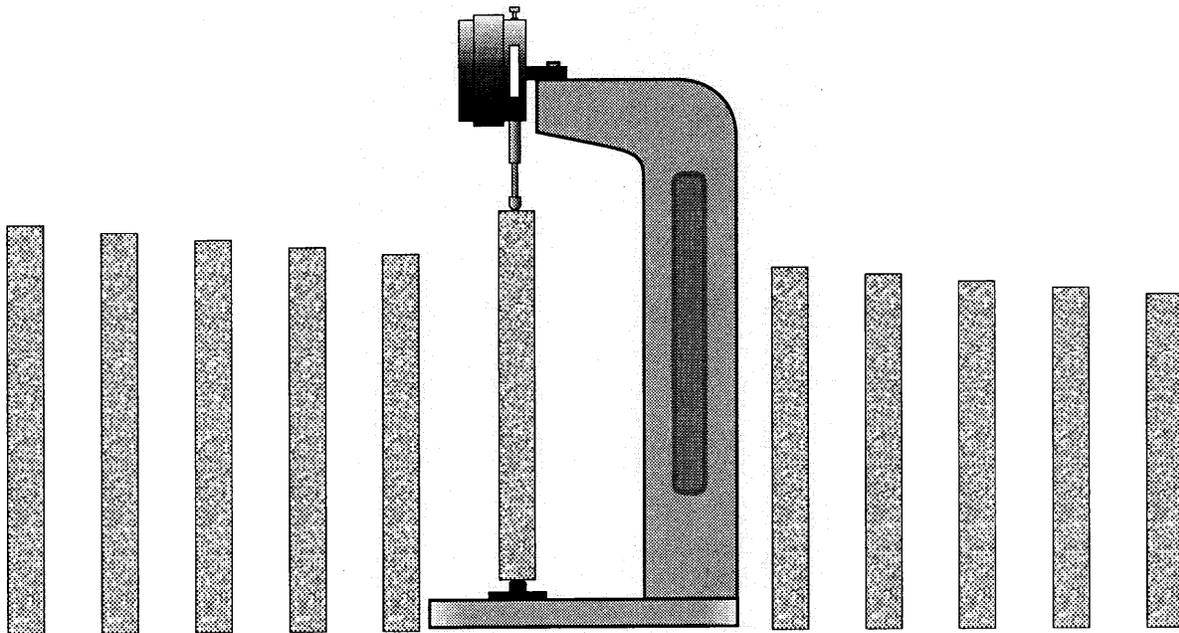


FINAL REPORT

USE OF FLY ASH, SLAG, OR SILICA FUME TO INHIBIT ALKALI-SILICA REACTIVITY



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| 16. Abstract <p>This study had two objectives: (1) to evaluate the effectiveness of particular mineral admixtures when combined with portland cements of varying alkali content in preventing expansion due to alkali-silica reactivity (ASR), and (2) to determine if set minimum amounts of various types of mineral admixtures could be established for use with cements of varying alkali content to provide protection from ASR.</p> <p>Mortar bars made with Pyrex glass aggregate were stored moist at 38°C for 366 days and measured periodically for length change. Control mortars were mixed with portland cements having an alkali content ranging from 0.18% to 0.92% Na₂O equivalent. Test mortars were mixed replacing various percentages of portland cement with Class F fly ash (15%, 25%, and 35%), slag (20%, 35%, and 50%), or silica fume (3% and 7%). Test mortars were also mixed using IP cement produced using Class F fly ash (18%, 20% and 22%). Expansions of control mortars with alkali contents of 0.4% or less were negligible through the 336-day test period. With cements having an alkali content above 0.4%, equilibrium between cement alkali content and mortar bar expansion was reached at 56 days, when a strong linear relationship between increasing expansion and increasing alkali content developed. A regression analysis was performed on data from the control batches, and the resulting equation was used to normalize data from the test batches.</p> <p>The expansion of mortars containing fly ash, slag, and silica fume was lower than the expansion of the control batches for portland cement having an alkali content of 0.6% and above for all replacement levels of the tested materials. The amount of expansion varied with the type of material, percentage replacement, and cement alkali content. Using an expansion of 0.10% as the maximum indicative of acceptable performance in inhibiting ASR, minimum amounts of Class F fly ash, slag, and silica fume were established for use with portland cement depending on the alkali content of the cement.</p> | | | |
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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This study had two objectives: (1) to evaluate the effectiveness of particular mineral admixtures when combined with portland cements of varying alkali content in preventing expansion due to alkali-silica reactivity (ASR), and (2) to determine if set minimum amounts of various types of mineral admixtures could be established for use with cements of varying alkali content to provide protection from ASR.

Mortar bars made with Pyrex glass aggregate were stored moist at 38° C for 366 days and measured periodically for length change. Control mortars were mixed with portland cements having an alkali content ranging from 0.18% to 0.92% Na₂O equivalent. Test mortars were mixed replacing various percentages of portland cement with Class F fly ash (15%, 25%, and 35%), slag (20%, 35%, and 50%), or silica fume (3% and 7%). Test mortars were also mixed using IP cement produced using Class F fly ash (18%, 20%, and 22%). Expansions of control mortars with alkali contents of 0.4% or less were negligible through the 336-day test period. With cements having an alkali content above 0.4%, equilibrium between cement alkali content and mortar bar expansion was reached at 56 days, when a strong linear relationship between increasing expansion and increasing alkali content developed. A regression analysis was performed on data from the control batches, and the resulting equation was used to normalize data from the test batches.

The expansion of mortars containing fly ash, slag, and silica fume was lower than the expansion of the control batches for portland cement having an alkali content of 0.6% and above for all replacement levels of the tested materials. The amount of expansion varied with the type of material, percentage replacement, and cement alkali content. Using an expansion of 0.10% as the maximum indicative of acceptable performance in inhibiting ASR, minimum amounts of Class F fly ash, slag, and silica fume were established for use with portland cement depending on the alkali content of the cement.

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INTRODUCTION

Alkali-silica reactivity (ASR) is a reaction that can occur between hydroxide ions present in the pore solution of hydraulic cement concrete and aggregates that contain particular forms of silica. An alkali-silica gel is produced by this reaction that can absorb water and swell. The swelling can cause expansion and cracking of the concrete, resulting in an increased rate of deterioration, the misalignment of structural members, and a reduced service life.

When the aggregates to be used in a concrete are thought to contain reactive forms of silica and the concrete will be exposed to moisture in service, two options are generally recommended to minimize the potential for deterioration due to ASR. One option is to limit the alkali content of the portland cement since this is thought to be directly related to the potential for reactivity. Traditionally, an alkali (sodium and potassium) content below 0.60% calculated as sodium oxide (Na_2O equivalent) has been considered sufficiently low to minimize the potential for damaging ASR. However, a review of the literature has brought this into doubt (Lane, 1994). The second option, to be used when the alkali content of the portland cement is above the limit, is to use mineral admixtures with a proven ability to inhibit ASR as a portion of the cementitious material in the production of the concrete. Fly ash conforming to the Class F requirements specified in ASTM C 618 (ASTM, 1993), ground granulated blast-furnace slag, and silica fume have all been shown to be effective for this purpose when used in appropriate amounts (Buck, 1987; Farbiarz, Schuman, Carasquillo & Snow, 1989; Hogan & Meusel, 1981; Pepper & Mather, 1959).

When these two options are written into a specification, the general form is to establish a maximum limit on the total alkali content of portland cement. If the alkali content is below this limit, the cement can be used as 100% of the cementitious material. If the limit is exceeded, minimum amounts of the cement must be replaced with an appropriate amount of mineral admixture. Two problems are perceived with this approach:

1. It assumes that the potential for damaging reactivity in a concrete containing reactive aggregates is controlled by the alkali content in a threshold-type fashion and that this

threshold value is known with confidence. However, serious questions exist about how well this threshold is known.

2. It assumes that if the alkali content of the cement is above the threshold value, then replacing a specified amount of the cement with a mineral admixture will provide acceptable assurance that damaging reactivity will not occur without regard to the actual alkali content of the cement. Thus, a cement with an alkali content exceeding the limit by 0.05% is treated the same as a cement with an alkali content exceeding the limit by 0.5%. Consequently, this approach ignores the concept that the alkali content of the cement directly affects the potential for reactivity and, therefore, the amount of mineral admixture needed for protection.

The standard method for evaluating the ability of mineral admixtures or slag to prevent ASR is ASTM C 441 (Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction) (ASTM, 1993). This method involves the fabrication of mortar bars from mixtures of portland cement, mineral admixtures, or slag and aggregate composed of Pyrex glass, which is highly alkali-reactive. The mortar bars are stored in a warm, moist environment and measured for changes in length. The effectiveness of the mineral admixture in preventing expansion is judged by either the absolute expansion of a particular mixture or the reduction in expansion provided by the mineral admixture with respect to the expansion of a control mixture.

When this project was started, the criteria for Class F and Class C fly ash specified in ASTM C 618 (Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete) (ASTM, 1993) set the maximum acceptable expansion in the ASTM C 441 test at 0.02%. For slag, the appendix of ASTM C 989 (Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars) (ASTM, 1993) suggests using either the 0.02% expansion with job materials or a 75% or greater reduction in expansion using a high-alkali cement. The specification for silica fume, ASTM C 1240 (ASTM, 1993) requires that it provide an 80% or greater reduction.

These specification limits were adopted from test programs conducted in the 1950s, including the work of Pepper and Mather (1959). Recently, there has been a growing concern in the concrete industry that the 0.02% expansion limit and the 75% reduction in expansion are unrealistic values given the performance of concretes containing pozzolans or slag in the field and the test results being obtained in accordance with ASTM C 441 today. Consequently, ASTM C 618 was recently changed to require that the expansion of mortar bars made with the mineral admixture being tested not exceed the expansion of control bars made with a portland cement having an alkali content of 0.50 to 0.60%.

In response to durability problems, including ASR, the Virginia Department of Transportation (VDOT) recently revised its concrete specifications to require the use of fly ash, slag, or silica fume in all concrete where the alkali content of the cement exceeds 0.40% Na₂O

equivalent (Lane, 1994). This project was initiated to develop more information concerning the relationship between cement alkali content and the ability of various mineral admixtures and slag to inhibit ASR and, if necessary, improve upon the evaluation criteria and specifications to prevent ASR deterioration.

PURPOSE AND SCOPE

This investigation was carried out under laboratory conditions using procedures patterned after those specified in ASTM C 441. Materials included several portland cements with a range of alkali content, fly ash from several sources, slag, silica fume, and aggregate composed of Pyrex glass crushed to sand sizes.

The objectives of this study were as follows:

1. To evaluate the effectiveness of particular mineral admixtures when combined with portland cements of varying alkali content in preventing expansion due to ASR.
2. To determine if set minimum amounts of various types of mineral admixtures can be established for use with cements of varying alkali content to provide protection from ASR.

MATERIALS AND METHODS

Portland cements and three blended cements ranging in alkali content from 0.18 to 0.92% were obtained from four plants in the mid-Atlantic states. The chemical composition of the portland cements is shown in Table 1. The chemical composition of fly ashes from four sources and slag and silica fume from one source each is shown in Table 2. The three blended cements were produced at the cement plant by intergrinding cement clinker (cement A) with 18, 20, and 22% fly ash (FA2). Pyrex glass No. 7740 was obtained from two sources. The Pyrex from one source was in the form of broken glassware, and that from the other source was in the form of plate approximately 25 mm thick. The glass was crushed, washed, and put through a sieve in accordance with ASTM C 441. The chemical composition of the glass is shown in Table 3.

