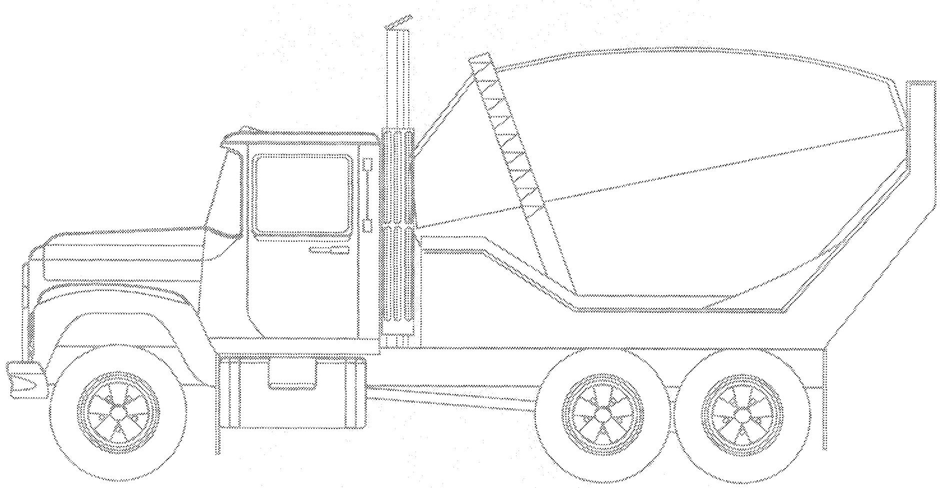
FINAL REPORT

EFFECTS OF BLENDS OF CEMENT KILN DUST AND FLY ASH ON PROPERTIES OF CONCRETE



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Effects of Blends of Cement Kiln Dust and Fly Ash on Properties of Concrete

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Abstract

This study evaluated concretes containing cement kiln dust (CKD) and fly ash to determine whether satisfactory properties can be achieved for long-lasting performance in the field. The results indicate that certain combinations of cement, CKD, and fly ash may provide concretes with acceptable performance. A determination of acceptable combinations will require extensive study which was beyond the scope of this project.

Excessive expansions occurred when CKD blends were used in mortars subjected to cyclic wetting and drying at a temperature of 80^0C (176^0F). The addition of CKD to fly ash concrete did not improve strength development, but did reduce the coulomb values (AASHTO T277 or ASTM C 1202) at early ages, indicating reduced chloride permeability. However, at later ages fly ash concretes containing cement with an alkali content of 0.70% or above had very low coulomb values indicating high resistance to chloride penetration irrespective of the alkali activation.

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ABSTRACT

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INTRODUCTION

Cement kiln dust (CKD) is a by-product of the production of portland cement.[1] Some CKD is recycled through the cement production process at the plant, but the amount is limited because of its effect on the chemical composition of the cement. Large amounts of CKD remain for which a suitable use must be found to avoid costly disposal. If CKD can be used in hydraulic cement concrete, economic and environmental benefits would accrue. However, as with any material in the production of concrete, it is important that the properties of the concrete should not be adversely affected.

CKD is a highly variable material. It contains free lime or carbonated lime and raw feed minerals, which are not effective in developing strength. Studies have shown that concretes in which a portion of the cement was replaced with CKD achieve lower compressive strengths than straight portland cement concretes.[2,3] CKD also contains varying amounts of alkalies, sulfates, and chlorides, which may lead to durability problems. The alkali content of concrete is a serious concern because of the deterioration caused by alkali-aggregate reactions. When longevity is needed, steps should be taken to minimize the potential for alkali-related distress. Some of these drawbacks related to durability may be overcome by blending CKD with a pozzolanic material such as fly ash.[4,5] Because of their increased alkali content, concretes containing CKD may have more rapid strength gain and a reduction in permeability when combined with fly ash as a replacement for cement. However, there is a justifiable concern about the trade-off between the possible short-term benefits of increased alkali content and the potential for detrimental effects on long-term durability. In Europe, in order to ensure a service life of 100 years, cements with a low alkali content are used in combination with pozzolanic materials.[6]

PURPOSE AND SCOPE

This study evaluated concretes containing blends of fly ash and CKD to determine whether satisfactory properties and durability can be achieved. Durability studies were limited to the determination of chloride permeability (AASHTO T 277), resistance to alkali-silica reactivity, and resistance to sulfate attack. Concrete and mortar batches containing various combinations of portland cement, Class F fly ash, and CKD were prepared and tested in the laboratory.

MATERIALS

Three cements of varying alkali content were used. Their chemical composition is given in Table 1. CKD was obtained from a plant at two different times and designated as CKD1 and CKD2. Class F fly ash from one source was used. The analyses for the CKD and fly ash are given in Table 2. Blends of fly ash and CKD (FA/CKD) were prepared in the laboratory. Also, two samples of commercially available material, pre-blended at different fixed ratios of FA/CKD (70/30 and 45/55) were included. The chemical and physical analyses for these blends are given in Table 3. These blends contained ingredients obtained from the same sources as the laboratory blends. At present, certain commercial blends of FA/CKD are allowed by VDOT. The specified replacement rate when using these materials is 40% or more to replace 35% by mass of portland cement in the concrete mixture.

Table 1: Analysis of Cements (%)

	Type I/II (R)	Type I/II(ST)	Type I (S)
SiO2	21.0	20.7	20.4
Al2O3	4.4	4.6	4.9
Fe2O3	2.9	3.5	2.0
CaO	63.7	66.0	62.3
MgO	2.8	1.1	3.9
SO3	2.5	2.3	3.3
Na2O	0.21	0.1	- -
K2O	0.66	0.1	- -
C3S	56.7	65.5	- -
C2S	17.4	9.8	- -
C3A	7.59	7.6	9.6
C4AF	8.84	10.6	- -
NaEq	0.64	0.18	0.92
Loss on Ignition	1.05%	1.6	2.05%
Blaine	3883	3883	- -

Table 2: Analysis of CKD and Fly Ash (%)

	CKD1	CKD2	Fly Ash
SiO2	20.6	14.0	54.4
Al2O3	5.3	3.2	25.1
Fe2O3	3.1	1.4	7.7
CaO	54.6	32.8	5.6
MgO	2.6	2.6	1.6
SO3	7.1	9.6	0.6
Na2O	0.5	0.48	0.4
K2O	3.4	7.05	3.2
NaEq	2.7	5.11	2.5
Loss on Ignition	14.1	14.9	1.6
Moisture	- -	- -	0.1%

Table 3: Analysis of FA/CKD blends (%)

	70/30	45/55
SiO2	45.7	32.2
Al2O3	21.7	18.3
Fe2O3	6.4	5.3
CaO	17.3	27.2
MgO	1.7	1.9
SO3	2.3	3.5
Na2O	0.55	0.31
K2O	3.83	2.64
NaEq	3.07	2.04
Loss on Ignition	8.6	---
Moisture	0.08	0.11
Fineness(-325)	79.0	76.3
Specific Gravity	2.41	2.53

Aggregates susceptible to alkali-silica reactivity (ASR) used in the study were a metamorphosed rhyolite and a natural siliceous sand containing chert. The dry-rodded unit weight of the reactive coarse aggregate was 55.3 kg/m^3 (93.2 lb/yd^3) and the specific gravity was 2.67. The natural sand had a fineness modulus of 2.7 and a specific gravity of 2.58. A crushed dolomitic limestone that has not exhibited ASR in the field was also used in some concrete batches as a non-reactive aggregate. The dry-rodded unit weight of the limestone coarse aggregate was 58.9 kg/m^3 (99.2 lb/yd^3) and the specific gravity was 2.81. The limestone fine

Table 4: Mortar batches for ASR

Batches	PC	Alkali Cont.	CKD[a]	Fly Ash	FA/CKD[b]
1	100	0.40			
2	100	0.60			
3	100	0.70			
4	100	0.92			
5	65	0.40	20*	15	
6	85	0.40		15	
7	65	0.60	10	25	
8	65	0.60	20	15	
9	90	0.70	10		
10	75	0.70	5*	20	
11	65	0.70	10	25	
12	65	0.70	20	15	
13	85	0.70		15	
14	80	0.70		20	
15	75	0.70		25	
16	90	0.92	10		
17	65	0.92	10	25	
18	65	0.92	20	15	
19	65				70/30
20	65				45/55

[a] An * indicates that only CKD1 was used. The remaining batches were duplicated using CKD2.
[b] 45% of the FA/CKD blend replaced 35% of portland cement (PC).

aggregate had a fineness modulus of 3.0 and a specific gravity of 2.80. The nominal maximum size of coarse aggregates was 25 mm (1 in).

