THE RELATIONSHIP BETWEEN LABORATORY AND FIELD EXPANSION – OBSERVATIONS AT THE KINGSTON OUTDOOR EXPOSURE SITE FOR ASR AFTER TWENTY YEARS

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Abstract

This paper reports on the performance of the Ontario Ministry of Transportation (MTO) outdoor exposure site for alkali-reactive concrete after 20 years and provides a summary of the various studies conducted at this site. This outdoor exposure site was established in Kingston, Ontario in 1991. The alkali-silica reactive aggregate was the Spratt siliceous limestone aggregate, which was used in six air-entrained concrete mixtures using various cements and supplementary cementing materials (SCMs). Blocks 0.6 x 0.6 x 2 m, and pavement slabs 0.2 x 1.2 x 4 m were cast. After 20 years, the field expansion of reactive concrete mixtures in unreinforced blocks exceeded the expansion measured in the laboratory at two years by an average of over 50%, indicating that the concrete prism expansion test conservatively estimates the long term expansion of reactive concrete mixtures. The accelerated mortar bar test expansion at an age of 14 days in solution was found to be a better predictor of long term performance of SCMs than the expansion measured at 28 days.

Keywords: alkali-silica reaction, preventative measures, outdoor exposure, Spratt aggregate, supplementary cementing materials

1 INTRODUCTION

The MTO outdoor exposure site was constructed in 1991 for two purposes: 1) to test the effectiveness of different combinations and amounts of SCMs to control or mitigate ASR and 2) to correlate short term lab testing with long term field performance. Concrete structures are typically expected to last for 75 years and often for longer. Prevention of reduced service life due to ASR in Ontario has traditionally been achieved through specifying the use of non-reactive aggregates. In future this approach may not be as sustainable with the decreasing availability of near market, good quality and non-reactive concrete aggregate sources. Correlation of short term laboratory testing with long term field performance is key to providing engineers with confidence that the selected measures to prevent ASR will work over the intended lifespan of a structure. MTO's outdoor exposure site attempts to bridge the gap between short term laboratory testing and actual long term field performance of structures. Field performance studies to confirm that the beneficial effects of SCMs observed in the laboratory carry into the future are few. Hooton, Rogers and Ramlochan (2008) [1], Rogers, Hooton and Ramlochan (2006) [2] and Rogers, Lane and Hooton (2000) [3] have

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previously reported on the 16-year, 14-year and 8-year performance of the site. This paper marks the 20-year anniversary of the site.

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2 EXPERIMENTAL DESIGN

2.1 Overview

Six concrete mixtures were made containing a variety of SCMs and cement types. Each of the mixtures is represented by one pavement slab and two beams, one of which is steel reinforced and the second not reinforced at the exposure site (Figure 1). These elements were chosen for demonstration because they simulate typical structures used in highway infrastructure. Three prisms were also cast of each mixture at the time of construction, stored appropriately at 38°C and measured following the requirements of CSA A23.2-14A [4]. It should be noted that these mixtures were not boosted by the addition of alkali as required by the current CSA concrete prism expansion test and have relatively low alkali contents. Accelerated mortar bar testing according to CSA A23.2-25A [5] was also conducted using the same reactive aggregate, cements and SCMs in proportions equivalent to the field concrete mixes.

Several additional studies have been conducted based in whole or in part on the Kingston outdoor exposure site: Afrani and Rogers (1994) [6] studied the effects of different curing regimes on the scaling resistance of each of the six mixtures; Nokken, Hooton and Rogers (2004) [7] reported on temperature data collected over a 5 year period from thermocouples that were placed at various depths into the concrete slab and unreinforced beam of Mixture 1; and most recently Shehata et al. (2008) [8] reported on the reactivity of reclaimed concrete aggregate produced from concrete affected by alkali silica reaction. To facilitate the latter study a spare beam of the most expansive mixture present at the site was sacrificed at 12 years of age.