Mortars containing Pyrex glass were mixed and tested to evaluate the effectiveness of cement-mineral admixture combinations in inhibiting ASR. The testing was in accordance with ASTM C 441 except that the mineral admixture replacements were made on a mass rather than an absolute volume basis and bars were stored and measured periodically over a 336-day period in addition to the specified 14-day period. The basic plan for material combinations is outlined in Table 4; for the majority of combinations, two batches of mortar were mixed on separate days, and control batches containing the same cement as the test batches were mixed each day a test

TABLE 1: CHEMICAL ANALYSIS OF CEMENTS (%)

| Cement | A | B | C | D | E |
|--------------------------------|-------------|----------|-----------|-------------|------------|
| Type | I/II | I | II | I/II | III |
| SiO ₂ | 21.01 | 20.45 | 21.54 | 20.68 | 20.75 |
| Al ₂ O ₃ | 4.41 | 4.92 | 3.97 | 4.65 | 4.41 |
| Fe ₂ O ₃ | 2.91 | 2.04 | 2.71 | 3.48 | 1.98 |
| CaO | 63.68 | 62.32 | 63.18 | 65.95 | 63.77 |
| MgO | 2.75 | 3.90 | 3.25 | 1.10 | 3.04 |
| SO ₃ | 2.47 | 3.32 | 2.69 | 2.27 | 3.94 |
| Na ₂ O | 0.21 | | 0.10 | 0.11 | |
| K ₂ O | 0.66 | | 0.75 | 0.11 | |
| C ₃ S | 56.73 | | 52.68 | 65.54 | 58.20 |
| C ₂ S | 17.43 | | 22.01 | 9.84 | |
| C ₃ A | 75.90 | 9.60 | 6.96 | 7.65 | 8.30 |
| C ₄ AF | 88.40 | | 8.26 | 10.60 | |
| Na ₂ OEq | 0.64 | 0.92 | 0.60 | 0.18 | 0.57 |
| Loss on Ignition | 0.15 | 2.05 | 1.44 | 1.60 | 1.44 |
| Blaine (m ² /kg) | 388 | | | 388 | |

batch was mixed. Storage containers were constructed of 150-mm (6-in) PVC pipe and lined with blotting paper as wicking; each was fitted with a rack to hold six specimens. The three specimens from each batch were distributed among the containers used to store the specimens from the batches mixed on the same day to minimize the effect of variations caused by individual storage containers.

Selected material combinations were also tested to evaluate the effect on compressive strength of various replacement levels of portland cement with fly ash, slag, and silica fume. Mortars were mixed and cubes fabricated in accordance with ASTM C 109 using a siliceous, graded sand aggregate. Cubes were tested at 3, 7, and 28 days for compressive strength. The combinations tested are shown in Table 4.

TABLE 2: CHEMICAL ANALYSIS OF FLY ASH, SILICA FUME, AND SLAG

| | FA1 | FA2 | FA3 | FA4 | S1 | SF1 |
|--------------------------------|------------|------------|------------|------------|-----------|------------|
| SiO ₂ | 53.01 | 54.40 | 53.86 | 50.10 | 37.59 | 94.61 |
| Al ₂ O ₃ | 31.30 | 25.14 | 31.80 | 30.15 | 3.34 | 0.31 |
| Fe ₂ O ₃ | 5.62 | 7.73 | 3.13 | 6.03 | 0.46 | 0.13 |
| CaO | 1.02 | 5.61 | 1.18 | 1.82 | 17.61 | 0.46 |
| MgO | 0.53 | 1.65 | 0.63 | 0.62 | 11.25 | 0.41 |
| SO ₃ | 0.54 | 0.63 | 0.06 | 1.33 | 1.94 | |
| Na ₂ O | 0.22 | 0.37 | 0.19 | 0.33 | 0.22 | 0.15 |
| K ₂ O | 1.73 | 3.22 | 2.38 | 2.07 | 0.34 | 0.56 |
| NaEq | 1.36 | 2.49 | 1.76 | 1.69 | 0.44 | 0.52 |
| Loss on Ignition | 4.47 | 1.59 | 5.07 | 6.66 | | 3.29 |
| Moisture | | 0.05 | | | | 0.15 |

TABLE 3: ANALYSIS OF PYREX GLASS

| | 2 | 1 |
|--------------------------------|----------|----------|
| SiO ₂ | 88.67 | 89.21 |
| Al ₂ O ₃ | 2.32 | 2.22 |
| Na ₂ O | 3.88 | 3.86 |
| K ₂ O | 0.43 | 0.76 |
| NaEq | 4.16 | 4.36 |

TABLE 4: MATERIAL COMBINATIONS FOR MORTAR TESTS

| Cementitious Material | Cement Alkali (Na ₂ O Equivalent) | | | | | | |
|--------------------------|--|------|------|------|------|------|------|
| | 0.18 | 0.40 | 0.50 | 0.60 | 0.70 | 0.75 | 0.92 |
| 100% PC | X | X | X | X,Y | X | X | X,Y |
| 15% FA | | | X | X,Y | X | X | |
| 20% FA | | | | | X | | |
| 25% FA | | | X | X,Y | | X | X,Y |
| 35% FA | | | | X,Y | | X | X,Y |
| 20% Slag | | | | X,Y | | X | |
| 35% Slag | | | X | X,Y | | X | X,Y |
| 50% Slag | | | | X,Y | | X | X,Y |
| 3% SF | | | | X,Y | | X | |
| 7% SF | | | | X,Y | | X | X,Y |

X = Combinations used in mortar bar expansion tests.

Y = Combinations used in compressive strength tests.

RESULTS AND DISCUSSION

Expansion Tests

The results of the expansion tests conducted are presented in Appendices A through D and are summarized graphically in Figures 1 through 15. Figures 1 through 4 present the expansion data from control mixes of straight portland cement mortars with varying alkali content at 14, 28, 56, and 336 days, respectively. Mortar bars produced with cements with an alkali content up to 0.40% expanded very little in these tests, even at 336 days.

Because of the extreme ASR of Pyrex glass, the expansion of mortar bars made with portland cement in this test is believed to be primarily a function of the hydroxide ion concentration of the pore solution in the bar, provided a sufficient supply of moisture was available to cause swelling of the gel produced. The hydroxide ion concentration should, in turn, be primarily a function of the alkali content of the cement; however, the use of Pyrex glass in this test has been criticized because sodium in the Pyrex may be released during the test and thus increase the hydroxide ion concentration of the pore solution (Struble & Brockman, 1989).

Portland Cement Controls

As the alkali content of the cement increased above 0.40%, a general increase in expansion was observed. In Figure 1 (14-day expansions), this trend appears to be fairly linear up to an alkali content of 0.70%; above 0.70%, the increase tails off, with increasing alkali content resulting in little additional expansion. A similar tendency, although to a lesser degree, was observed in the 28-day data illustrated in Figure 2. An examination of Figures 1 and 2 indicates that the relationship between alkali content and expansion is curvilinear at these early test ages.

However, by 56 days, as shown in Figure 3, and through the 336-day test period shown in Figure 4, expansion appears to increase linearly with increasing alkali content above 0.40% for the range of alkali contents tested. A linear regression analysis of the 56-day data yielded a correlation coefficient (r) of 0.910; the correlation coefficient for the 336-day data was 0.906 with a sample population (n) of 27 in each case. These regressions are statistically significant at the 95% level as indicated by a comparison of the correlation coefficient to the tabulated critical r value ($r_{xy,0.05;n=27} = 0.324$) (Koch & Link, 1980; Till, 1974). The linear relationship of alkali content and expansion explains 83 and 82% (r^2 values) of the variance in expansion results for the 56-day and 336-day measurements, respectively. Because the linear relationship is statistically significant, it can be quantified by calculating the regression line.