METHODOLOGY

Mortar

To evaluate the effect of using CKD and FA/CKD blends on ASR, specimens made from mortar batches having different combinations of cementitious material as given in Table 4 were tested in accordance with ASTM C 441. The expansion of the specimens was measured periodically for a period of 336 days. Four alkali contents were used for the controls: 0.40, 0.60, 0.70, and 0.92. To obtain alkali contents of 0.40 and 0.70, portland cements were blended. The experimental mixtures contained cement with CKD or cement with blends of FA/CKD.

For sulfate resistance, two test procedures were used. In one, the resistance to sulfates from external sources was evaluated in accordance with ASTM C 1012. In this procedure, the change in length of mortar bars prepared with the four cementitious material combinations given in Table 5 and exposed to a 5% Na_2SO_4 and 5% $MgSO_4$ solution was measured. In the other test procedure, the combined effects of internal sulfate attack and ASR were evaluated by determining the change in length of specimens stored in water at room temperature after being subjected to an initial period of cyclic wetting and drying at elevated temperatures. This procedure was adapted from ASTM C 342 and the Duggan test.[7] Nine cementitious material combinations (Table 5) were used. The test procedure is called modified ASTM C342 and is summarized in the Appendix.

Table 5: Cementitious Material Combinations for the Sulfate Tests

Batch	ASTM C1012	ASTM C342 + Duggan
1	Type I (S)	Type I (S)
2	Type I/II (R)	Type I/II (R)
3	15% FA + 20% CKD1	15% FA
4	15% FA + 10% CKD1	20% CKD2
5		15% FA + 20% CKD2
6		15% FA + 10% CKD2
7		20% CKD1
8		15% FA + 20% CKD1
9		15% FA + 10% CKD1

Mixtures with FA or CKD were prepared using Type I(S).

Concrete

Concrete batches were prepared using the cementitious material combinations given in Table 6. The coarse aggregate in all batches except B14-B16 was a crushed metarhyolite. Batches B14-B16 contained crushed dolomitic aggregate. A natural siliceous fine aggregate was used in batches containing the metarhyolite; whereas, the fine aggregate in the batches made with the crushed dolomitic limestone was manufactured from the same rock. All batches had an equal mass of cementitious material 377 kg/m^3 (635 lb/yd^3) except B9, B10, B25, and B26, which contained commercial blends of FA/CKD, and all batches had the same W/CM of 0.45. When the commercial blends of FA/CKD were used, 45% replaced 35% of portland cement by mass. In B9 and B25, the 70/30 (FA/CKD) blend was used, and in B10 and B26, the 45/55 blend was used. Two portland cements were blended to obtain 0.40 and 0.70 alkali content, and in some batches, 1N NaOH solution was added to the mixing water in concretes containing the portland cement with the high alkali content to increase the effective alkali content to 1.25% by mass of portland cement. The different alkali contents used are given in Table 6.

The freshly mixed concrete was tested for slump (ASTM C 143), air content (ASTM C 231, pressure method), and unit weight (ASTM C 138). Concrete cylinders measuring 100 by 200 mm (4 by 8 in) were fabricated from each batch. Cylinders were tested for compressive strength at 3, 7, and 28 days in accordance with AASHTO T 22 using neoprene pads in steel end caps, and they were tested for splitting tensile strength at 28 days (ASTM C 496). Concrete cylinders 100 by 100 mm (4 by 4 in) were cast for a permeability test (AASHTO T 277 or ASTM C 1202). These cylinders were sawed in half and the top 100 by 50 mm (4 by 2 in) was tested at 28 days and 1 year. Length-change prisms measuring 75 by 75 by 285 mm (3 by 3 by 11.25 in) were also made to measure the expansion of the concretes. Two beams were stored moist at 38°C (100° F), and two were stored moist at 80°C (176° F). The beams were measured periodically for change in length.

RESULTS AND DISCUSSION

Mortar

The results of the ASTM C 441 testing for the effectiveness of mitigating ASR are displayed in Figures 1 through 4 for 56 days and 336 days. The data in Figures 3 and 4 were normalized to the regression line of expansion on alkali content for the control batches. Normalizing corrects for the variability between control batches with the same alkali content.[8] Figures 1 and 2 display the expansion of control specimens containing portland cements with varying alkali content at ages of 56 and 336 days. These data were part of a concurrent project evaluating the ability of fly ash, slag, and silica fume to inhibit ASR.[8] In that study, the control mixtures showed a linear relationship between the alkali content and the expansion as the alkali content exceeded 0.40%. The correlation coefficient (r) was 0.910 for 56-day data and 0.906 at 1 year. For alkali contents up to 0.40%, the expansion was negligible. It was recommended that

Table 6: Cementitious Materials in Concrete (%)

#	Cem. Alk. (%)	PC	CKD[a]	FA
1	0.70	100	0	0
2	0.70	75	5	20
3	0.70	75	10	15
4	0.70	65	10	25
5	0.70	65	20	15
6	0.70	85	0	15
7	0.70	80	0	20
8	0.70	75	0	25
9[b]	0.70	65	13.5	31.5
10[c]	0.70	65	24.75	20.25
11	0.40	100	0	0
12	0.40	65	20	15
13	0.40	85	0	15
14[d]	0.70	100	0	0
15[d]	0.70	65	20	15
16[d]	0.70	85	0	15
17	1.25	100	0	0
18	1.25	75	5	20
19	1.25	75	10	15
20	1.25	65	10	25
21	1.25	65	20	15
22	1.25	85	0	15
23	1.25	80	0	20
24	1.25	75	0	25
25[b]	1.25	65	13.5	31.5
26[c]	1.25	65	24.75	20.25
27	0.70	75	10	15
28	0.70	65	10	25
29	0.70	65	20	15
30	0.40	65	20	15
31	0.70	90	10	0
32	0.40	90	10	0

[a] Batches 27-30 contained CKD2; remaining batches had CKD1.
[b] FA/CKD blend (70/30)
[c] FA/CKD blend (45/55)
[d] Contained nonreactive aggregates (Batches 14-16); remaining batches had reactive aggregates.