2.2 Materials and mix designs

Aggregates

The alkali-silica reactive material used for the demonstration was the Spratt coarse aggregate from a quarry near Ottawa, Ontario. The Spratt aggregate consists of medium grey fine crystalline limestone of Middle Ordovician age. The slightly siliceous (9% SiO_2) nature of the material has made it an ideal aggregate for calibration and investigation of alkali-silica reaction expansion tests (Rogers and Hooton, 1991 [9]; Fournier and Malhotra, 1996 [10]; Bleszynski et al., 2000 [11]). The Spratt aggregate for this study was crushed in 1985 and placed in a 120-tonne stockpile. The stone was well graded from 20 to 5 mm and met all of the normal physical requirements for concrete aggregate.

The fine aggregate used in the field concrete and prisms consisted of a natural sand from a glacio-fluvial deposit near Seeleys Bay, Ontario. The sand was composed of igneous and high grade metamorphic rock particles and derived minerals and had a long history of satisfactory performance in concrete.

Cementitious Materials and Mixture Proportions

The five cementitious materials used in different combinations in this study were high-alkali Portland cement (HAPC), low-alkali Portland cement (LAPC), blended silica fume cement (SF) (CSA Type 10 SF), ground granulated blast furnace slag (GGBFS) and Type F fly ash (Type F FA). The proportions of cementing materials used in each mixture are shown in Table 1. Table 2 includes further details on the alkali content of the different cementitious materials as well as the proportions of cements, aggregates and SCMs used in each mix. Further information on the chemical and physical properties of the different cementing materials as well as the properties of the concrete mixtures was reported in Afrani and Rogers (1994) [6].

2.3 Construction and testing

Construction

Mixing and placement of the concrete mixtures occurred in September 1991. A concrete batching plant and transit mixer were necessary due to the quantity of concrete needed. Each mixture was batched in $3m^3$ loads. The plant was approximately 5 minutes travel time from the test site. A non-reinforced beam 0.6 x 0.6 x 2 m and a steel reinforced beam (steel area of 1.41%) of the same size and a 0.2 x 1.2 x 4 m pavement slab were cast from each mixture. The concrete was compacted and finished by professional concrete finishers. The pavement slabs and beams were cured with wet burlap and plastic sheets for 4 days after placement.

Instrumentation and test samples

Stainless steel bolts 100 mm long were placed vertically in the upper surface flush with the surface of the concrete of both the slabs and the beams before the concrete had set. Holes had been drilled in the end of each of the bolts to accept the measuring pins of a dial gauge measuring device with a nominal length of 508 mm readable to 0.0001 inch (0.0025 mm). Six measuring stations were set on the surface of each beam and six measuring stations on the surface of each slab.

Three concrete prisms (75 x 75 x 400 mm) were also cast at the time of construction from each mixture. The prisms were demoulded after three days and the initial length measured. After measuring the beams were individually wrapped in paper towels and placed in a sealed plastic bag with 100 ml of water. The beams were then placed on racks in sealed boxes with water on the bottom and stored at 38°C. Accelerated mortar bar testing (CSA A23.2-25A) was also conducted using the Spratt coarse aggregate crushed to sand size. Each mortar mixture carefully replicated the field concrete mixtures with the same proportions of cements and SCMs. The water to cementitious materials ratio for all mortar mixtures was set at 0.50. Mortar bar test results are summarized in Table 3.

2.4 Monitoring and measurement

One week following casting and after the concrete had cooled to ambient temperature, initial measurements were taken of the length of the pavement slabs and beams. Measurements were taken three times on different days to ensure that errors had not occurred. Thereafter, measurements have been taken on a yearly basis close to the anniversary date of construction. The concrete prisms stored at 38°C were measured following the requirements of CSA A23.2-14A at various ages up to one year and yearly thereafter up to ten years.

The temperature and microclimate of the exposure site was also monitored using a data logger and thermocouples. Temperature was measured at depths of 50 mm, 150 mm and 300 mm in the concrete every hour for 10 years, as well the air temperature was measured at 150 mm above the slab. The climate of the site is moderately severe with many freeze-thaw cycles every winter and an average annual precipitation of 800 mm. The data collected indicates the concrete undergoes many freeze-thaw cycles every winter depending on the depth in concrete and what criteria is used to define a freeze temperature. Further details of this study can be found in a paper by Nokken, Hooton and Rogers (2004) [7].