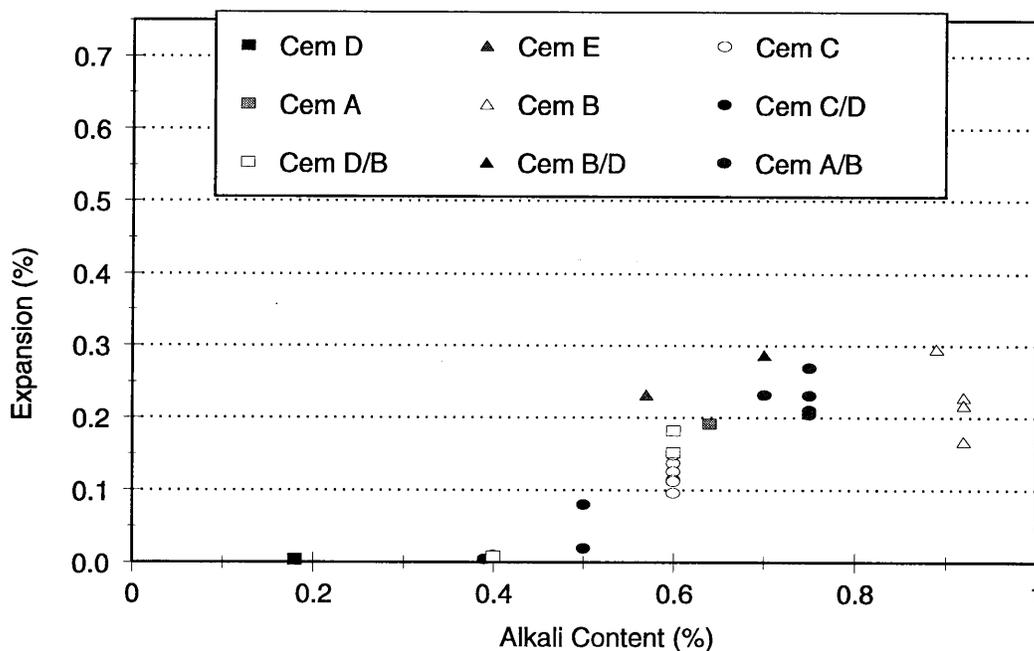


FIGURE 1. 14-Day Expansions of Control Mortars

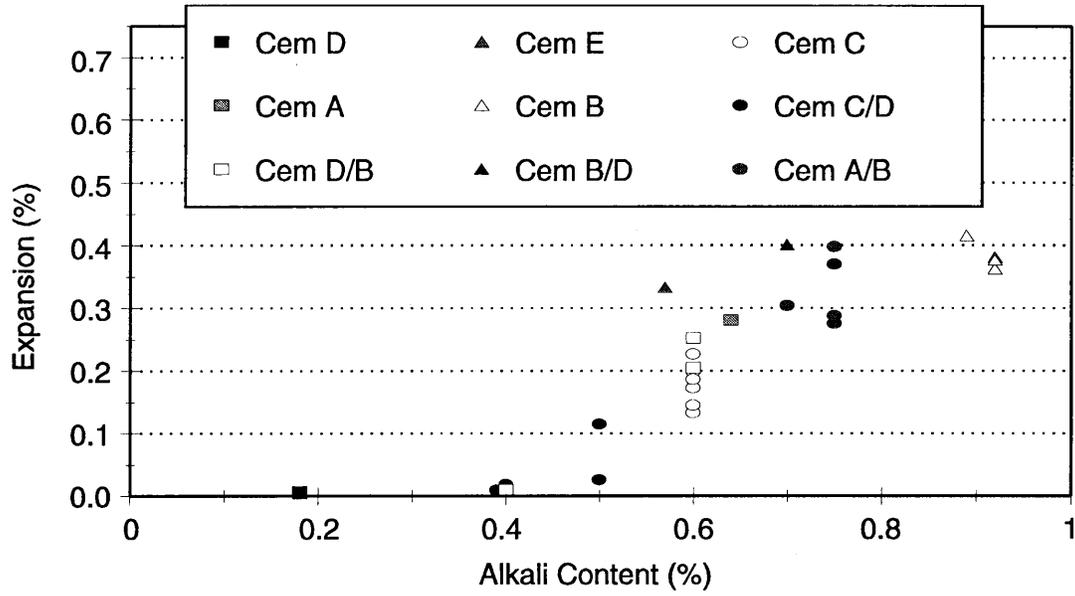


FIGURE 2. 28-Day Expansions of Control Mortars

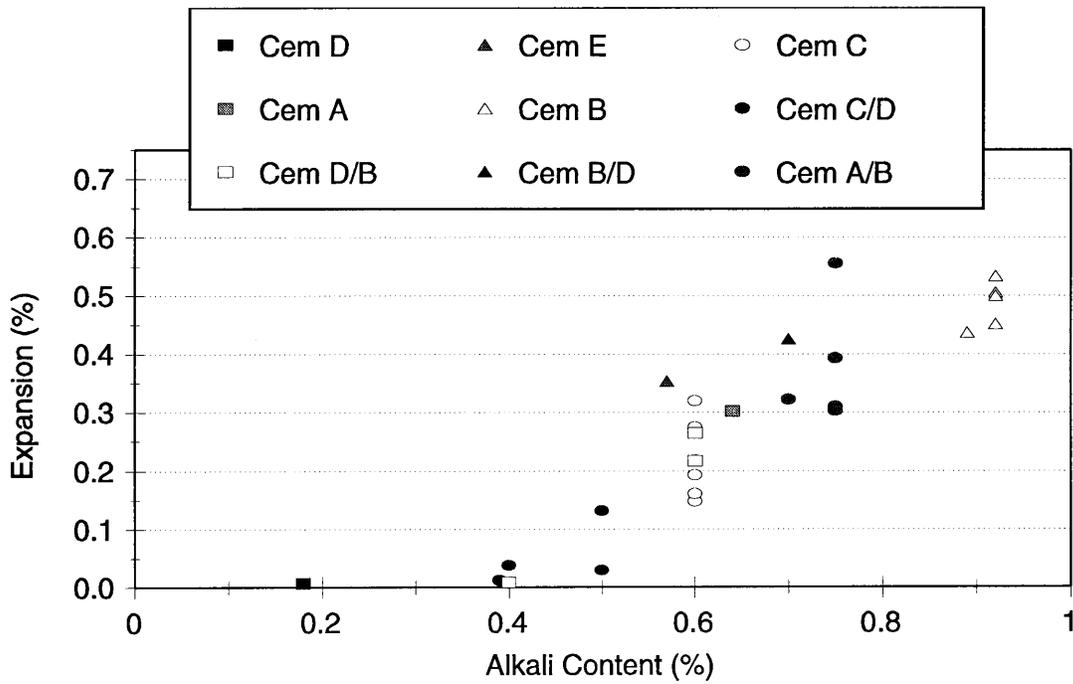


FIGURE 3. 56-Day Expansions of Control Mortars

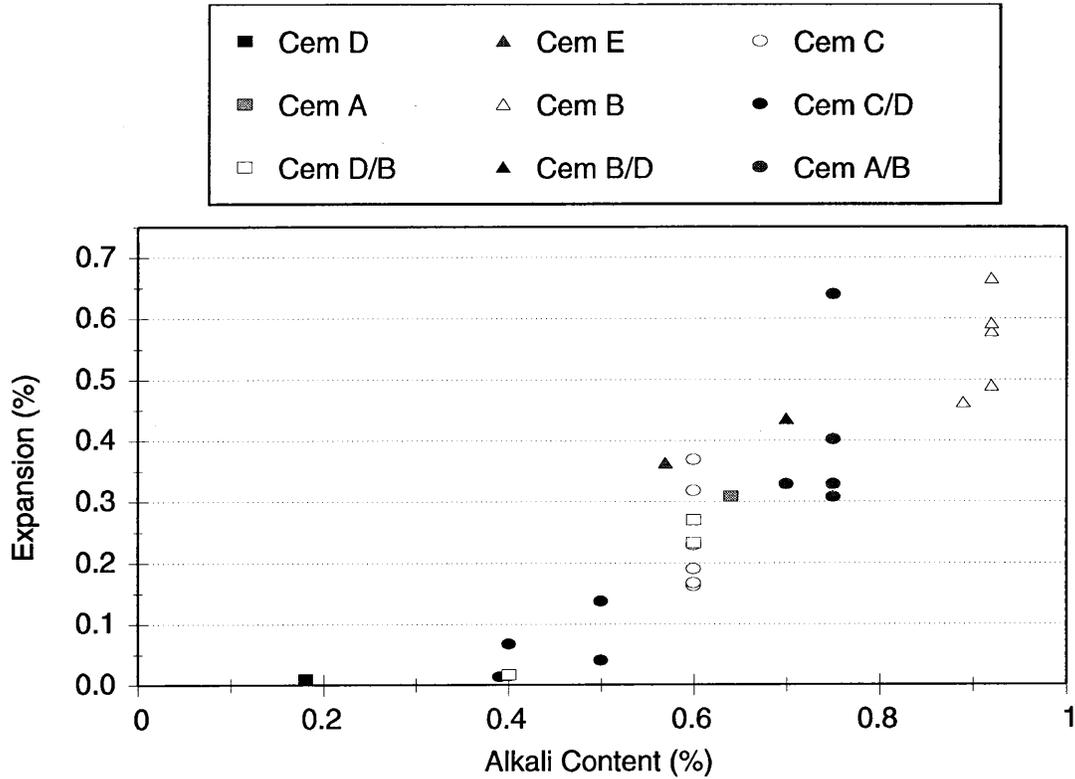


FIGURE 4. 336-Day Expansions of Control Mortars

The regression equations for the 56-day and 336-day data are shown in Equations 1 and 2, respectively:

$$56 \text{ day} \quad y = 0.0093x - 0.0033 \quad (1)$$

$$336 \text{ day} \quad y = 0.0105x - 0.0038 \quad (2)$$

where:

$$y = \text{expansion } (\%)$$

$$x = \text{alkali content } (\%)$$

The standard error of the y estimate was 0.0717% for the 56-day regression and 0.0835% for the 336-day regression. The average measured y values were 0.2636% and 0.3033%, respectively.

The leveling-off of expansion at the higher alkali contents at 14 and 28 days suggests that at these earlier ages, with the higher alkali cements, the pore solution hydroxide ion (OH^-) concentration had not reached equilibrium with respect to the alkali contained in the cement. This finding is in keeping with Diamond's report that the alkali concentration of cement paste

pore solutions stabilizes after a month or so (Diamond, 1989). It is interesting because much of the criticism of the ASTM C 441 test is focused on the rapid reactivity of the Pyrex glass and the short 14-day test period, relative to the reactivity of particular pozzolans, particularly fly ash (Stark, Morgan, Okamoto & Diamond, 1993) without consideration being given to the release of alkalis from the cement. The delay in reaching equilibrium may occur because more of the alkalis in the higher alkali cements are present in less soluble phases of the cement than in the lower alkali cements or are contained deeper within the cement grains. In either case, a longer hydration period is necessary for complete release. An analysis of the pore solution expressed from specimens by the application of compressive forces (Diamond, 1989) at different ages may provide useful information in this regard. From the data obtained in this study, it appears that 14- and 28-day data present a rather incomplete picture of the effect of cement alkalis on expansion due to ASR. By 56 days, the reaction has stabilized and remains so through a 336-day period.

The strong linear relationship between expansion and cement alkali content at 56 days ($r = 0.910$) and later ages for alkali contents above 0.40% indicates that the expansion of portland cement mortars in the test is primarily a function of the alkali content of the cement. Figures 5 and 6 show the 56-day and 336-day data with the regression line and its 95% confidence limits. The confidence limits are calculated for various quantities of alkali content from Equations 3 and 4 as described by Natrella (1963).

$$c.f. = Y_c \pm W_1 \quad (3)$$

$$W_1 = \sqrt{2F} s_y \left[\frac{1}{n} + \frac{(x - \bar{x})^2}{S_{xx}} \right]^{\frac{1}{2}} \quad (4)$$

where:

W_1 = interval for confidence limit

Y_c = expansion predicted by regression

F = F statistic for $1 - \alpha$ level of confidence ($2, n-2$) degrees of freedom

n = number of samples

$$s_y = \sqrt{\sum \frac{(y - y_c)^2}{n-2}}$$

The spread of data for a given alkali content indicates the combined effect of factors other than alkali content on expansion in the test. Such factors include the hydraulic activity of the particular cement, variations in moisture conditions in the storage containers that may affect the rate of reactivity or the swelling potential of the reaction product, and the Pyrex glass itself. In addition to its extreme reactivity, Pyrex glass contains sodium that is released as the Pyrex reacts and its inherent reactivity may be affected by factors such as thermal history and particle shape (Struble & Brockman, 1989).

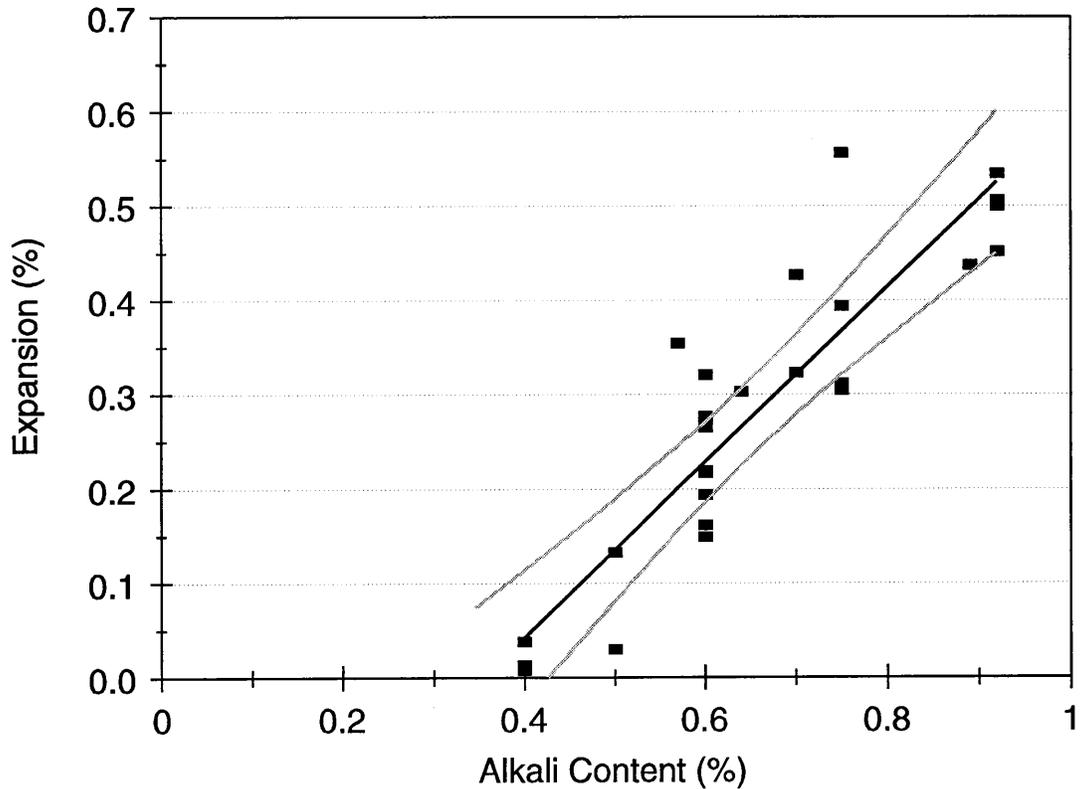


FIGURE 5. 56-Day Expansions of Control Mortars with Regression Line (*solid*) and 95% Confidence Limits

Figure 7 shows the 336-day data for the control mixtures differentiated by Pyrex glass. The data indicate that glass 2 produced higher expansions than glass 1. The relevant chemistry of the glasses (Table 3) appears quite similar. The physical form of the glasses was quite different: glass 1 was crushed from broken glassware and glass 2 was crushed from plate. These differences affect the particle shape and surface texture of the resulting aggregate particles produced by crushing and thus combine with the thermal history to affect the reactivity. From Figure 7 it can be seen that the effect of the glass on expansion was negligible at the 0.18% alkali content and nearly so at the 0.40% content. The three extreme expansions obtained with glass 2 (Figure 7) all occurred with batches that were mixed approximately 6 months after the earlier batches. This suggests that some time-dependent factor may also be affecting the results. Unfortunately, a more complete explanation of these extreme results is elusive.