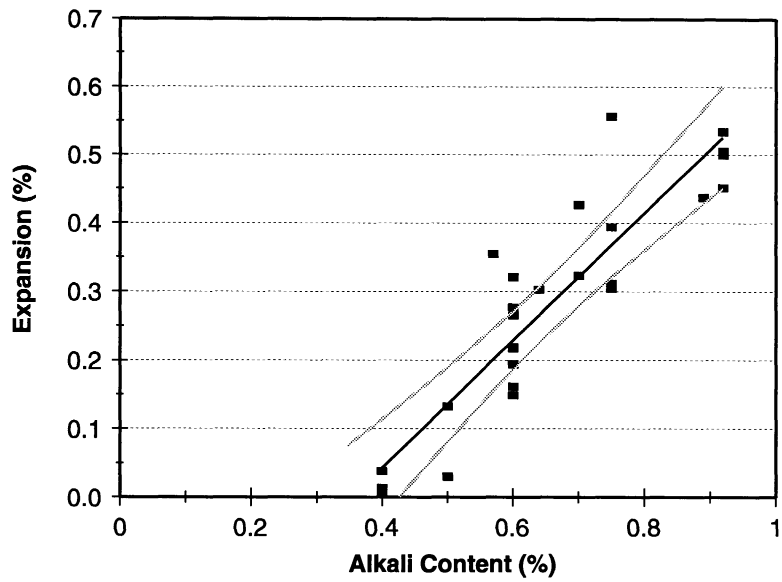

Figure 1. Control mortars at 56 days (regression with 95% confidence limits).

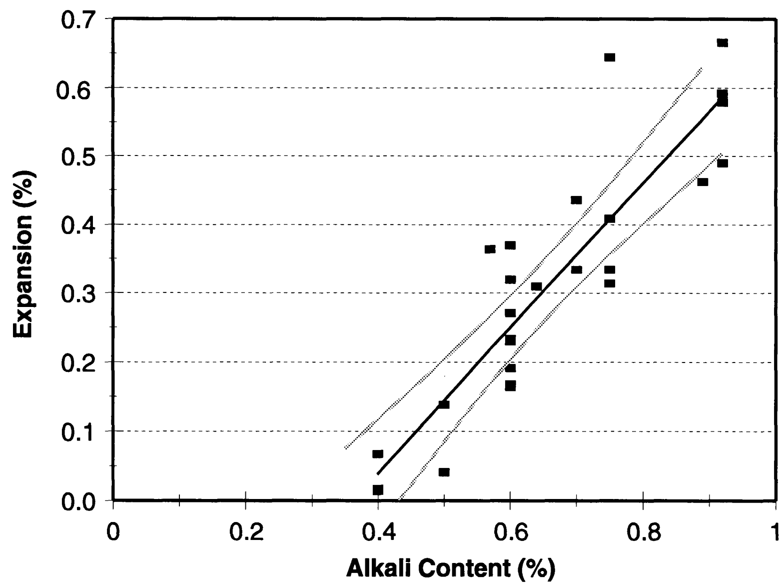

Figure 2. Control mortars at 336 days (regression with 95% confidence limits).

0.10% be established as the maximum permissible expansion for mixtures providing acceptable performance in preventing excessive expansions due to ASR.

Figures 3 and 4 display the expansion of the experimental mixtures containing CKD, FA/CKD blends, and fly ash at the same ages. This data is presented in tabular form in Appendix B. The regression line for portland cement control batches is also plotted on the

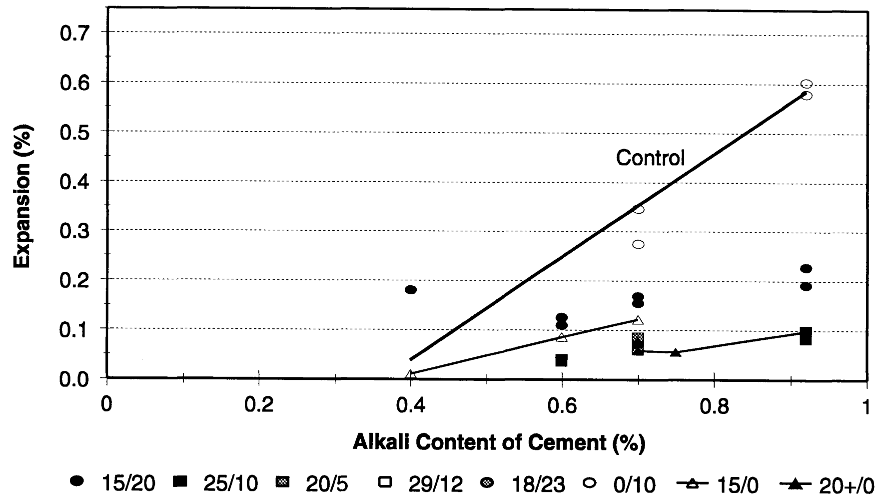

Figure 3. Expansion data for FA/CKD blends at 56 days. Regression line for controls (portland cement only) and lines connecting fly ash data are also shown.

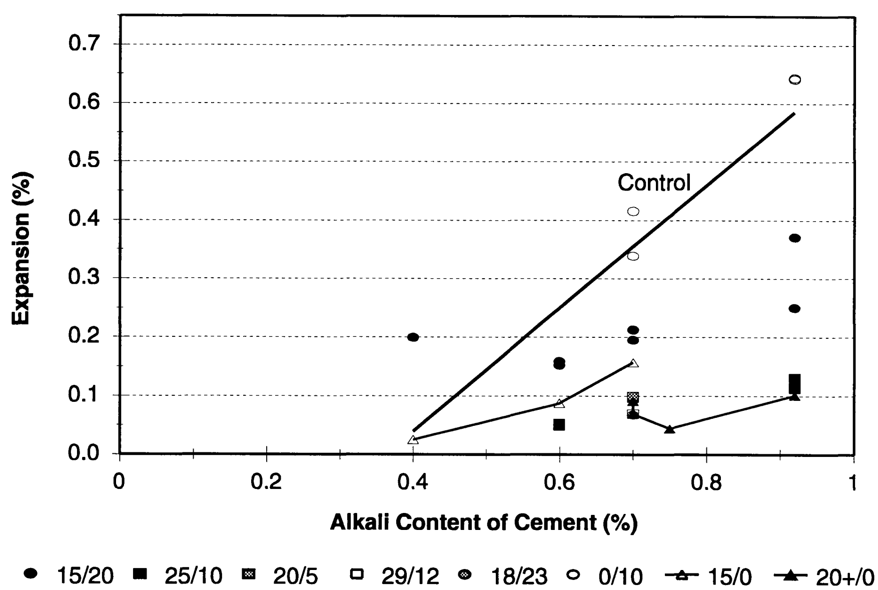

Figure 4. Expansion data for FA/CKD blends at 336 days.

figures. The expansion of batches where CKD (0/10) alone was used to replace cement was fairly close to the expansions of the control batches and was much higher than the expansion of batches containing fly ash at the same cement alkali level. At 56 and 336 days, the expansion of mortars containing 15% fly ash with 20% CKD (15/20) increased slightly with increasing cement alkali content, compared to the control batches. The expansions were less than that of the controls for cement alkali contents of 0.60% or above, but much higher than the control at 0.40% alkali content. By the 14 day measurement, the expansion of all batches with the 15/20 replacement of cement exceeded the limit of 0.1%; whereas expansions of batches with 15% FA replacement (15/0) remained below the 0.1% limit through 336 days with cements having alkali contents of 0.60% and below.

Mortars containing 25% FA with 10% CKD (25/10) also had expansions which increased slightly with increasing cement alkali content, but at a lower expansion level than the 15/20 batches. Expansions of the 25/10 batches were under 0.10 % when combined with the 0.60% alkali cement through the 336 day period. With the 0.70% alkali cement, the 25/10 combination, as well as the 20/5 were just at 0.1% expansion. Expansions of mortars with 25% FA replacements (25/0) of the 0.70% and 0.75% alkali cement remained below the 0.1% limit through 336 days. When combined with the 0.92% alkali cement, both 25/10 combinations (CKD1 and CKD2) exceeded 0.10 percent expansion; whereas the 35% FA (35/0) had an expansion just at 0.1%.