After 12 years, a series of 100 mm diameter cores were taken from each slab and beam for each concrete mixture. The cores were subjected to a variety of testing including: petrographic analysis through thin section microscopy and scanning electron microscopy using back-scattered imaging and energy-dispersive X-ray analysis, depth of carbonation, damage rating index, chloride bulk diffusion, permeability index, and de-icer chloride penetration. The results of this 12-year coring and testing are described in previous studies [1,2].

3 RESULTS

Expansion of the concrete prisms at 38°C for each of the six different mixtures up to an age of 10 years is shown in Figure 2. Mixture 6, as expected, clearly shows the highest expansions and with most of the expansion occurring in the first (75%) and second (86%) years. The rate of expansion slowed significantly between years 1 and 2 (0.002% expansion/year) and then again between years 2 and 6 (0.005% expansion/year). Measurements taken between years 6 and 10 show further decrease in the rate of expansion of mixture 6 prisms (0.001% expansion/year) with a flattening trend on the graph (Figure 2). The rates of expansion were comparable for all mixes between years 1 and 2. Between years 2 and 6 and years 6 to 10 mixtures 1 through 4 behaved most similarly (Figure 2). Expansion of mixture 5 was comparable to mixtures 1 through 4 until year 4. Beyond year 4 the rate of expansion of mixture 5 increased suggesting the use of LAPC with no other mitigation measures delayed the onset of expansion in the short term. Although the 10 year expansion value for the mixture 5 prisms is close to that for mixture 3 (Figure 2), the rate of expansion between years 4 and 10 increased slightly as compared with the other mixtures. Due to the flattening trends and subsequent lack of additional expansion, the experiment was discontinued at 10 years.

Expansion of the unreinforced and reinforced concrete beams and pavement slabs at the exposure site for all six mixtures up to an age of 20 years is shown in Figures 3 to 5 respectively. No correction has been made in the data for thermal expansion effects caused by taking annual measurements at the exposure site at slightly different ambient temperatures each year. As a result the curves are not smooth, however the error was judged to be small. As can be seen from Figures 3-5 expansion of mixture 6 started after 2 years in the exposure site.

The expansion trends for mixtures 2, 3 and 5; and 1 and 4 are similar in both the unreinforced and reinforced blocks after 5 years of age (Figure 3). Expansion trends for all mixtures in Figure 4 are more tightly constrained and roughly parallel, particularly between years 8 and 20. Comparison of expansion trends in Figures 3 and 4 in particular highlight how the reinforcing steel has depressed the rate of expansion in all mixtures 2, 3, 5 and 6. Expansion trends of mixtures 1 and 4 are similar between the two graphs due to the lower amounts of expansion in both reinforced and unreinforced beams.

Figure 6 further shows how the presence of 1.41% by area of longitudinal steel reinforcement has restrained the expansion by 42% of that of the non-reinforced beams of mixture 6 at 20 years. A significantly greater reduction of expansion of between 65 and 70% was reported by Hobbs (1988) [12] who used 0.91% steel reinforcement in his study. The unrestrained expansion reported by Hobbs [12] was also significantly greater (0.5-0.8% at approximately 100 days) using an artificial reactive aggregate under laboratory conditions. Compared to real field conditions where greater creep may be expected, the reported restraint may be unrealistic [1,2,3].

Visible cracking was observed at 5 years in both the unreinforced and reinforced beams of mixture 6, while visible cracking in the pavement slab of mixture 6 was not obvious until year 12. By 7 years, pattern cracking was reported as obvious on all exposed beam surfaces of mixture 6 [1,2,3]. Currently at 20 years, map pattern cracking is pronounced in all concrete elements composed of mixtures 5 and 6. Maximum open crack width for unreinforced and reinforced beams of mixture 6 was measured at 3 mm wide. Most cracks present have distinct staining that presents as an orangey to beige coloured halo surrounding the crack opening that is 1 mm to >1 cm in width. Locally dark grey to grey brown or white material is found infilling the cracks that are possibly a reaction product. Maximum open crack width observed in the mixture 5 reinforced beam was ≤ 1 mm and was associated with orangey stained haloes up to 1 cm wide.