The relatively high variability of results presents certain constraints on the manner in which data produced in accordance with ASTM C 441 should be used. For instance, a direct comparison of results from batches made at different times or using Pyrex obtained at different times or from different sources may be misleading. These factors will especially affect the comparison of results from different laboratories. Consequently, the direct comparison of

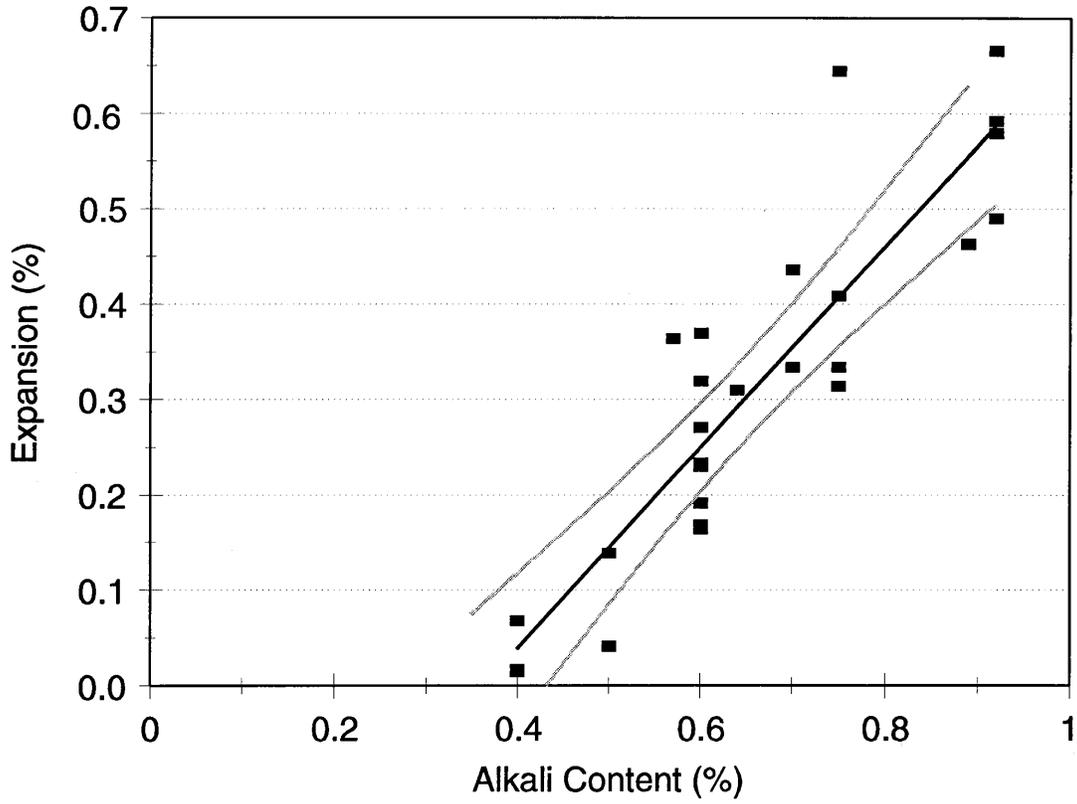


FIGURE 6. 336-Day Expansions of Control Mortars with Regression Line (solid) and 95% Confidence Limits

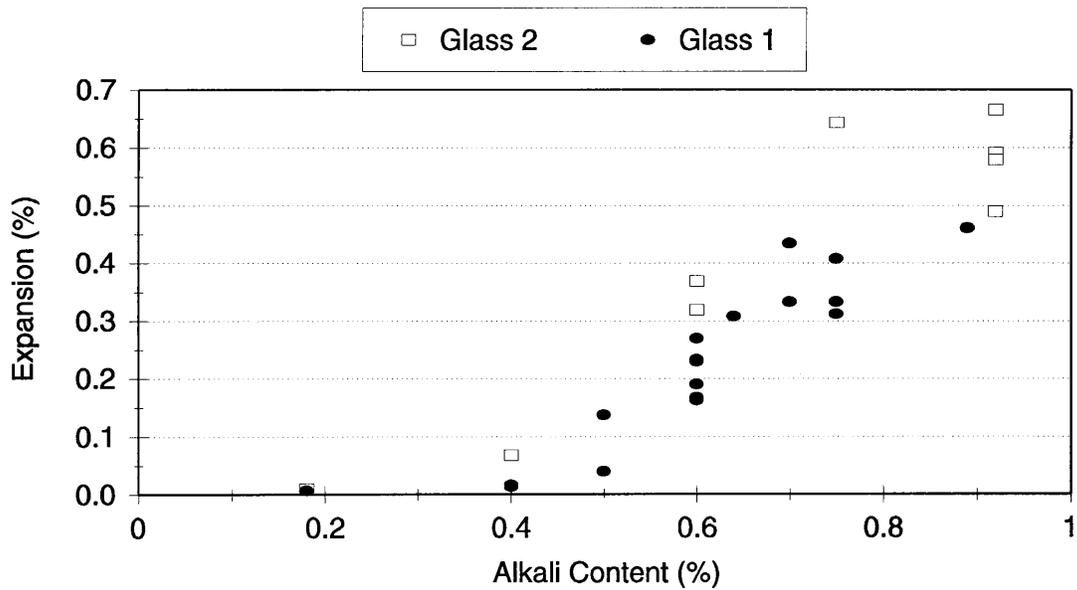


FIGURE 7. 336-Day Expansions of Control Mortars Identified by Pyrex Glass Source

individual test results against an absolute expansion limit established in another laboratory with a different set of materials may be suspect.

However, as mentioned earlier, the regressions of the 56-day and 336-day results support a conclusion that other sources of variability are nonetheless relatively minor in comparison to the effect of the cement alkalis. Thus, provided some means exist to relate the results of different batches to one another, they may be used to compare the relative potential of portland cements and combinations of portland cements and mineral admixtures to cause damaging ASR.

The data, regression lines, and confidence limits shown in Figures 5 and 6 can be used to delineate between cement alkali levels likely and unlikely to cause ASR problems. It is clear from Figures 5 and 6 that at an alkali content of up to 0.40%, expansions are negligible; as the alkali content exceeds 0.40%, expansions and, therefore, reactivity increase. Defining what amount of reactivity is tolerable and what is excessive is more problematic.

Traditionally, a portland cement alkali content of 0.60% or less has been considered to provide acceptable protection from ASR when reactive aggregates are used. In these tests, expansions with 0.60% alkali cements ranged from approximately 0.15 to 0.28% (0.35% for a Type III, 0.57% alkali cement) at 56 days. These expansions are well in excess of those produced with cements having an alkali content at or below 0.40% (maximum expansion < 0.05%). Because the primary concern is the prevention of damage, it is instructive to note that it has generally been observed that for mortar bars, cracking begins to occur as expansion approaches or exceeds 0.10% (R. D. Hooton, U. of Toronto, 1995, personal communication). Because of this association with damage, the use of 0.10% expansion to delineate between acceptable and excessive expansion seems justified.

An examination of Figures 1 through 6 shows that the use of 0.10% expansion allows a good separation of the mixtures based on expansion and alkali content. In a similar series of tests, Buck (1987) concluded that mortar bar expansions of 0.10% or less through 1 year should be considered to indicate acceptable performance. The use of 0.10% expansion as the maximum acceptable expansion by implication sets a maximum acceptable alkali content for portland cement below the traditional 0.60% limit. Although this may seem to be a new and unique finding, ASTM Committee C 1 reported in 1946 that in expansion tests conducted using mortar bars with natural aggregate materials, excessive expansions occurred with cements having an alkali content of 0.58% and higher but did not occur in cements having an alkali content of 0.40% or lower (ASTM, 1946). Similarly, Woolf (1952) reported that excessive expansions could occur with cements having an alkali content below the 0.60% limit.

Consideration should also be given to certain realities regarding concrete under actual service conditions. Because portland cement concrete is a relatively permeable material with respect to ionic transport, the alkalis within a concrete element can migrate. Cyclic wetting and drying, freezing and thawing, and stray electric currents can cause localized concentrations of alkalis high enough to initiate damaging ASR (Hadley, 1968; Ozol, 1990; Xu & Hooton, 1993).

Further, alkalis from outside sources such as deicing salt and brackish water or seawater can penetrate a permeable concrete. In this light, using a maximum portland cement alkali content lower than the traditional 0.60% seems prudent for straight portland cement concretes used in transportation structures and pavements.

With the use of a maximum acceptable expansion in these tests of 0.10%, the points at which the regression lines and confidence limits intersect the 0.10% line can be used to determine a maximum acceptable alkali content for portland cements to inhibit ASR. These values are shown in Table 5.

TABLE 5: MAXIMUM ALKALI CONTENT (%Na₂O EQUIVALENT) OF PORTLAND CEMENT THAT LIMITS EXPANSION OF PYREX GLASS MORTAR BARS TO 0.10%

| | 56 Day | 336 Day |
|-----------------|--------|---------|
| Upper limit | 0.38 | 0.38 |
| Regression line | 0.46 | 0.46 |
| Lower limit | 0.52 | 0.51 |

The decision concerning which value to use centers on a consideration of risk. As can be seen from the values, the difference between 56-day and 336-day values is negligible. Although the regression line is an average fit of the data, it must be recognized that there is some degree of uncertainty about its position as expressed by the 95% confidence limits. The upper limit defines the maximum expansion reasonably expected from a given alkali content assuming the regression is a true predictor of expansion. Likewise, the lower limit defines the minimum expansion.

Because concrete structures are intended to have a lengthy service life that can be considerably reduced by the effects of ASR and because of the many uncertainties that exist concerning the factors that control the progress of ASR in the field, it seems prudent to adopt a more conservative approach that would provide an engineering "margin of safety." Although this would suggest adoption of the 336-day upper limit value of 0.38% as the maximum portland cement alkali content that would ensure excessive expansions would not occur, the authors feel that adoption of a limit of 0.40% will provide adequate protection given the manner in which the confidence limits were determined. Given the precision of the methods for measuring the alkali content of cements (ASTM, 1993), such measurements can be assumed to be accurate to within 0.05%. Consequently, a cement with an alkali content as high as 0.45% could test as complying with a limit of 0.40% to prevent excessive expansions. This is very nearly the alkali content at which the regression line crosses 0.10% expansion (0.46% Na₂O).