The 41% replacements of the 0.70% alkali cement with the 70/30 and 45/55 (equivalent 29/12 and 18/23) FA/CKD blends had virtually identical expansions which did not exceed the 0.1% expansion limit at 336 days. The results from the other tested combinations suggested that a combination having a higher percentage of CKD than fly ash would yield a higher expansion. These expansions are comparable to that of the 25/0 combination with the 0.70% alkali cement. Although the 45/55 (18/23) blend yielded an expansion much less than the roughly equivalent 15/20 blends, insufficient data is available to determine if the differences in expansion are real; and, if so, the reasons for the differences.

The variable results with respect to acceptable performance of the different combinations of CKD, fly ash, and cement alkali content suggest the importance of the chemical composition of the mixture on the potential for ASR. The chemical composition of the mixture is a function of the composition of the individual constituents (cement, fly ash , and CKD) as well as their relative amounts in the mixture. These compositional effects are rather complex, and the determination of parametric limits that would ensure acceptable performance is beyond the scope of this study.

The results of sulfate tests (ASTM C 1012), which measured the length change of mortar bars exposed to 5% Na_2SO_4 and 5% MgSO4 solution up to an age of 336 days, are summarized in Figure 5. In this test, the acceptance criterion used was a maximum expansion of 0.1% at 6 months for moderate sulfate resistance, and an expansion of 0.05% at 6 months for high sulfate resistance. Among the 4 mortar batches, only the control batch (B1), which contained Type I (S) cement, exceeded 0.05% at 6 months indicating moderate resistance to external sulfate attack. The Type II (R) control and the mixtures with combinations of the Type I (S) with CKD and fly ash had expansions within the acceptable range for high sulfate resistance.

The modified ASTM C 342 test (Appendix A) indicates the sulfate and ASR resistance of mixtures through a length change of specimens up to 1 year when exposed to high temperatures and an initial period of cyclic drying and wetting. The results of this test are given in Figure 6 and Figure 7. In Figure 6, showing the results of tests conducted with the heating cycle at 54° C

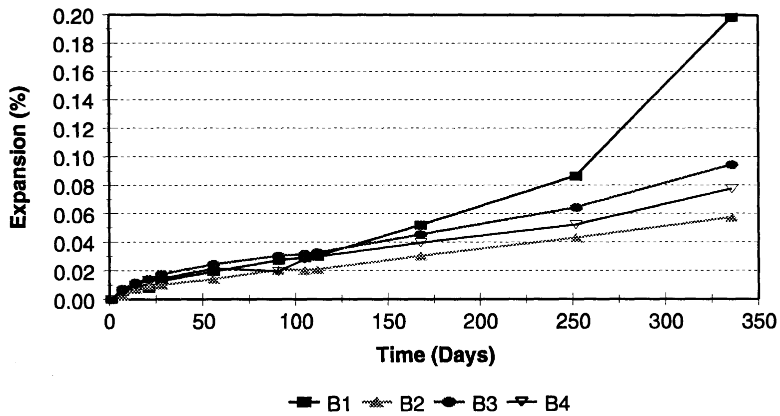

Figure 5. Sulfate data (ASTM C1012, B1-B4 given in Table 5).

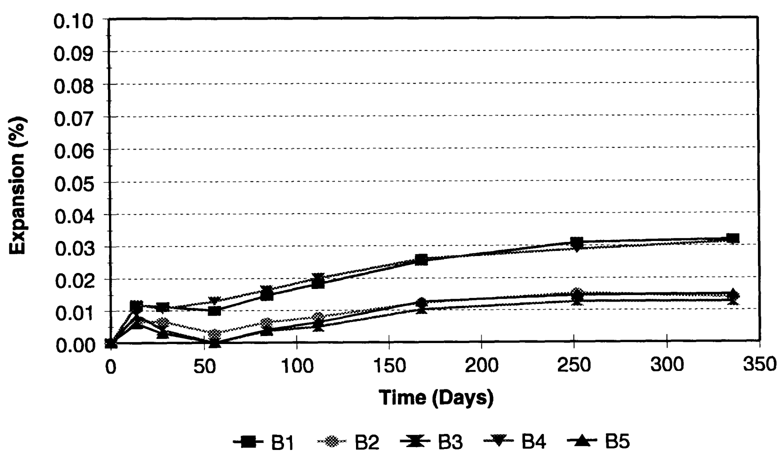

Figure 6A. Modified C342 data at 54°C (B1-B5 given in Table 5).

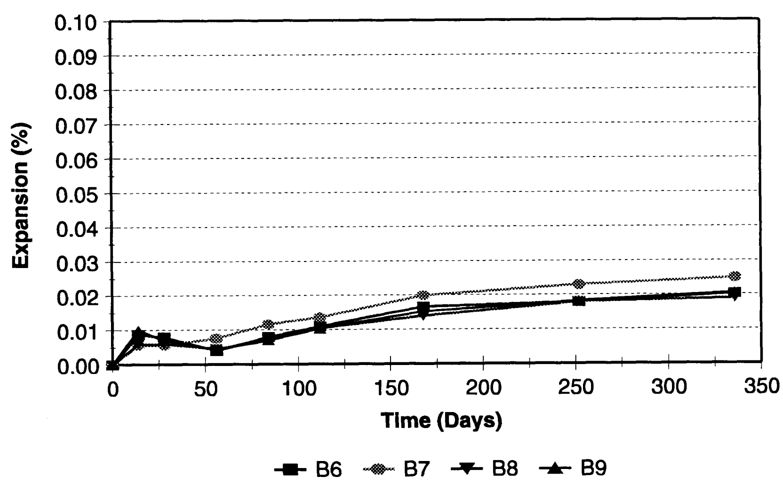

Figure 6B. Modified C342 data at 54°C (B6-B9 given in Table 5).

(130° F), the Type I control cement and a test blend of 0/20 FA/CKD2 replacement exhibited the largest expansions. These expansions were slightly over 0.03% at 336 days and are considered negligible. In Figure 7, the expansions of specimens exposed to the higher temperature of 80°C (176° F) are shown. The mixtures containing the 0/20 blend (CKD1 and CKD2) with Type I (S) cement showed the highest levels of expansion, followed by a mixture containing the Type I cement with the 15/20 blend containing CKD2. The control with Type I (S) cement, the 15/20 blend with CKD1and the 15/10 blend with CKD2 had somewhat lower expansions. All these expansions are larger than 0.2%. Expansions exceeding 0.1% are considered excessive. The mixtures containing the Type II (R) control cement with lower alkali content, and the 15/0 blend had the lowest expansions which were about 0.05%. The mixture with the 15/10 blend with CKD1 had a slightly higher expansion than the Type II (R) control cement. In this test, mixtures containing CKD2 produced higher expansions than similar mixtures containing CKD1, which probably resulted from the higher sulfate and alkali content of CKD2.

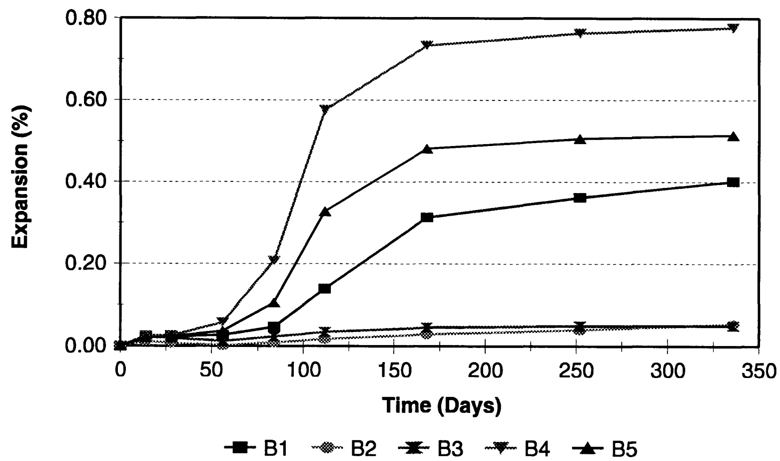

Figure 7A. Modified C342 data at 80°C (B1-B5 given in Table 5).