The map cracking patterns observed in the pavement slabs of mixtures 5 and 6 at 20 years are distinctly different. The cracks present in mixture 5 tend to be narrower (fine hairline cracks <0.01 mm wide) and more closely spaced (2 to 5 mm domains) in comparison with mixture 6. The cracking pattern of the mixture 5 pavement slab most closely resembles an elephant or alligator skin-like appearance with a high density network of evenly distributed microcracks throughout the slab. In contrast the cracking pattern of the mixture 6 pavement slab consists of both a microcrack network as well as a system of wider cracks that are more distantly spaced (4 to 10 cm). The microcrack network or alligator skin texture is less prominent or less well distributed with mixture 6 in comparison with mixture 5. The larger crack network in the mixture 6 pavement slab appears more like the traditionally described ASR-related map pattern cracking with wider cracks, associated haloes and staining, and resembles the map cracking observed in the beams of mixtures 5 and 6. The slower, more controlled rate of expansion in mixture 5 may have led to the more evenly distributed pattern of smaller cracks in contrast to mixture 6 which experienced a faster rate of expansion (>85% of it's total expansion was achieved in the first two years). The faster rate of expansion likely resulted in more focussed failures on larger single cracks.

Minor to moderate intensity map cracking was also observed at 20 years in both the unreinforced and reinforced beams of mixtures 3 and 2. Maximum open crack width was measured at <<1 mm on the upper surface toward the east side of the blocks. Orangey staining and haloes around cracks similar to beams 5 and 6 was also observed.

Weak hairline cracking was also observed on the edges of the upper surface of reinforced beam for mixture 4. This feature may not necessarily be due to ASR, localized shrinkage cracking is a possibility.

Figure 7 shows the relationship between mortar bar expansion and expansion of prisms at 2 and 10 years as well as pavement slabs and reinforced and unreinforced beams at 20 years of age.

4 CONCLUSIONS

The concrete made with high-alkali cement cracked at an age of 5 years. Where the high-alkali cement was replaced with various amounts of SCMs, expansion has been considerably less but cracking has occurred in some cases. The following materials have been shown to be less effective at reducing long term damage: 25% ground granulated blast-furnace slag, 18% Type F fly ash, and low-alkali cement (<0.6% Na_2O_e). The most effective measures for control of ASR cracking and expansion were 50% ground granulated blast-furnace slag and a ternary blend of 25% slag plus 3.8% silica fume interground with a high-alkali Portland cement. Of these two concrete mixes, the one that also exhibited superior de-icer salt-scaling resistance was the ternary blend. Monitoring of the outdoor exposure site will continue indefinitely.

5 REFERENCES

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TABLE 1: Cementing materials used in the concrete mixtures [1,2,3].

Mixture number	Cementing materials, % by mass
1	50% high-alkali Portland cement and 50% granulated blast-furnace slag
2	82% high-alkali Portland cement and 18% type F fly ash
3	75% high-alkali Portland cement and 25% granulated blast-furnace slag
4	24% high-alkali Portland cement, 51% silica fume cement containing 7.5% silica fume and 25% ground granulated blast-furnace slag, for a total silica fume content of 3.8% by mass of binder
5	100% low-alkali Portland cement
6	100% high-alkali Portland cement

TABLE 3: Accelerated mortar bar expansion data (CSA A23.2-25A) [1,2,3].

Mixture number	Mortar bar expansion in per cent			
	14 day	21 day	28 day	14 day duplicate
1	0.059	-	-	-
2	0.111	0.171	0.249	0.118
3	0.187	-	-	-
4	0.041	0.089	0.153	-
5	0.435	0.484	0.553	0.471
6	0.315	0.378	0.480	0.330

TABLE 2: Concrete mixture designs, binder alkalies and hardened concrete properties [1,2].