Fly Ash, Slag, and Silica Fume Mortars

Figure 8 presents 56-day data showing the measured expansions of several mortars containing slag replacements along with the expansions of control mortars containing only portland cement. This figure illustrates the large variability between control batches with the same alkali content and how that variability is reflected in the expansion of the test mortars containing slag. As mentioned earlier, this situation interferes with the direct comparison of results from different batches. Because a control batch containing the same portland cement was mixed along with all test mortars, the expansions of the test mortars can be normalized to the regression line of expansion on alkali content for the control batches. Equation 5 was used to normalize the test mortar results to the regression line.

$$y_n = y_t - \left(\frac{y_c - y_p}{y_p} y_t \right) \quad (5)$$

where:

$y_n = y$ normalized

$y_t = y$ test value

$y_c = y$ control test value

$y_p = y$ predicted regression

The expansion results for each test batch were normalized to the respective regression line, permitting comparison of results.

Figures 9 through 11 present the 336-day normalized expansion data for mortars containing various amounts of Class F fly ash (Figure 9), slag (Figure 10), and silica fume (Figure 11) plotted against the alkali content of the control cement. In all cases, the replacement of cement with the mineral admixture produced expansions lower than those produced by the control mixtures at a given cement alkali content. This reduction in expansion seems to be a function of the type of mineral admixture, amount of cement replacement, and alkali content of the portland cement.

Figures 9A and 9B show the data for the Class F fly ash mixtures. The four fly ashes tested were used at replacement levels ranging between 15 and 35% by mass of total cementitious material. With cements of 0.60% alkali and lower, all replacement levels were effective in maintaining expansions below 0.10%. As the cement alkali content increased above 0.60%, replacements of 20 to 25% were necessary to control expansion and appear effective with cements having an alkali content up to 0.75 to 0.80%. Replacements with 35% fly ash held expansion of the 0.92% alkali cement to about 0.1%.

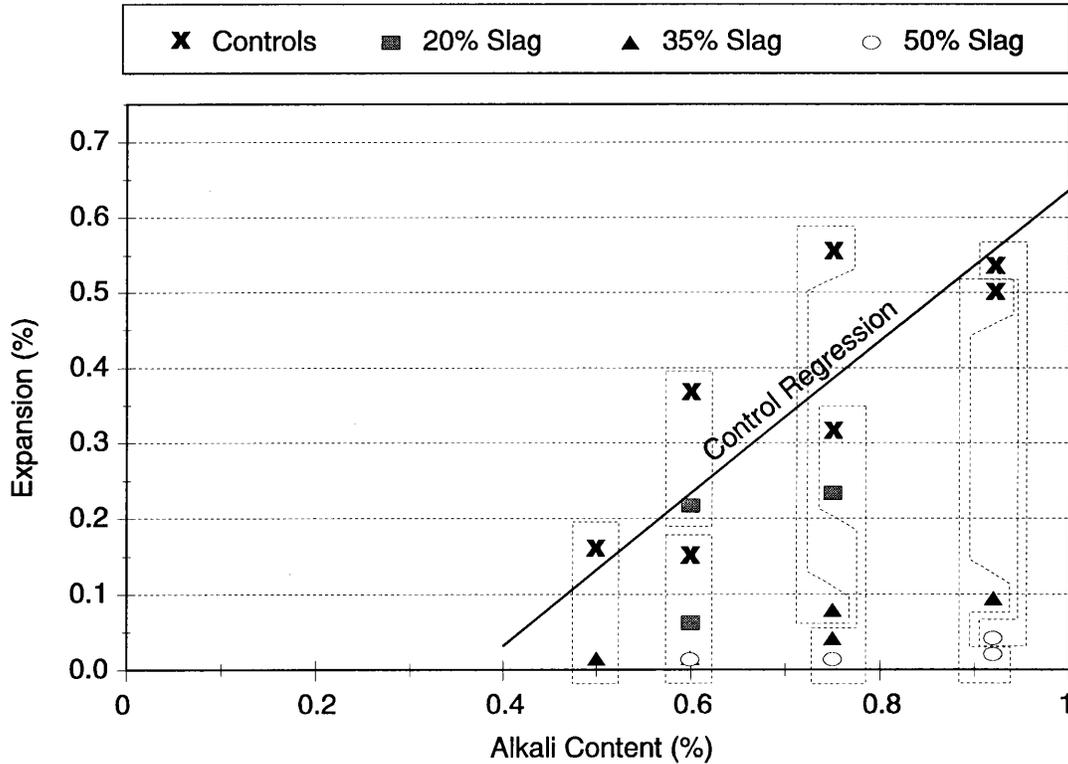


FIGURE 8. 56-Day Expansions of Slag Mortars with Respective Control Mortar (by shading)

Expansions of three IP cements produced using the same portland cement clinker and three different amounts of the same Class F fly ash are also shown in Figure 9B. For these cements, expansion decreased as the percentage of pozzolan increased. The average expansion of the 18% blend exceeded 0.10%. Expansions with the 20 and 22% blends were maintained below 0.10%. The alkali content of the portland cement was about 0.64%. A 20% blend of the tested IP cement should be effective, provided the alkali content of the portland cement does not exceed 0.70%.

An examination of Figures 10 and 11 indicates similar trends with the slag and silica fume results. For the 336-day slag data (Figure 10), 20% replacement of cement having 0.60% alkali produced expansions slightly above 0.10%, 35% replacement appears effective with cements having up to 0.80% alkali, and 50% replacement maintains expansions well below 0.10% with the tested materials.

With the silica fume mortars, 3% replacement of 0.60% alkali cement yielded an expansion just above the 0.10% maximum at 336 days. The 7% silica fume replacement held expansions below 0.10% with the 0.60% and 0.75% alkali cements. Expansions of the 7% replacement were at or above the 0.10% limit with the 0.92% alkali cement. An examination of

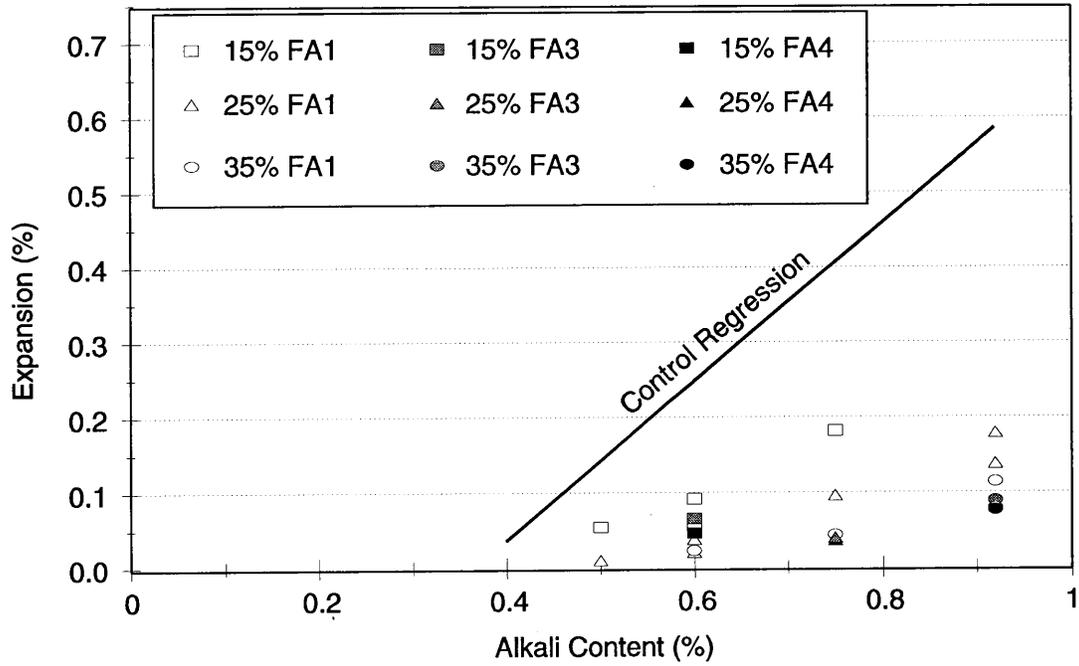


FIGURE 9A. 336-Day Expansions of Fly Ash Mortars (FA1, FA3, FA4) Plotted Against Alkali Content of Control Cement

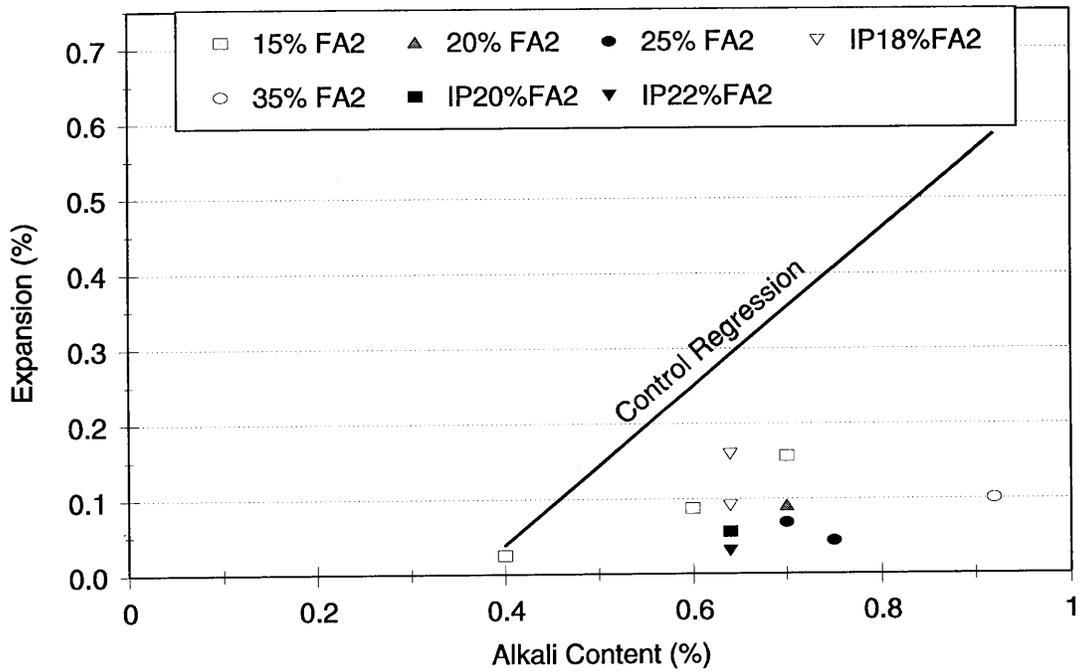


FIGURE 9B. 336-Day Expansions of Fly Ash Mortars (FA2 and IP with FA2) Plotted Against Alkali Content of Control Cement