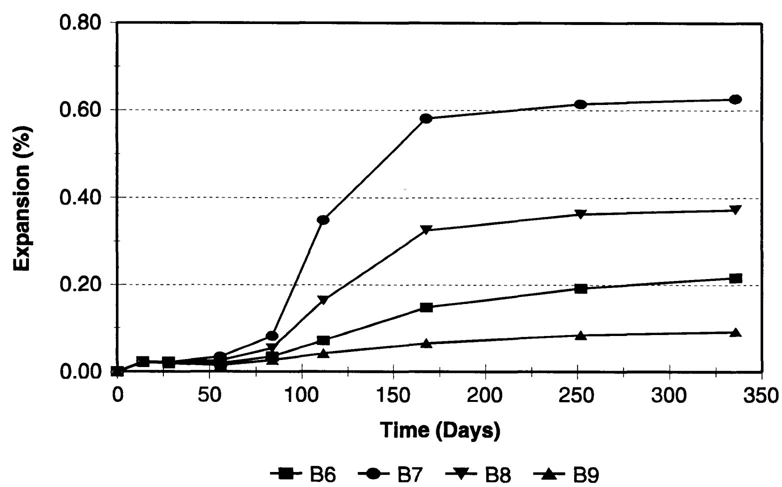

Figure 7B. Modified C342 data at 80°C (B6-B9 given in Table 5).

The results of the modified C 342 tests indicate that the presence of CKD in concretes exposed to temperatures exceeding 54°C for short periods and subsequently exposed to moisture may result in deleteriously large changes in volume. The amount of change in volume was affected by the chemistry of the CKD and the amount of fly ash present in the mixture. Expansions that could be considered excessive occurred in mixtures containing CKD as low as 10% with 15% FA. Steam-cured precast concrete used in transportation systems experiences the type of conditions simulated in this test. These results suggest that the curing temperature of concrete containing CKD should be carefully controlled to avoid exceeding 54°C.

Concrete

The results of air content, slump, and unit weight are given in Table 7. Air content ranged from 4.0 to 8.0 %, slump from 35 to 165 mm (1.3 to 6.5 in), and unit weight from 2,191 to 2,409 kg/m^3 (136.8 to 150.4 lb/ft^3). All of the concretes had the proper amount of air and were workable.

The results of the compressive and splitting tensile strength are given in Table 8, and the permeability tests are given in Table 9. The compressive strength data at 3, 7, and 28 days for the control and fly ash mixtures containing cement with 0.70% alkali content are given in Figure 8. Figure 9 displays data for the concretes with CKD1 and blends of FA/CKD1. The results given in Table 8, some of which are displayed in Figures 8 and 9, indicate that control concretes had the highest strength at all ages tested. The addition of CKD into concretes with fly ash did not result in benefits in strength development of fly ash mixtures, even though it has been claimed that high alkali contents in CKD would activate the strength development of fly ash concretes. Such benefits were also not obtained in fly ash concretes in which the alkali content was boosted using NaOH to an equivalent cement alkali content of 1.25%. It may require much larger amounts of alkalies to activate the system for strength.

The results of the permeability tests in Table 9 are displayed for an alkali content of 0.70% in Figure 10 and 1.25% in Figure 11. The results indicate that for concretes with an alkali content of 0.70%, the coulomb values at 28 days were in the high range for the control and fly ash concretes, indicating low resistance to the penetration of chlorides. At 1 year, control mixtures attained moderate coulomb values, but all fly ash concretes had very low coulomb values, indicating high resistance to the penetration of chlorides. The concretes with blends of FA/CKD exhibited moderate to low permeability values at 28 days, which declined to very low values as was the case with fly ash concretes at later ages. Figure 11 indicates similar behavior with concrete containing cement where the alkali content was raised to 1.25%; thus, the early coulomb values of fly ash concretes can be reduced by increasing the alkali content of the concrete by incorporating CKD into the mixture or adding NaOH solution. However, even without boosting the alkali content, concretes containing cement with an alkali content of 0.70% and fly ash provided very low coulomb values at 1 year.

Table 7: Characteristics of Freshly Mixed Concrete

Batch	Air Content (%)	Slump (mm)	Unit Wt. (Kg/m^3)
1	6.5	50	2262
2	5.3	70	2313
3	4.8	50	2300
4	4.6	100	2275
5	7.0	65	2236
6	6.0	75	2268
7	5.7	70	2262
8	5.6	115	2249
9	4.5	125	2281
10	7.0	150	2204
11	5.9	65	2287
12	4.4	65	2307
13	6.3	140	2243
14	4.3	35	2409
15	5.3	50	2371
16	5.6	50	2358
17	5.8	55	2294
18	4.6	75	2281
19	4.7	65	2294
20	4.6	70	2287
21	4.0	45	2326
22	5.3	50	2319
23	5.0	50	2287
24	5.6	70	2281
25	4.7	110	2268
26	5.5	100	2255
27	6.0	85	2262
28	5.6	70	2275
29	5.3	75	2275
30	5.9	135	2236
31	8.0	140	2191
32	7.2	165	2217

Table 8: Strength Data (MPa)

Batch	Compressive strength			Splitting tensile
	3 day	7 day *	28 day	
1	23.5	27.6	34.9	3.83
2	21.2	24.1	32.4	3.55
3	21.1	26.3	32.5	3.28
4	18.6	22.2	32.7	3.76
5	17.0	19.3	26.1	3.24
6	20.8	25.4	30.1	3.07
7	20.4	25.1	31.9	3.21
8	16.6	22.3	31.1	2.96
9	16.0	20.8	31.0	3.38
10	15.0	17.1	24.4	2.72
11	25.2	23.6	36.1	3.48
12	21.8	25.3	33.6	3.17
13	17.8	17.8	24.4	3.21
14	28.4	35.7	39.0	4.14
15	19.5	24.4	28.7	3.45
16	24.4	30.9	34.9	4.00
17	21.1	30.5	28.5	3.17
18	19.8	24.1	31.5	3.14
19	20.7	22.9	30.1	2.96
20	19.0	22.7	31.3	3.41
21	20.1	24.2	32.2	2.83
22	18.9	22.1	29.1	2.93
23	18.8	21.7	28.6	3.07
24	17.9	21.4	27.5	2.96
25	16.1	19.9	28.8	3.17
26	16.3	18.9	26.8	2.96
27	20.3	23.4	30.0	3.07
28	17.7	22.1	31.4	3.10
29	20.0	22.7	29.6	3.14
30	16.8	20.1	26.5	3.17
31	18.5	20.8	25.2	2.90
32	21.5	25.7	29.5	3.24

* Numbers 14-16 were tested at 14 days

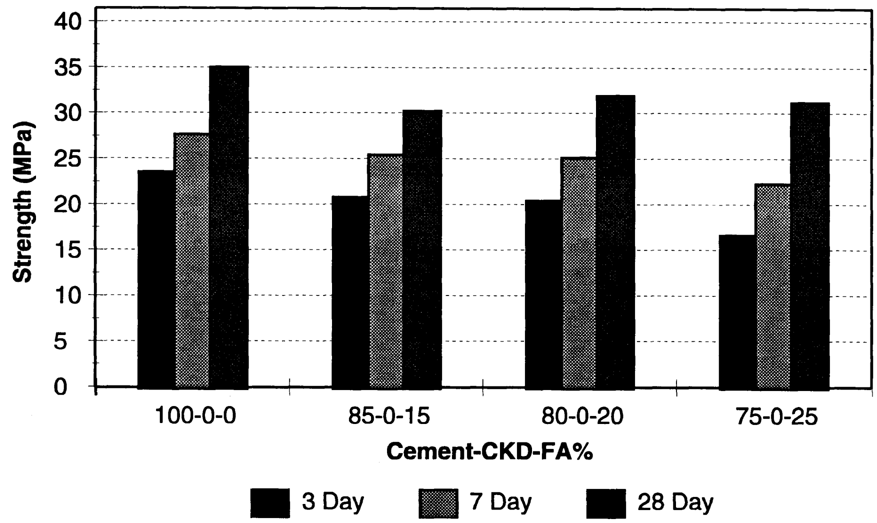

Figure 8. Compressive strength data for the control and fly ash concretes containing cement with 0.70% alkali content.