	Description	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Portland Cement	High-alkali, kg/m^3, 0.79% Na_2O_e	207.5	350.6	311.3	100.4	-	415
	Low-alkali, kg/m^3, 0.46% Na_2O_e	-	-	-	-	415	-
Silica fume	Silica-fume cement, kg/m^3, 0.88% Na_2O_e, Note 1	-	-	-	210.8	-	-
Slag	Granulated blast-furnace slag, kg/m^3, 0.66% Na_2O_e	207.5	-	103.8	103.8	-	-
Fly ash	Type F, kg/m^3, 0.27% Na_2O_e	-	77.0	-	-	-	-
Total binder	kg/m^3	415	427.6	415.1	415	415	415
Fine aggregate	Natural sand, kg/m^3 + 3% moisture	622	606	628	622	636	636
Coarse aggregate	Spratt quarry, kg/m^3 + 1% moisture	1152	1152	1152	1152	1152	1152
Strengths	Effective w/cm	0.38	0.37	0.39	0.34	0.40	0.39
27 day	Compressive strength, MPa Splitting tensile, MPa	40.0 3.7	39.0 3.4	41.8 3.8	47.9 4.0	39.6 3.8	35.6 3.5
82 day	Compressive strength, MPa Splitting tensile, MPa	44.9 3.9	50.0 3.8	42.7 4.3	52.8 4.1	46.2 4.3	44.3 3.8
1 year	Compressive strength, MPa Splitting tensile, MPa	49.7 3.8	52.4 4.3	50.9 3.3	63.2 4.8	54.2 3.4	49.2 3.2
7.25 year	Compressive strength, MPa Splitting tensile, MPa	58.5 3.6	60.4 3.8	59.0 3.7	61.8 3.6	62.2 4.4	57.9 3.5
Alkali content	Kg/m^3 Na_2O equiv. of mix, Note 2	3.01	2.98	3.14	3.33	1.91	3.28

Note 1: Portland silica fume cement (CSA Type 10 SF) contained 7.5% silica fume for an effective silica fume content of 3.8%.
Note 2: No alkali such as NaOH or KOH was added to any mixture ; the alkali values given are of those of the cement and SCM.
" – ": Not present.

FIGURE 1: Kingston outdoor exposure site summer 2005.

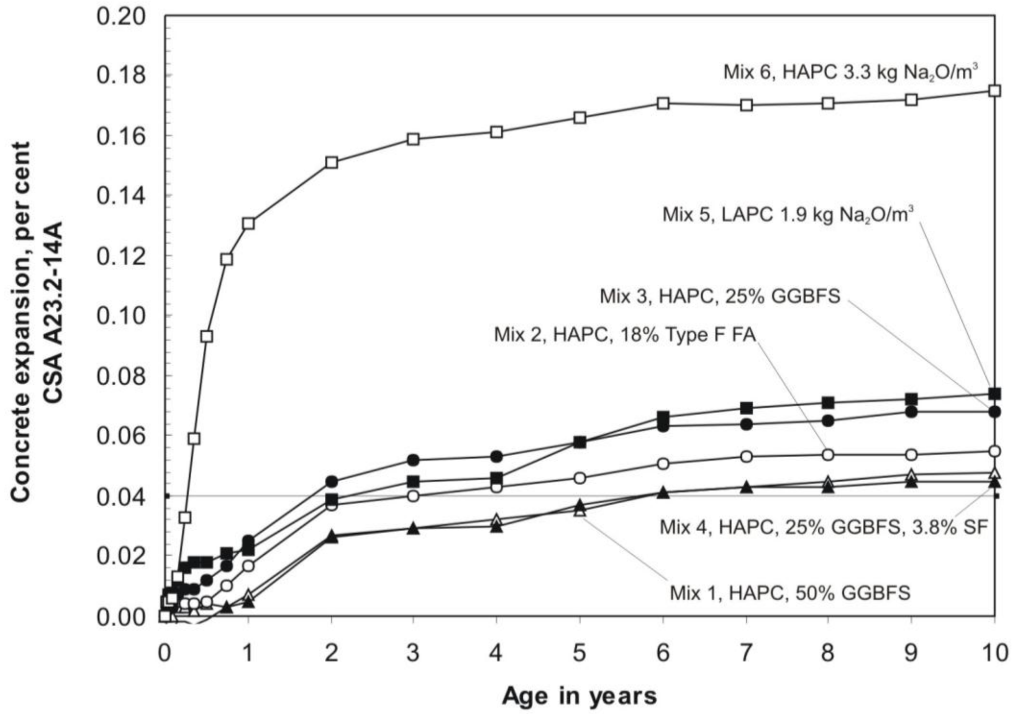

FIGURE 2: Expansion of concrete prisms in the laboratory at 38°C.