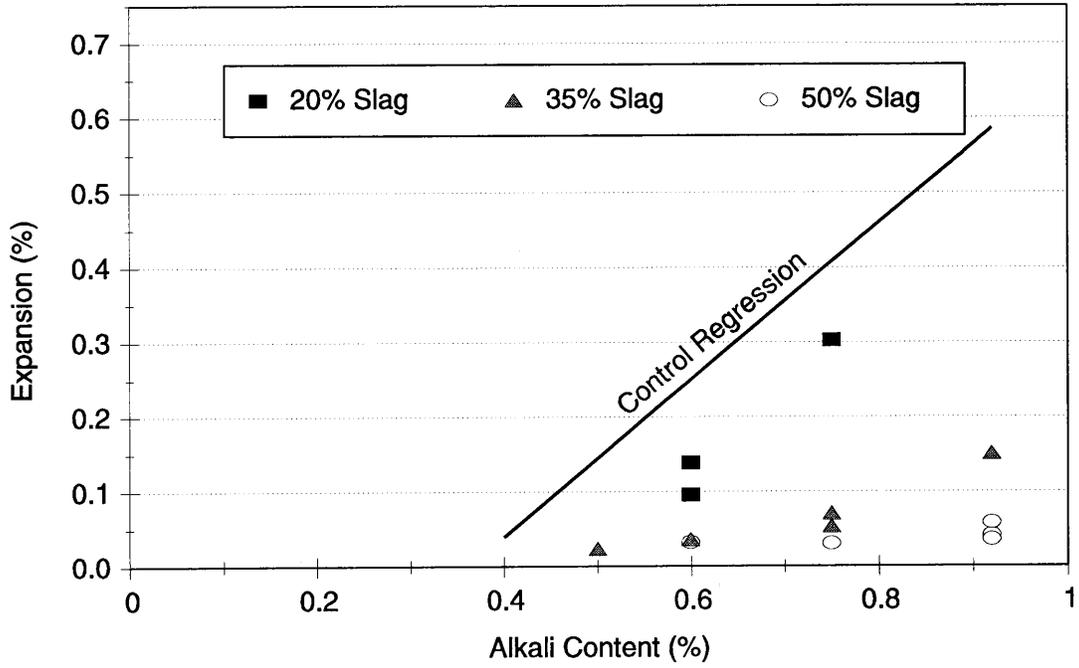


FIGURE 10. 336-Day Expansions of Slag Mortars Plotted Against Alkali Content of Control Cement

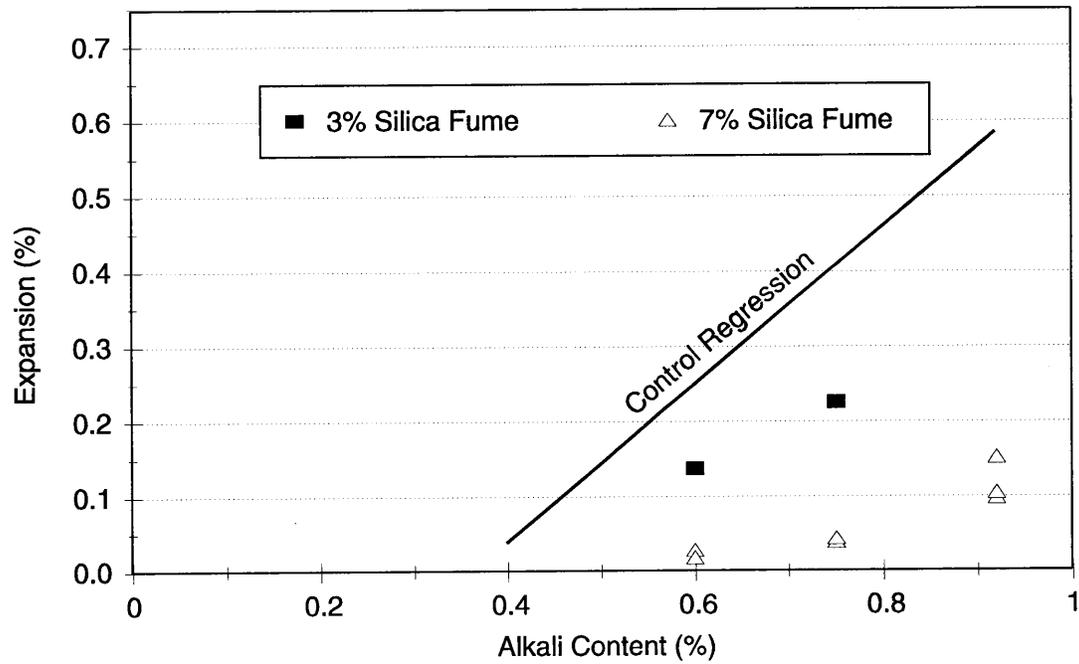


FIGURE 11. 336-Day Expansions of Silica Fume Mortars Plotted Against Alkali Content of Control Cement

Figure 11 suggests that a 7% replacement with silica fume is effective up to an alkali content of 0.90%. A higher percentage of silica fume replacement would be needed as the alkali content of the cement increased above this level.

Alternative Plotting Methods for Alkali Content

Until now, the discussion has examined the expansion of test mixtures relative to the alkali content of the portland cement used. Although this is perhaps the simplest way to present the data, there are two alternatives worth looking at. Both involve different ways of calculating the alkali content of the batch and thus change the relative position of individual batches on the x-axis of the figures. The test mortars contained only a percentage of the portland cement used in the control batches and consequently have a lower alkali content contributed by the cement. In Figures 12 and 13, expansions of the fly ash and slag mortars are plotted against the alkali content of the cement multiplied by the percentage of portland cement used in that particular batch. When plotted in this fashion, both the fly ash and slag plots show similar trends in that the data seem to split into two groups. In each case, the lowest replacement level (15% fly ash; 20% slag) seems to plot along one line whereas the higher replacement levels (20, 25, and 35% fly ash; 35 and 50% slag) seem to plot along a second line. Although this plotting method shows some promise, particularly with respect to consideration of the mass of alkali contributed to the mix by the cement, additional data points representing lower replacements of lower alkali cements and higher replacements of higher alkali cements are needed to complete such an analysis.

The second alternative takes into consideration the alkalies contributed by the mineral admixture and determines a total alkali content of the mixture. The total alkali content is calculated by summing the proportionate alkali content of the portland cement with some fraction of the proportionate total (acid soluble) alkali content of the mineral admixture being used (Hobbs, 1988; Portland Cement Association, 1994). The fraction used depends on the specific mineral admixture type being considered. For fly ash, the fraction is 17% of the total alkali content; for slag, 50%; and for silica fume, 100%. Thus, Equation 6 may be used to calculate the total alkali content of the mixture:

$$T = P (CA) + (1 - P) (F) (MA) \quad (6)$$

where:

T = total alkali content of mixture

P = fractional proportion of cement

CA = alkali content of cement

MA = alkali content of mineral admixture

F = multiplying fraction: 0.17 fly ash; 0.50 slag; 1.0 silica fume

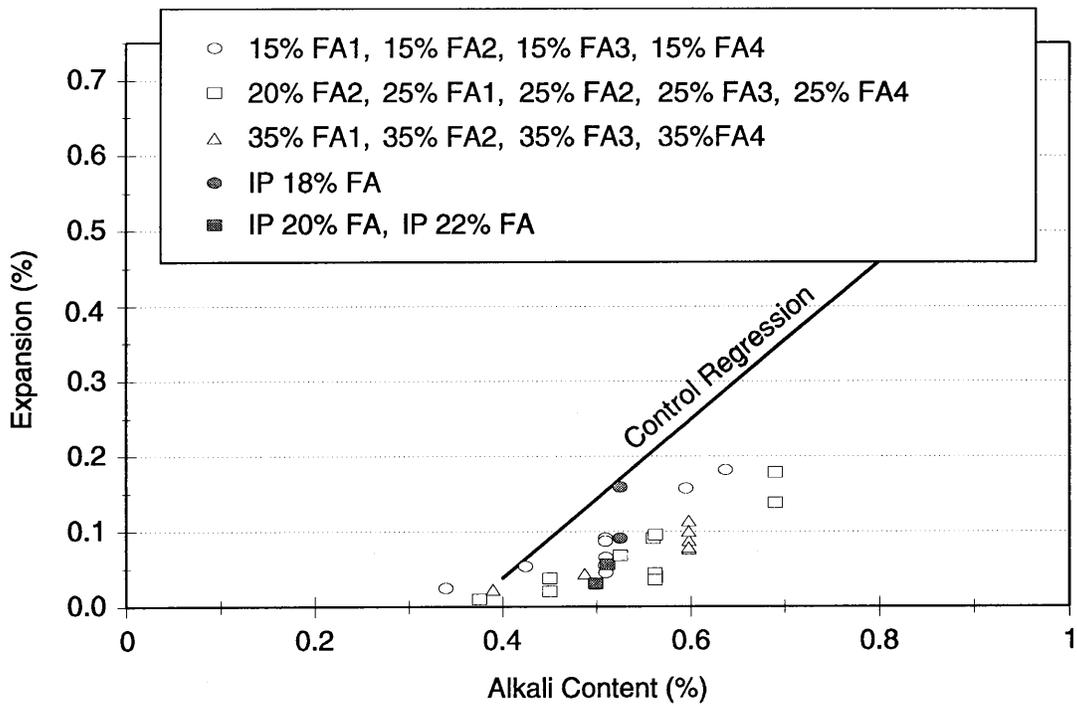


FIGURE 12. 336-Day Expansions of Fly Ash Mortars. The alkali content indicated is the alkali content of the cement used multiplied by the fractional proportion of cement in the mortar.

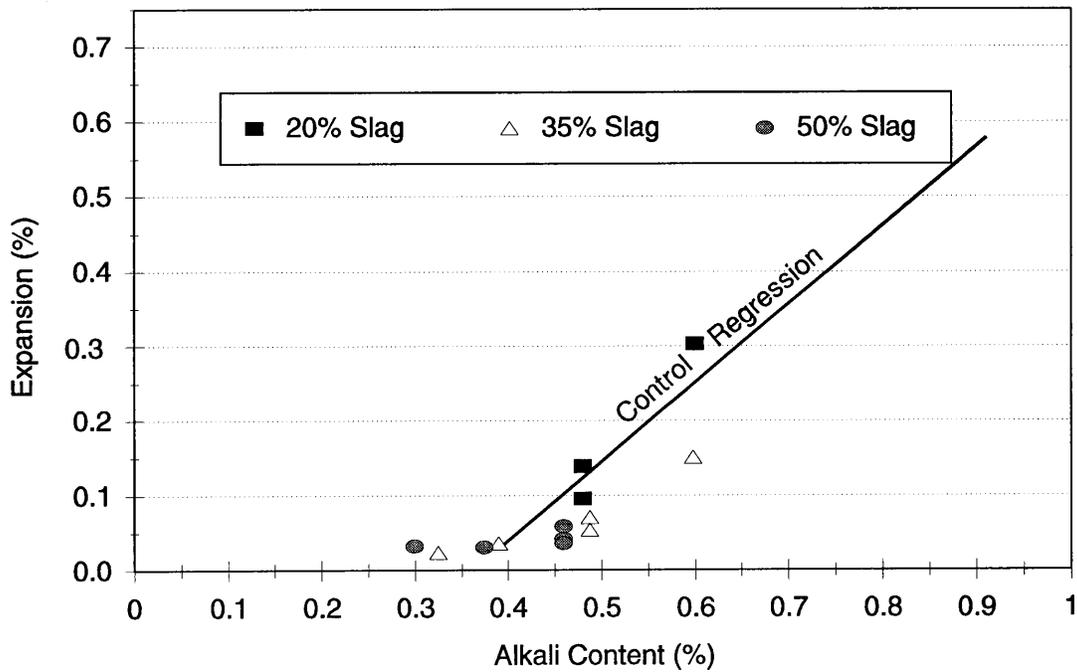


FIGURE 13. 336-Day Expansions of Slag Mortars. The alkali content indicated is the alkali content of the cement used multiplied by the fractional proportion of cement in the mortar.