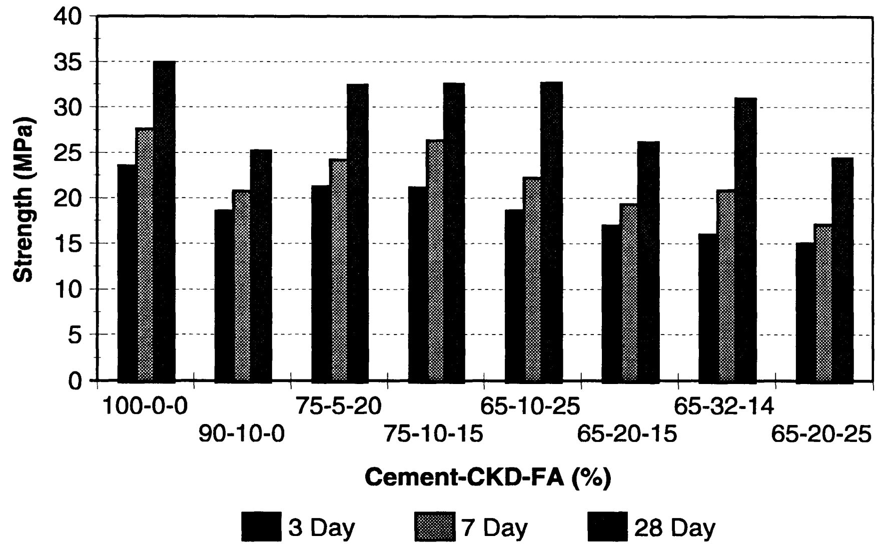

Figure 9. Compressive strength data for the CKD1 and FA/CKD1 blends containing cement with 0.70% alkali content.

Table 9: Permeability Data

#	Permeability (coulombs)	
	28 day	1 year
1	4332	2948
2	1809	339
3	2088	414
4	1623	239
5	2290	409
6	4340	891
7	3943	632
8	4883	573
9	4633	224
10	2165	311
11	5131	3372
12	2562	452
13	5222	1635
14	2709	1715
15	2238	360
16	2514	486
17	3708	1992
18	1398	267
19	1945	410
20	1123	225
21	1580	353
22	2426	457
23	2040	366
24	1679	313
25	1166	204
26	1597	325
27	2302	431
28	1628	249
29	2375	410
30	3600	619
31	4544	3270
32	5572	3491

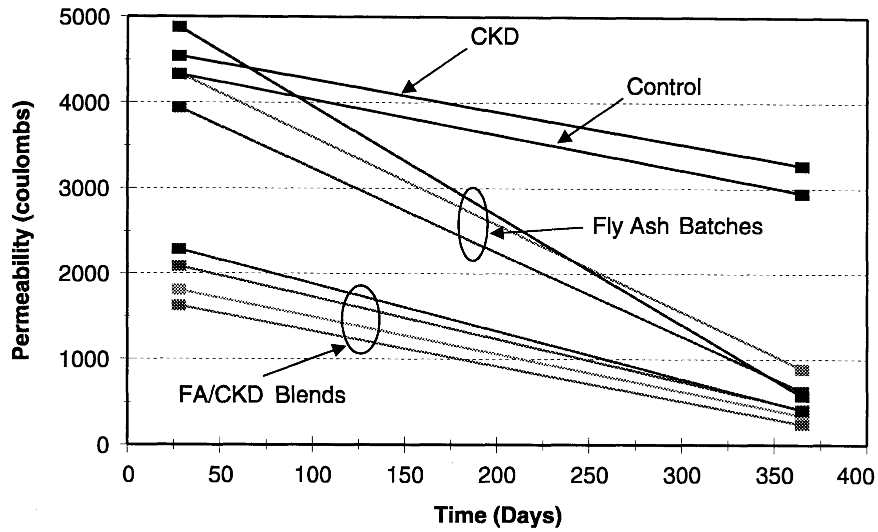

Figure 10. Permeability of control and experimental concretes containing cements with an alkali content of 0.7%.

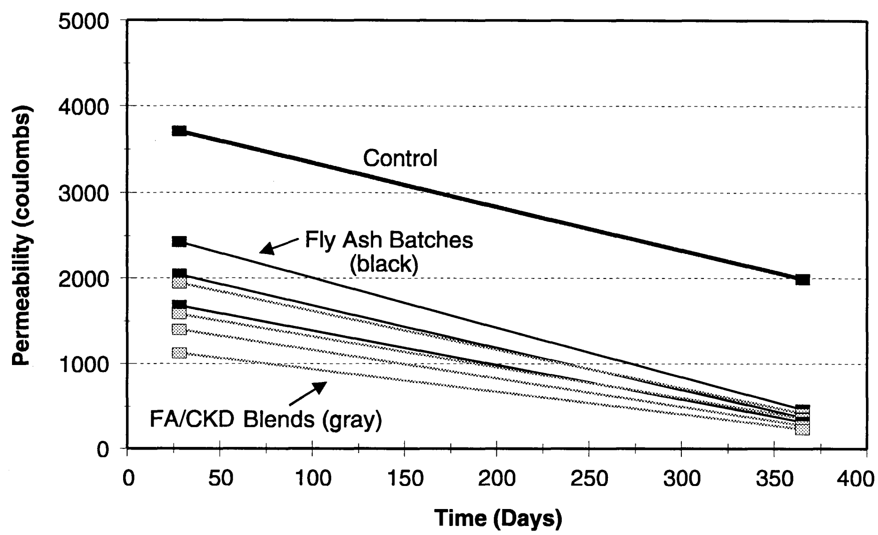

Figure 11. Permeability of control and experimental concretes containing cements with an alkali content of 1.25%.

Currently, VDOT is considering the use of permeability as a specification requirement for the acceptance of concrete. Traditionally, strength at 28 days has been used as the primary specification requirement for concrete. With many concretes, the expected permeability level may not be reached for an extended period of time -- up to 1 year. If coulomb values are required at 28 days because of practicality in enforcing the specifications, activation of the fly ash concretes with alkalis could provide the kind of low coulomb values at early ages that normally occur at later ages. However, alkali activation should be studied thoroughly for long-term durability, and such a study should be sought through the NCHRP. Other ways of accelerating the development of low permeability are possible. For example, increasing the curing temperature of fly ash concretes results in reduced permeability values at 28 days without any durability concerns. Also, the long-term permeability values are important in the service life of the structure, since minimal chloride penetration into regular bridge deck concretes is expected to occur within the first year.