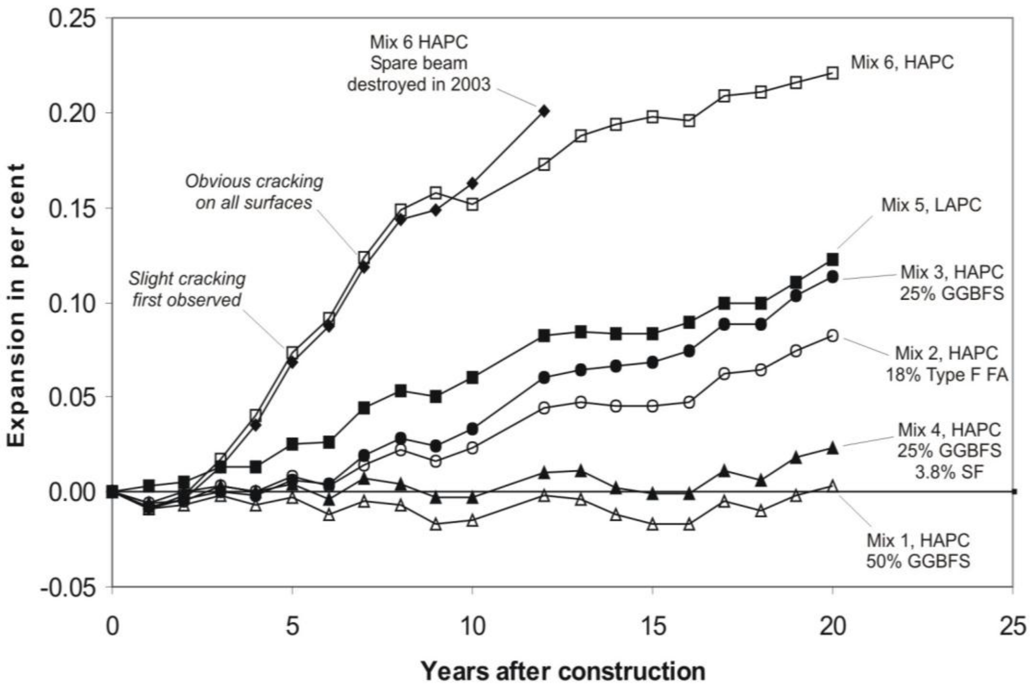

FIGURE 3: Expansion of outdoor exposed unreinforced concrete beams.