Fly ash and slag expansion data are plotted against the total alkali content of the mixture (equivalent percent alkali basis) in Figures 14 and 15. This method has been touted as more realistic because it does consider the total mass of alkali in different mixtures on an equal basis. However, in both figures, large differences in expansions are seen between mixtures containing roughly equivalent amounts of alkali. In both cases, much lower expansions occur with mixtures containing higher amounts of fly ash or slag than occur with mixtures having lower amounts. Although this serves to illustrate the effectiveness of fly ash and slag even with relatively high-alkali cements, it indicates that it can be misleading to consider total alkali content calculated in this manner while disregarding the amount of fly ash or slag present. This method shows little utility when compared to either of the previous methods.

Compressive Strength Tests

The results of the compressive strength tests are shown in Figures 16 and 17. Tests were conducted using two control cements. With the 0.60% alkali control cement (cement C) (Figure 16), fly ash was used at 15, 25, and 35% replacement levels; slag at 20, 35, and 50% levels; and silica fume at 3 and 7% levels. With the 0.92% alkali control cement (cement B), only the higher replacement levels of each mineral admixture, 25 and 35% fly ash, 35 and 50% slag, and 7% silica fume, were used because lower replacement levels would not be adequate to control ASR.

As would be expected, replacements with fly ash and slag retarded strength development at the 3-day test age. By 7 days, reductions were noted only with fly ash at the 15, 25, and 35% replacements of the 0.60% alkali cement and the 35% replacement of the 0.92% alkali cement. At the 28-day test age, only the 35% fly ash replacement of the 0.60% alkali cement fell short of the control mixture. These results illustrate that replacements of cement with mineral admixtures and slag can delay the early strength development of concretes. The delays are largely overcome at 7 days. By 28 days, slag and silica fume replacements provide strengths greatly in excess of those of the control mixtures.

It should be anticipated that the use of fly ash and slag may cause some delay in construction due to this retardation effect. However, this delay should primarily affect only form removal times and may be overcome by increasing the total cementitious material in the concrete mixture while maintaining the stipulated percentage of mineral admixture. Thorough mixture design evaluation and trial batching of materials should enable construction to proceed without undue delay to the project. The improved durability and extended service life provided by mineral admixtures and slag far outweigh the costs of slight delays in strength development.

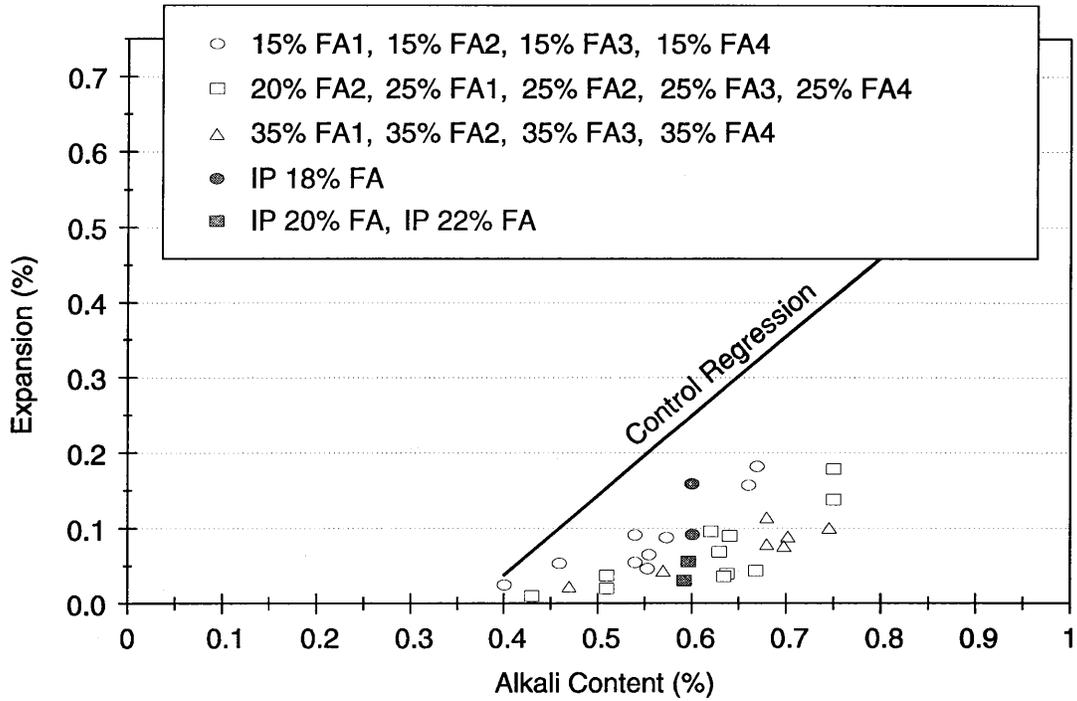


FIGURE 14. 336-Day Expansions of Fly Ash Mortars. The alkali content indicated is the total alkali content of the batch as calculated using Equation 6. It includes contributions from cement and fly ash.

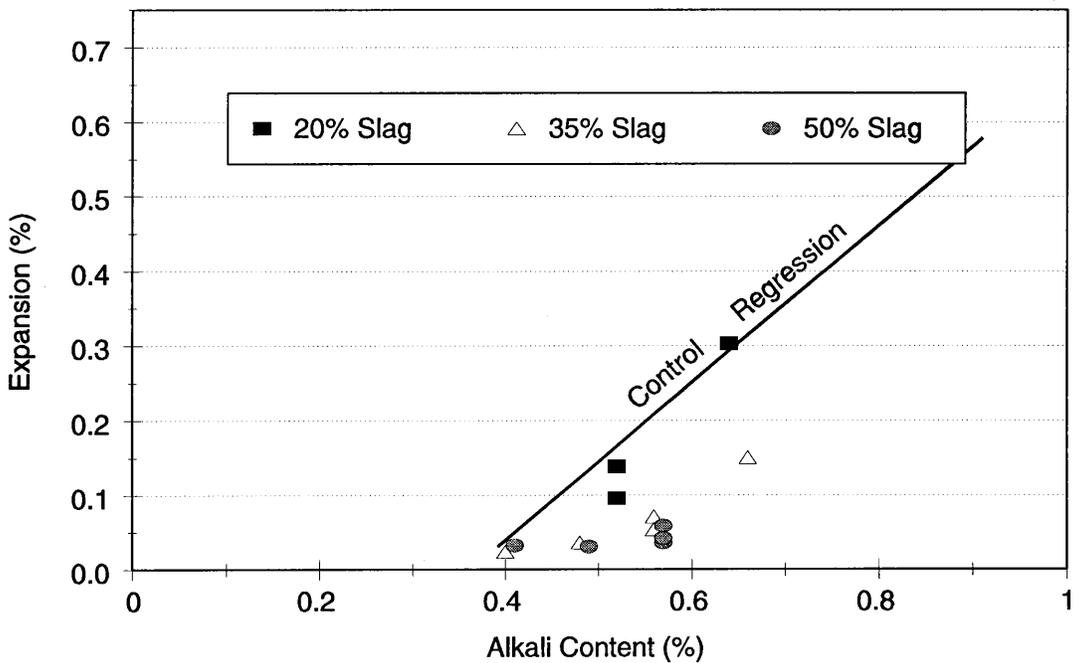


FIGURE 15. 336-Day Expansions of Slag Mortars. The alkali content indicated is the total alkali content of the batch as calculated using Equation 6. It includes contributions from cement and slag.

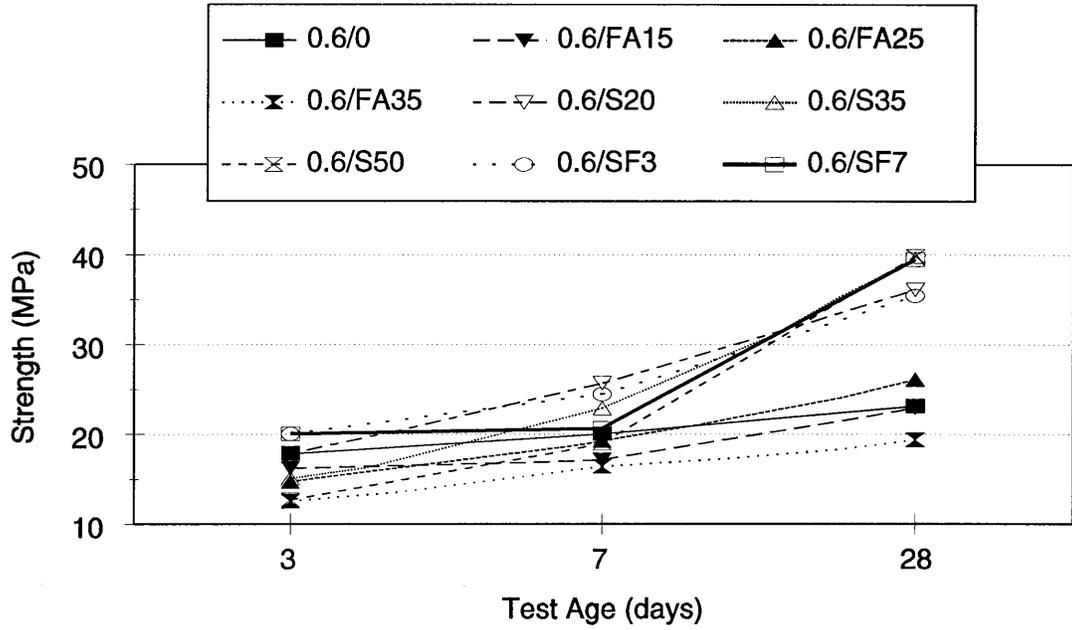


FIGURE 16. Compressive Strengths of Mortars Made with Cement C (0.60% Na₂O Equivalent) and Various Percentage Replacements with Fly Ash (FA1), Slag (S1), and Silica Fume (SF1)

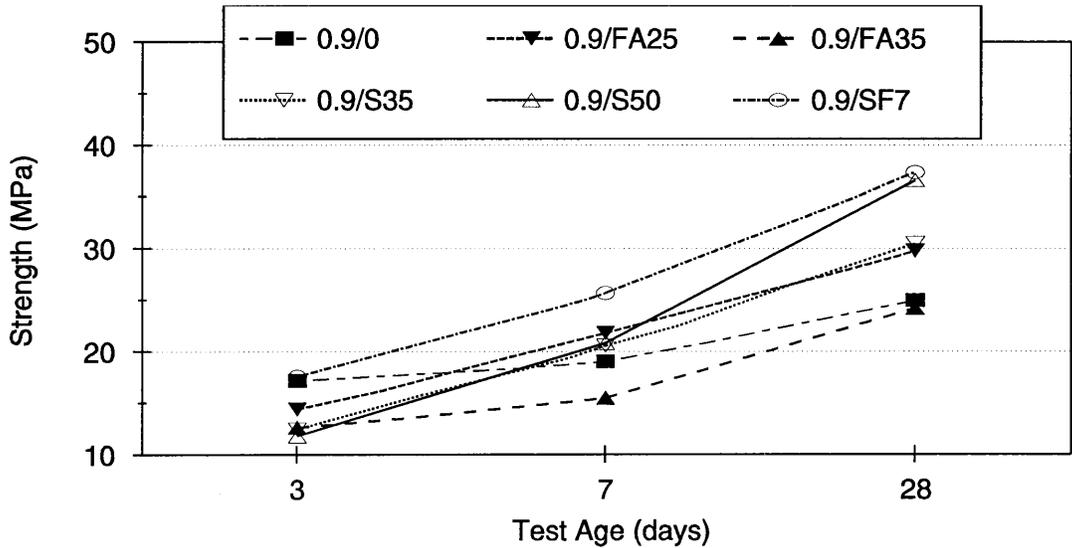


FIGURE 17. Compressive Strengths of Mortars Made with Cement B (0.92% Na₂O Equivalent) and Various Percentage Replacements with Fly Ash (FA1), Slag (S1), and Silica Fume (SF1)