The results of the concrete prism expansion tests are given in Appendix C. A linear expansion of 0.04%, the value at which distress becomes evident, or greater is considered excessive. Of the samples stored at 38°C (100°F), only batch 17, which contained the reactive aggregate and cement alkali content raised to 1.25% Na_2O equivalent, exceeded 0.04% expansion through 336 days. The excessive expansion in this case is considered to result from ASR. The mineral admixture combinations used in the concretes with a cement alkali content of 1.25% Na_2O equivalent, were effective in suppressing expansions.

When stored at 80°C (176°F), excessive expansion was noted with concretes from batches 14, 15 and 16, which had a 0.70% Na_2O equivalent alkali content and contained a dolomitic limestone aggregate. Excessive expansion was also noted with batches 17, 19, 22 and 23, while batches 18, 20, 21, 24, 26 and 30 approached the 0.04% limit of expansion at 336 days. Batches 17 to 26 had cement alkali contents raised to 1.25% Na_2O equivalent. The expansion in concretes with non-reactive dolomitic limestone aggregate was unexpected. The exact cause of the expansion of batches stored at 80°C (176°F) has not yet been determined and will be the subject of a future study. A recently approved standard test method (ASTM C 1293) to identify alkali-silica reactive aggregates provides for storing samples at 38°C (100°F).

CONCLUSIONS

1. The replacement of cement in mortar batches with CKD alone resulted in ASR expansions similar to those of the control batches without CKD. The replacement of cement with blends of fly ash and CKD (FA/CKD) resulted in lower expansions than those exhibited by the controls containing cements having alkali contents of 0.60% and above. For cements with an alkali content below 0.60%, the replacement with a 15/20 FA/CKD blend resulted in much higher expansion than the control batch without replacement. With one exception, batches containing a higher percentage of CKD than FA had excessive expansion (exceeding 0.1%). Batches containing FA/CKD blends (25/10 and 20/5) had expansions within the acceptable range as long as the cements had an alkali content of 0.70% or less. Excessive expansions were encountered with the 25/10 blend containing cement with an alkali content of 0.92%. Expansions of batches containing roughly equivalent amounts of fly ash without CKD were lower than the expansions of batches containing the FA/CKD blends.

2. Mortars containing 10 to 20% CKD that are subjected to high temperatures (80°C) and cyclic wetting and drying subsequently followed by moist exposure may result in high levels of expansion. This is true whether or not the mortars contain fly ash. The amount of expansion is dependent on the chemistry of the CKD and the cement and the amount of CKD and fly ash present in the mixture.

3. The presence of 5 to 25% CKD in concretes with fly ash did not result in benefits in strength development. Similarly, such benefits were not observed in fly ash concretes produced using high alkaline solutions to raise the effective cement alkali content to 1.25%.

4. Large reductions in coulomb values were observed in fly ash concretes produced with the 0.70% alkali cement, resulting in 1 year values in the very low range. Coulomb values of the control concretes were only reduced to the moderate range after 1 year. The addition of CKD or NaOH solutions to the concretes resulted in moderate to low coulomb values in concretes containing fly ash even at 28 days. All fly ash concretes containing cements with alkali contents of 0.70% or above had very low coulomb values at 1 year.

RECOMMENDATIONS

The chemical composition of CKD depends on cement plant operations and can be quite variable over time. The mechanical properties and the durability of concrete are largely a function of the chemistry of the concrete system and consequently are affected by the chemical composition of the individual constituent materials. A complete understanding of the variability of CKD chemistry and its effects on concrete properties is necessary to establish conditions for its use beyond experimental applications. Extensive studies are needed to identify the chemical parameters that can be used to characterize CKD and to ensure that concrete containing it will provide acceptable performance. Such an undertaking was beyond the scope of this project. A research problem statement should be submitted to NCHRP to investigate the long-term durability of concretes that contain CKD or have a high alkali content.

It is recommended that any use of CKD in concrete be limited in scope and restricted to blends in which the proportion of Class F fly ash exceeds the proportion of CKD. The chemical composition of the CKD blend and its individual constituents should be completely and carefully monitored.

Because of the potential for excessive expansion, CKD blends are not recommended for use in concrete that will be cured at temperatures exceeding 54° C (130° F) until further evaluations have been made.

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APPENDIX A

Modified ASTM C 342

LENGTH CHANGE OF MORTAR SPECIMENS
SUBJECTED TO WETTING AND DRYING
(Adapted from ASTM C 342 and the Duggan test)

1. At 24 hours remove the specimens from the molds.
2. Place the bars in distilled water at 23°C (73° F).
3. At 7 days take a reading.
4. Return the bars to the water and place in two temperature environments; one at 54° C (130° F) and the other at 80° C (176° F).
5. At 10 days remove the containers with the specimens from the oven and let them cool to room temperature.
6. At 14 days, remove the specimens from the water, measure and store the specimens in air at the respective temperatures.
7. At 17 days, cool the dry bars to room temperature, and then place the bars in their original water at 23° C (73° F).
8. At 21 days, place the containers with the specimens in water at the two respective temperatures.
9. At 24 days, cool the specimens in water to room temperature.
10. At 28 days, remove the specimens from the water, measure and place the specimens in air at the two respective temperatures.
11. At 31 days, cool the dry bars to room temperature, and then place the bars in their original water at 23° C (73° F).
12. Take readings at 56 days, 90 days, 6 months, and 1 year.

Appendix B: Expansion data of FA/CKD blends (%)

Batch ID	15/0	15/10 CKD1	25/10 CKD2	15/10 CKD2	15/10 CKD1	25/10 CKD1	20/0	0/10 CKD1	0/10 CKD2	15/20 CKD1	15/20 CKD2	20/5 CKD1	25/10 CKD1
Alkali (%)	0.4	0.4	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Days:													
1	0.0063	0.1350	0.0577	0.1123	0.1270	0.0497	0.0713	0.2880	0.3333	0.1783	0.1920	0.0743	0.0770
28	0.0037	0.1557	0.0667	0.1633	0.1487	0.0577	0.0743	0.4005	0.5050	0.2097	0.2283	0.0807	0.0797
56	0.0113	0.1807	0.0657	0.1950	0.1707	0.0560	0.0807	0.4235	0.5330	0.2390	0.2597	0.0890	0.0860
56d Nor	0.0110	0.1807	0.0424	0.1259	0.1102	0.0362	0.0593	0.2755	0.3467	0.1555	0.1689	0.0869	0.0840
84	0.0113	0.1857	0.0720	0.2113	0.1930	0.0630	0.0827	0.4445	0.5487	0.2470	0.2693	0.0903	0.0873
112	0.0130	0.1907	0.0800	0.2247	0.2057	0.0663	0.0823	0.4470	0.5523	0.2500	0.2730	0.0903	0.0877
168	0.0133	0.1907	0.0747	0.2303	0.2123	0.0653	0.0817	0.4460	0.5500	0.2513	0.2740	0.0910	0.0863
252	0.0127	0.1900	0.0867	0.2587	0.2410	0.0783	0.0817	0.4445	0.5470	0.2523	0.2737	0.0903	0.0850
366	0.0180	0.1997	0.0923	0.2650	0.2770	0.0843	0.0873	0.4515	0.5543	0.2603	0.2837	0.0963	0.0927
1 yr Nor	0.0250	0.1997	0.0531	0.1525	0.1594	0.0485	0.0690	0.3390	0.4163	0.1955	0.2130	0.1004	0.0965

