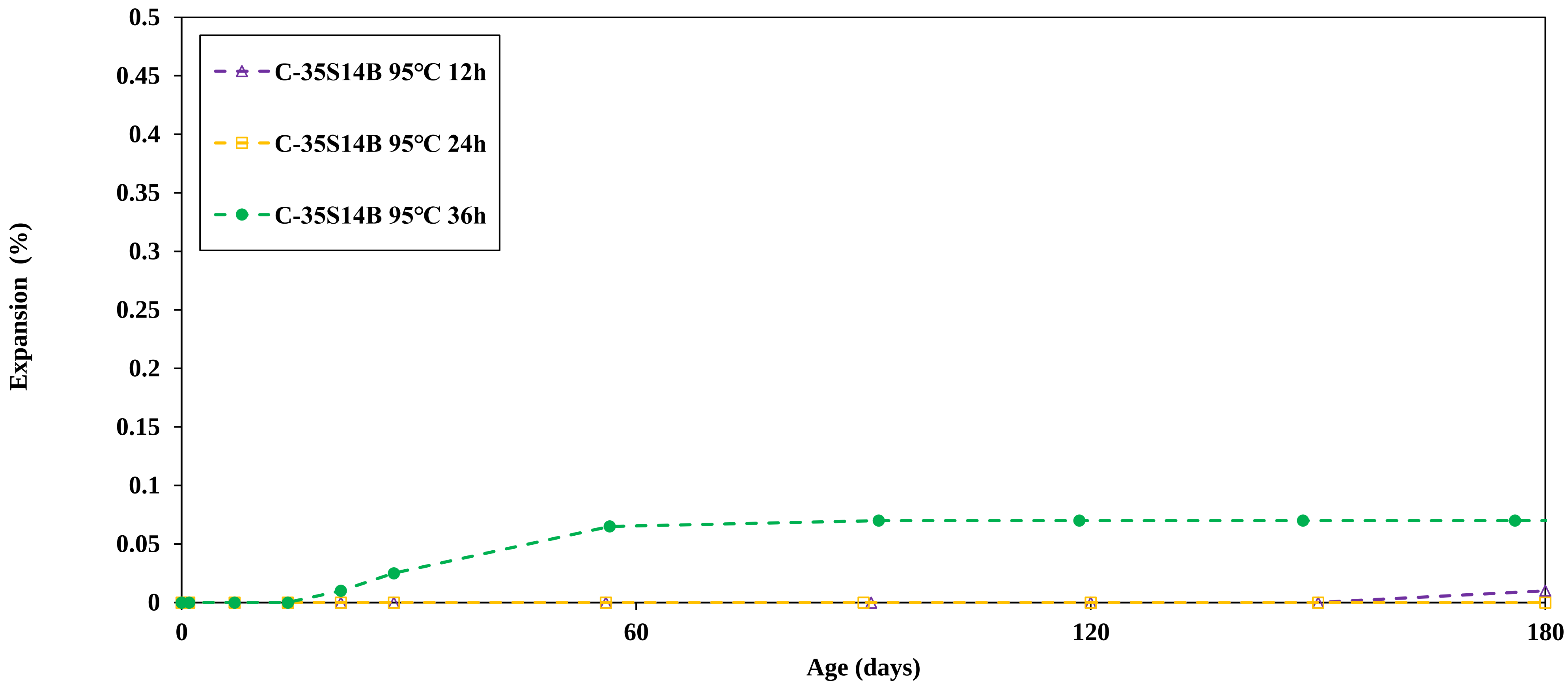


Phase transformation

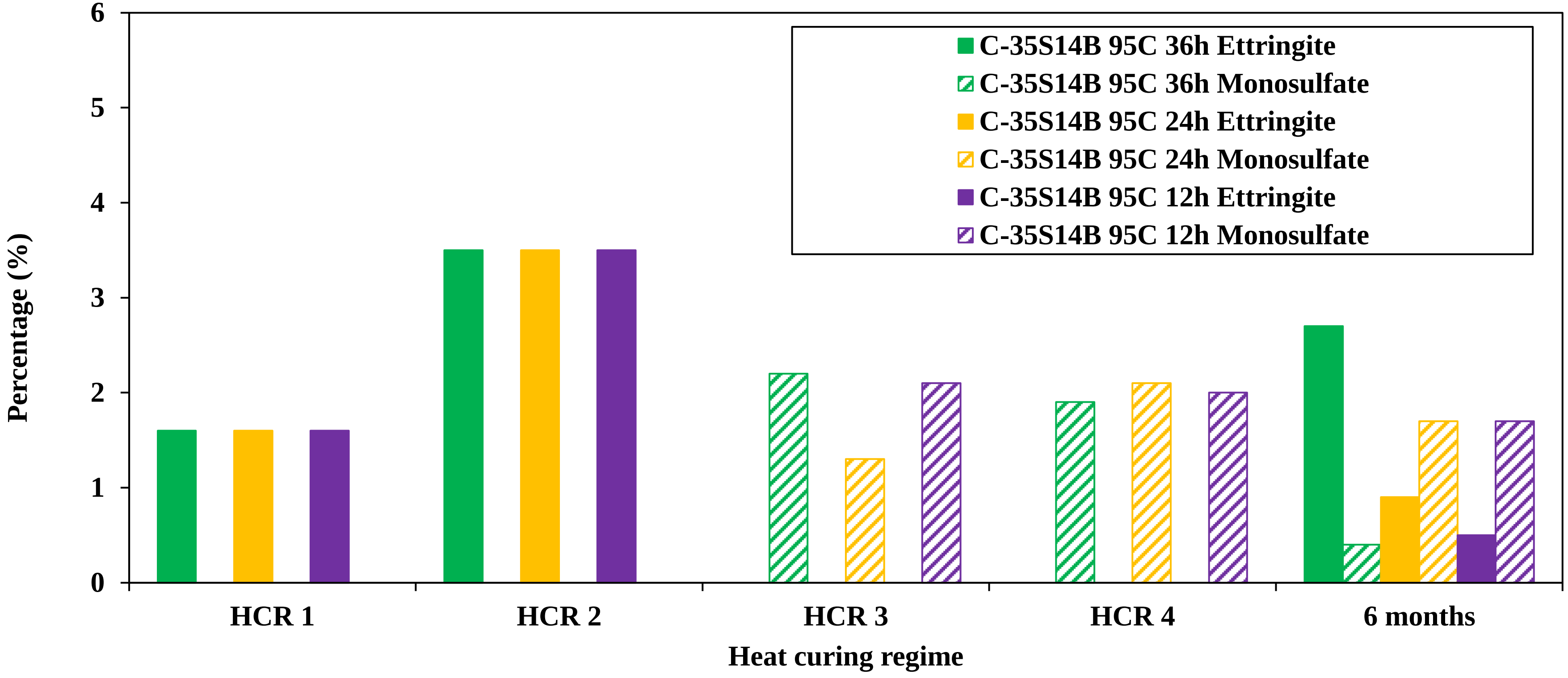




Effect of residence time at peak temperature on DEF



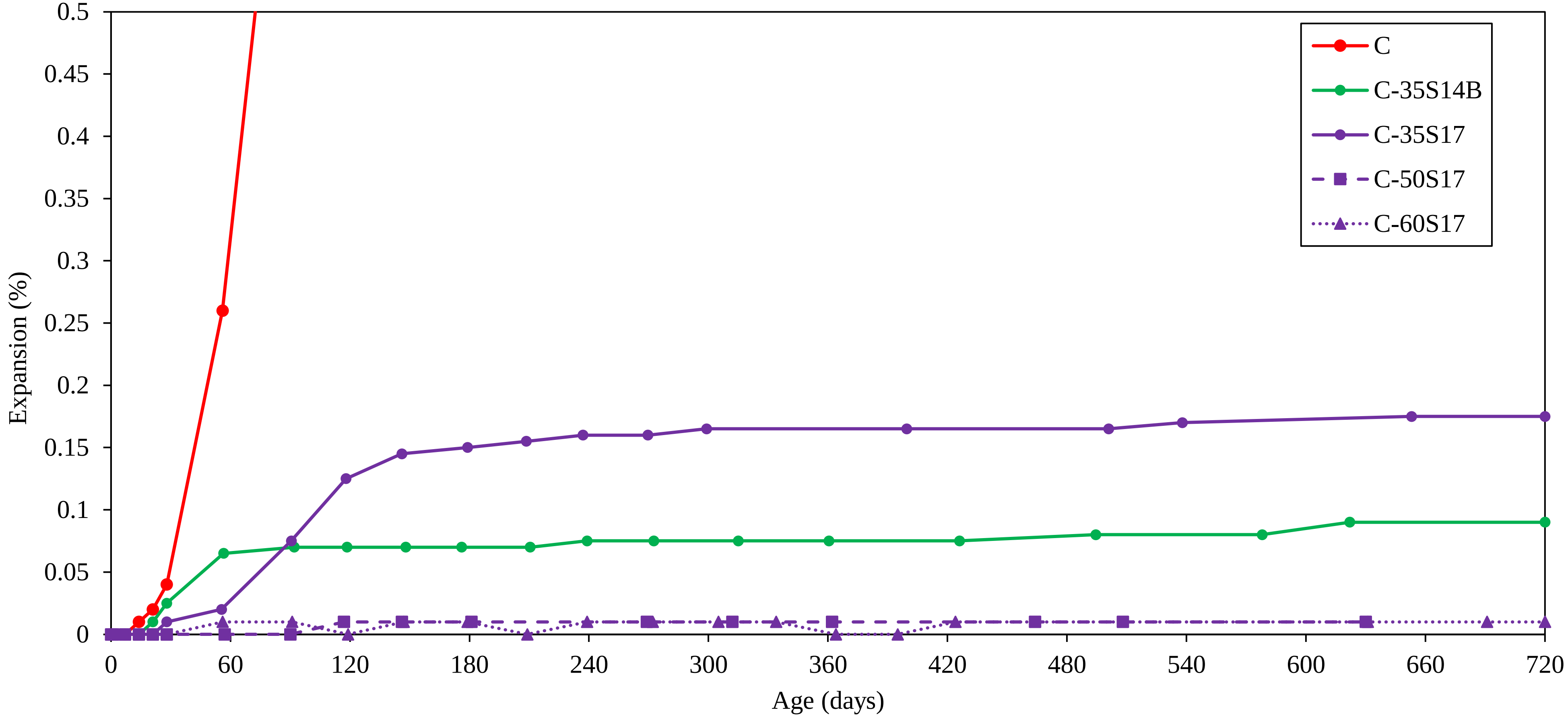
Phase transformation for S14 cementitious blends



Effect of residence time at maximum temperature (Slag Replacement 35%)

Slag	Expansion @180d (12 hours @95C)	Expansion @180d (24hours @95C)	Expansion @180d (36hours @95C)
S17	0.01	0.01	0.16
S14B	0.01	0.00	0.07

Effect of GGBFS Replacement Level on DEF



Recommendations

Based on the provided scientific evidence, the following recommendations are made:

1. For concrete elements subjected to temperatures between 158F-185F, modify Table 6.2.2.2 of ACI 201.2-23, to indicate a minimum GGBFS replacement level of 50% for ASTM C150/150M portland cements rather than "**Greater than or equal to 35% slag cement meeting the requirements of ASTM C989/C989M**"

2. Critical need to reassess recommendations in ACI Table 6.2.2.2 using current available cements and supplementary cementitious materials to ensure long term infrastructure durability

Questions