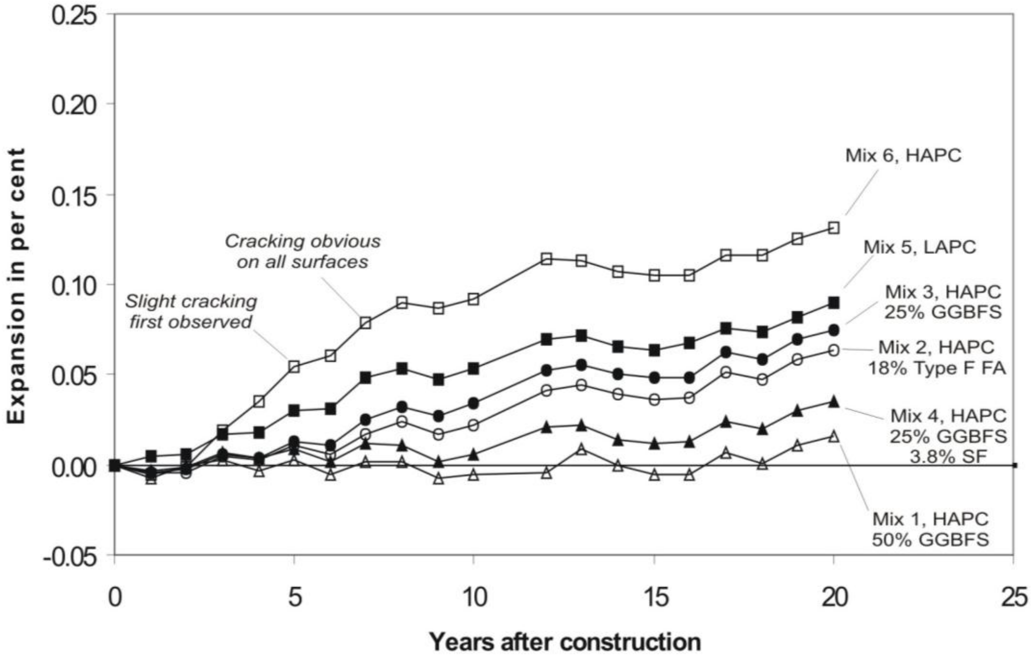

FIGURE 4: Expansion of outdoor exposed reinforced concrete beams.