Batch ID	29/12	18/23	25/10 CKD2	35/0	0/10 CKD1	0/10 CKD2	25/10 CKD2	25/10 CKD1	15/20 CKD1	25/10 CKD2	25/10 CKD1	20/5 CKD2
Alkali (%)	0.7	0.7	0.7	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Days:												
1	0.0563	0.0553	0.1137	0.0800	0.2653	0.2787	0.0703	0.0680	0.1292	0.0663	0.0613	0.1590
28	0.0587	0.0557	0.1030	0.0973	0.4383	0.4523	0.0870	0.0870	0.1579	0.0817	0.0770	0.1900
56	0.0627	0.0600	0.1160	0.1007	0.5717	0.5947	0.0967	0.0935	0.1889	0.0847	0.0807	0.2250
56d Nor	0.0612	0.0586	0.0755	0.0980	0.5797	0.6030	0.1012	0.0968	0.1916	0.0859	0.0818	0.2282
84	0.0640	0.0623	0.1167	0.1067	0.6333	0.6433	0.1037	0.0950	0.2126	0.0947	0.0907	0.2473
112	0.0637	0.0610	0.1200	0.1080	0.6653	0.6697	0.1073	0.0990	0.2266	0.1003	0.0967	0.2607
168	0.0630	0.0593	0.1210	0.1130	0.6700	0.6733	0.1127	0.0990	0.2332	0.1013	0.0987	0.2643
252	0.0627	0.0583	0.1203	0.1197	0.6780	0.6790	0.1253	0.1075	0.2609	0.1163	0.1173	0.2897
366	0.0670	0.0650	0.1303	0.1180	0.6833	0.6857	0.1330	0.1115	0.2669	0.1227	0.1237	0.3953
1 yr Nor	0.0698	0.0677	0.0979	0.1100	0.6422	0.6444	0.1312	0.1124	0.2508	0.1153	0.1162	0.3715

Appendix C: Expansion of concrete specimens (%)

At 38 C

Batch No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Alkali (%)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.7	0.7	0.7
Days:																
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0070	0.0005	0.0000	0.0000	0.0005	0.0010	0.0020	-0.0045	0.0010	-0.0005	0.0000	-0.0045	0.0045	-0.0070	0.0015	0.0000
28	-0.0010	-0.0020	0.0015	-0.0020	-0.0010	0.0010	0.0000	-0.0100	-0.0000	-0.0010	-0.0005	-0.0015	0.0090	-0.0035	0.0030	0.0015
56	0.0020	-0.0010	0.0025	-0.0005	0.0015	0.0045	0.0005	-0.0195	0.0005	-0.0010	0.0005	-0.0010	0.0115	-0.0005	0.0060	0.0040
84	-0.0015	-0.0015	0.0025	-0.0035	0.0030	0.0030	0.0000	-0.0225	0.0005	0.0015	-0.0045	-0.0025	0.0065	-0.0035	0.0015	-0.0030
168	0.0050	0.0005	0.0060	0.0035	0.0090	0.0055	0.0005	-0.0145	0.0020	0.0030	-0.0040	0.0025	0.0100	0.0040	0.0075	0.0000
252	0.0060	0.0020	-0.0000	0.0030	0.0100	0.0070	0.0050	-0.0150	0.0010	0.0050	-0.0005	-0.0005	0.0075	0.0085	0.0120	0.0035
336	0.0080	0.0030	0.0080	0.0035	0.0130	0.0080	0.0055	-0.0150	0.0045	0.0060	-0.0010	0.0015	0.0065	0.0110	0.0145	0.0060

Batch No.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Alkali (%)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	0.7	0.7	0.7	0.4	0.7	0.4
Days:																
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	-0.0050	-0.0020	-0.0010	-0.0030	0.0005	-0.0025	0.0005	-0.0050	0.0010	-0.0115	-0.0070	-0.0095			
28	0.0045	-0.0045	-0.0005	-0.0045	-0.0015	0.0035	-0.0005	-0.0010	-0.0050	0.0010	-0.0035	-0.0045	0.0000			
56	0.0085	0.0010	0.0050	-0.0015	0.0010	0.0025	-0.0025	0.0020	-0.0065	0.0015	-0.0040	-0.0050	-0.0005	-0.0020	0.0000	-0.0020
84	0.0175	-0.0025	0.0020	-0.0030	0.0015	0.0020	-0.0075	-0.0005	-0.0080	0.0005	0.0000	0.0000	0.0000	0.0035	0.0065	0.0045
168	0.0635	0.0030	0.0105	0.0025	0.0070	0.0125	0.0025	0.0045	-0.0010	0.0060	0.0005	-0.0045	0.0015	0.0065	0.0130	0.0080
252	0.1420	0.0045	0.0110	0.0040	0.0080	0.0180	0.0055	0.0060	0.0010	0.0055	0.0030	-0.0035	0.0040	0.0045	0.0150	0.0050
336	0.1725	0.0095	0.0175	0.0060	0.0160	0.0220	0.0090	0.0070	0.0040	0.0120	0.0050	0.0010	0.0115	0.0090	0.0215	0.0040

At 100 C

Batch No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Alkali (%)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.7	0.7	0.7
Days:																
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0075	0.0060	0.0040	0.0105	0.0050	0.0065	0.0045	0.0125	0.0105	0.0085	0.0010	0.0025	0.0090	0.0075	0.0020	0.0060
28	0.0005	0.0100	0.0095	0.0035	-0.0015	0.0130	0.0125	0.0080	0.0135	0.0105	-0.0000	0.0080	0.0115	0.0105	0.0080	0.0080
56	0.0140	0.0160	0.0130	0.0155	0.0120	0.0185	0.0130	0.0185	0.0145	0.0140	0.0030	0.0055	0.0190	0.0240	0.0215	0.0215
84	0.0145	0.0195	0.0115	0.0140	0.0110	0.0185	0.0200	0.0160	0.0140	0.0195	0.0040	0.0015	0.0125	0.0305	0.0275	0.0270
168	0.0250	0.0240	0.0205	0.0215	0.0200	0.0235	0.0135	0.0210	0.0235	0.0190	-0.0020	0.0000	0.0095	0.0785	0.0785	0.0620
252	0.0290	0.0245	0.0175	0.0210	0.0220	0.0240	0.0215	0.0195	0.0215	0.0205	0.0095	0.0040	0.0075	0.1195	0.1065	0.0960
336	0.0285	0.0225	0.0225	0.0185	0.0195	0.0220	0.0175	0.0000	0.0225	0.0155	0.0080	0.0025	0.0035	0.1585	0.1255	0.1170

Batch No.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Alkali (%)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	0.7	0.7	0.7	0.4	0.7	0.4
Days:																
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0165	0.0030	0.0080	0.0085	0.0025	0.0040	0.0045	0.0050	0.0030	0.0040	-0.0145	-0.0030	0.0010			
28	0.0310	0.0090	0.0135	0.0130	0.0120	0.0135	0.0100	0.0090	0.0090	0.0095	-0.0005	0.0075	0.0080			
56	0.0390	0.0205	0.0250	0.0175	0.0170	0.0160	0.0140	0.0145	0.0095	0.0140	0.0075	0.0145	0.0175	0.0165	0.0010	0.0065
84	0.0420	0.0120	0.0205	0.0205	0.0180	0.0195	0.0150	0.0185	0.0085	0.0150	0.0000	0.0000	0.0000	0.0270	0.0050	0.0100
168	0.0540	0.0220	0.0355	0.0300	0.0345	0.0360	0.0295	0.0300	0.0200	0.0300	0.0160	0.0210	0.0265	0.0300	0.0065	-0.0015
252	0.0650	0.0285	0.0410	0.0355	0.0345	0.0440	0.0365	0.0365	0.0240	0.0325	0.0190	0.0185	0.0245	0.0205	0.0070	0.0255
336	0.0720	0.0365	0.0465	0.0350	0.0400	0.0495	0.0405	0.0395	0.0270	0.0390	0.0215	0.0195	0.0260	0.0340	0.0125	0.0285