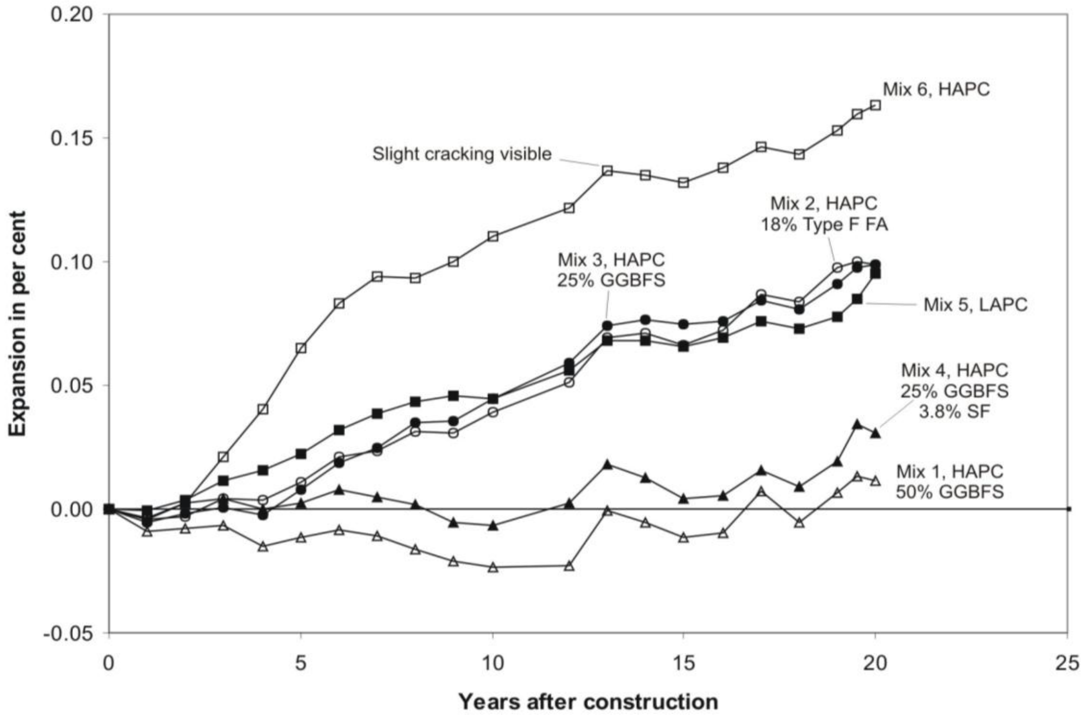

FIGURE 5: Expansion of outdoor exposed concrete pavement slabs

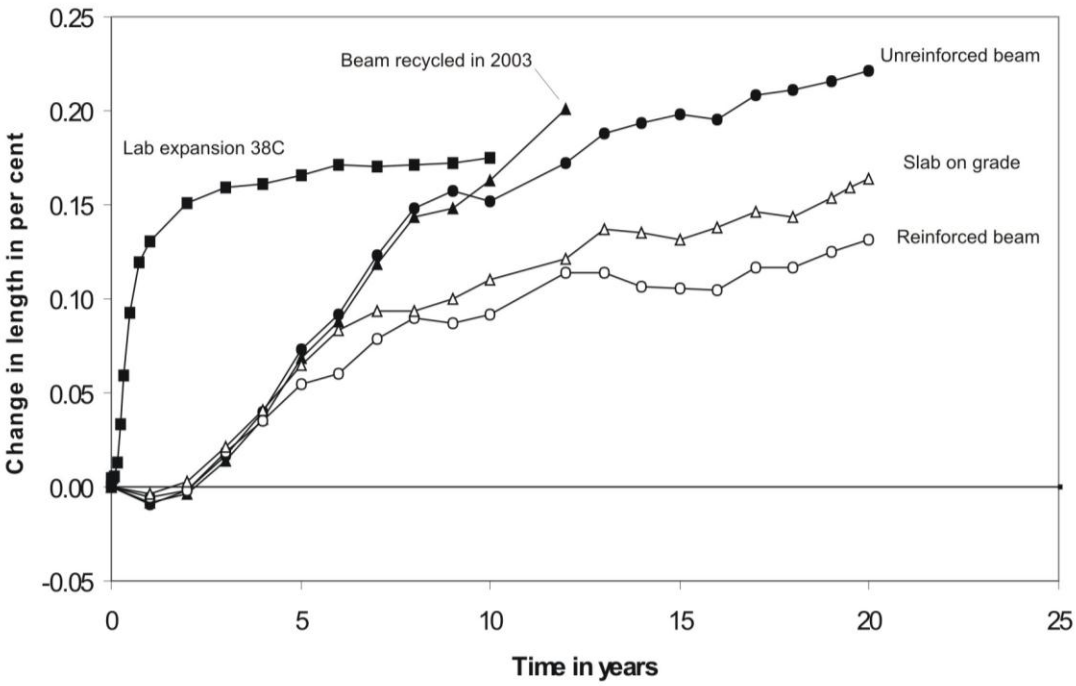

FIGURE 6: Expansion of mixture 6 (high-alkali cement) in various elements.

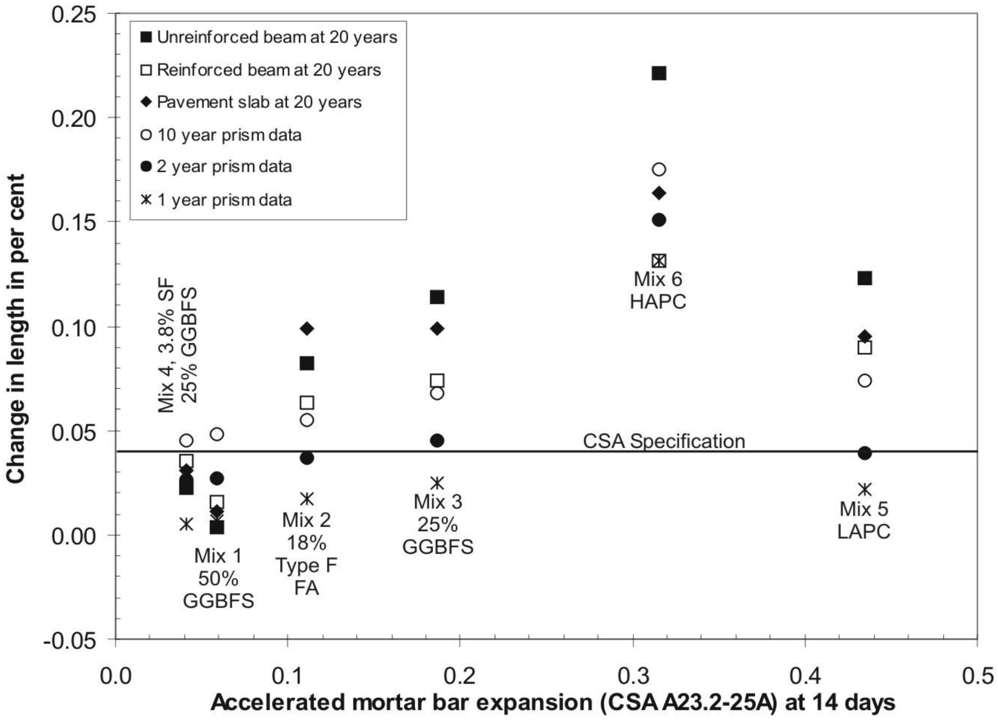

FIGURE 7: Mortar bar expansion versus concrete field expansion at 20 years.