CONCLUSIONS

1. A 56-day storage period is necessary to achieve equilibrium between the pore solution hydroxide ion concentration and the portland cement alkali content in test mortars as reflected by the expansion of mortar bars.
2. The expansion of portland cement mortars made with Pyrex glass is primarily a function of the cement alkali content. Cements with an alkali content at or below 0.40% produce negligible expansions. Above 0.40% alkali, expansion increases linearly with increasing alkali content.
3. A maximum expansion limit of 0.10% can be used to delineate between acceptable and excessive expansions of mortar bars made with Pyrex glass aggregate.
4. Based on the 95% confidence interval, the maximum portland cement alkali content that ensures that mortar bars containing Pyrex glass aggregate will not exhibit excessive expansions is 0.38%. For practical purposes, a value of 0.40% is considered sufficient.
5. Class F fly ash, slag, and silica fume, when used to replace a portion of portland cement, inhibit the excessive expansion of mortar bars containing Pyrex glass aggregate. The amount of inhibition achieved with these materials is primarily a function of the cement alkali content, replacement level, and material type.

RECOMMENDATIONS

1. Portland cements with an alkali content of 0.40% Na_2O or less may be used without restriction in the production of hydraulic cement concrete. However, it should be recognized that concretes which do not contain pozzolans or slag generally have a higher permeability than similar concretes that do contain these materials.
2. Hydraulic cement concrete produced with portland cement having an alkali content exceeding 0.40% should contain a minimum amount of Class F fly ash, slag, or silica fume as follows.

Class F Fly Ash (Total Alkali Content < 3.0% Na_2O Equivalent)

- Concrete produced with portland cements having an alkali content between 0.40 and 0.60% should contain a minimum of 15% fly ash by mass of total cementitious material.

- Concrete produced with portland cements having an alkali content between 0.60 and 0.80% should contain a minimum of 20 to 25% fly ash by mass of total cementitious material.
- Concrete produced with portland cements having an alkali content between 0.80 and 1.0% should contain a minimum of 35% fly ash by mass of total cementitious material.
- Class F fly ashes with a total alkali content exceeding 3.0% Na₂O equivalent should be evaluated as discussed in "Other Materials" below.

Grade 100 or 120 Slag

- Concrete produced with portland cements having an alkali content between 0.40 and 0.80% should contain a minimum of 35% slag by mass of total cementitious material.
- Concrete produced with portland cements having an alkali content exceeding 0.80% should contain a minimum of 50% slag by mass of total cementitious material.

Silica Fume

Concrete produced with portland cements having an alkali content between 0.40 and 0.90% should contain a minimum of 7% silica fume by mass of total cementitious material.

Other Materials

Other classes of fly ash, grades of slag, and mineral admixtures should be tested as outlined in this report with at least three portland cements having alkali contents spread equally across the range between 0.5 and 1.0%. Replicate batches should be tested on separate days for each alkali level. Control batches containing the same cement should be mixed on the same day as the test mixture. Using the 56-day results of the control batches, the 56-day test batch data should be normalized to the 56-day regression line published in this report. The test results should be compared to determine the minimum amounts of the mineral admixture necessary to prevent expansions in excess of 0.10%. The results of 56-day evaluations would be acceptable until such time as 336-day data were available.

3. Tests of the mineral admixtures studied in this project should be conducted with various Virginia aggregates using the rapid immersion method described by Stark et al. (1993) and the Canadian concrete prism test (Canadian Standards Association, 1994). The results could then be compared to the findings of this project in an effort to optimize the proportions of

materials needed to ensure the long-term durability of concretes used in Virginia's transportation system.

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APPENDIX A: CONTROL BATCHES

| Alkali Content | Batch ID | Exp % | | | | | |
|----------------|----------|---------|---------|---------|---------|---------|---------|
| | | 14 day | 28 day | 56 day | 84 day | 168 day | 1 Yr |
| 0.18 | A1 | 0.0053% | 0.0077% | 0.0085% | 0.0105% | 0.0052% | 0.0087% |
| 0.18 | H8 | 0.0033% | 0.0050% | 0.0073% | 0.0040% | 0.0080% | 0.0105% |
| 0.40 | A2 | 0.0050% | 0.0113% | 0.0135% | 0.0163% | 0.0132% | 0.0148% |
| 0.40 | H1 | 0.0103% | 0.0200% | 0.0387% | 0.0527% | 0.0653% | 0.0687% |
| 0.40 | B1 | 0.0085% | 0.0110% | 0.0095% | 0.0125% | 0.0155% | 0.0178% |
| 0.40 | B2 | 0.0083% | 0.0105% | 0.0085% | 0.0113% | 0.0145% | 0.0165% |
| 0.50 | G1 | 0.0807% | 0.1160% | 0.1330% | 0.1380% | 0.1373% | 0.1387% |
| 0.50 | B3 | 0.0198% | 0.0275% | 0.0308% | 0.0360% | 0.0403% | 0.0418% |
| 0.57 | A3 | 0.2328% | 0.3333% | 0.3548% | 0.3640% | 0.3608% | 0.3643% |
| 0.60 | B5 | 0.0965% | 0.1345% | 0.1493% | 0.1580% | 0.1623% | 0.1643% |
| 0.60 | A4 | 0.1380% | 0.2000% | 0.2190% | 0.2293% | 0.2273% | 0.2305% |
| 0.60 | C1 | 0.1267% | 0.1740% | 0.1943% | 0.1900% | 0.1903% | 0.1917% |
| 0.60 | D1 | 0.1143% | 0.1460% | 0.1623% | 0.1657% | 0.1647% | 0.1687% |
| 0.60 | H2 | 0.1127% | 0.1880% | 0.2767% | 0.3013% | 0.3170% | 0.3200% |
| 0.60 | B4 | 0.1520% | 0.2060% | 0.2178% | 0.2270% | 0.2305% | 0.2340% |
| 0.60 | C2 | 0.1827% | 0.2530% | 0.2650% | 0.2690% | 0.2677% | 0.2710% |
| 0.60 | N1 | 0.1490% | 0.2280% | 0.3213% | 0.3530% | 0.3670% | 0.3703% |
| 0.64 | A5 | 0.1923% | 0.2820% | 0.3033% | 0.3093% | 0.3068% | 0.3100% |
| 0.70 | E1 | 0.2870% | 0.4023% | 0.3237% | 0.4313% | 0.3307% | 0.3347% |
| 0.70 | F1 | 0.2327% | 0.3047% | 0.4270% | 0.3307% | 0.4313% | 0.4363% |
| 0.75 | G4 | 0.2697% | 0.3713% | 0.3943% | 0.4027% | 0.4037% | 0.4093% |
| 0.75 | D5 | 0.2110% | 0.2773% | 0.3047% | 0.3100% | 0.3097% | 0.3140% |
| 0.75 | B6 | 0.2055% | 0.2890% | 0.3120% | 0.3255% | 0.3305% | 0.3348% |
| 0.75 | M1 | 0.2317% | 0.3990% | 0.5573% | 0.6217% | 0.6417% | 0.6450% |
| 0.89 | A6 | 0.2960% | 0.4168% | 0.4378% | 0.4560% | 0.4565% | 0.4630% |
| 0.92 | H5 | 0.2297% | 0.3640% | 0.4523% | 0.4707% | 0.4840% | 0.4907% |
| 0.92 | I1 | 0.1673% | 0.3817% | 0.5063% | 0.5430% | 0.5707% | 0.5800% |
| 0.92 | L1 | 0.1923% | 0.3953% | 0.5347% | 0.6280% | 0.6593% | 0.6667% |
| 0.92 | J1 | 0.2187% | 0.3777% | 0.5007% | 0.5577% | 0.5817% | 0.5927% |

| Summary | | 14 day | 28 day | 56 day | 84 day | 168 day | 1 Yr |
|---------|-------|---------|---------|---------|---------|---------|---------|
| 0.18 | n | 2 | 2 | 2 | 2 | 2 | 2 |
| | avg | 0.0043% | 0.0064% | 0.0079% | 0.0073% | 0.0066% | 0.0096% |
| | s | 0.0014% | 0.0019% | 0.0008% | 0.0046% | 0.0019% | 0.0012% |
| 0.40 | n | 4 | 4 | 4 | 4 | 4 | 4 |
| | avg | 0.0080% | 0.0132% | 0.0175% | 0.0232% | 0.0271% | 0.0294% |
| | s | 0.0022% | 0.0046% | 0.0142% | 0.0198% | 0.0255% | 0.0262% |
| 0.50 | n | 2 | 2 | 2 | 2 | 2 | 2 |
| | avg | 0.0502% | 0.0718% | 0.0819% | 0.0870% | 0.0888% | 0.0902% |
| | s | 0.0431% | 0.0626% | 0.0723% | 0.0721% | 0.0686% | 0.0685% |
| 0.57 | n = 1 | ----- | ----- | ----- | ----- | ----- | ----- |
| 0.60 | n | 8 | 8 | 8 | 8 | 8 | 8 |
| | avg | 0.1340% | 0.1912% | 0.2257% | 0.2367% | 0.2408% | 0.2438% |
| | s | 0.0273% | 0.0397% | 0.0588% | 0.0679% | 0.0730% | 0.0732% |
| 0.64 | n = 1 | ----- | ----- | ----- | ----- | ----- | ----- |
| 0.70 | n | 2 | 2 | 2 | 2 | 2 | 2 |
| | avg | 0.2598% | 0.3535% | 0.3753% | 0.3810% | 0.3810% | 0.3855% |
| | s | 0.0384% | 0.0691% | 0.0731% | 0.0712% | 0.0712% | 0.0719% |
| 0.75 | n | 4 | 4 | 4 | 4 | 4 | 4 |
| | avg | 0.2295% | 0.3342% | 0.3921% | 0.4150% | 0.4214% | 0.4258% |
| | s | 0.0291% | 0.0602% | 0.1174% | 0.1436% | 0.1523% | 0.1518% |
| 0.89 | n = 1 | ----- | ----- | ----- | ----- | ----- | ----- |
| 0.92 | n | 4 | 4 | 4 | 4 | 4 | 4 |
| | avg | 0.2020% | 0.3797% | 0.4985% | 0.5498% | 0.5739% | 0.5825% |
| | s | 0.0279% | 0.0129% | 0.0342% | 0.0645% | 0.0718% | 0.0722% |

APPENDIX B: FLY ASH BATCHES

| Alkali Content | 15% FA2 | 15% FA1 | 25% FA1 | 15% FA1 | 25% FA1 | 15% FA1 | 25% FA1 | 15% FA1 | 35% FA1 | 15% FA2 | 15% FA3 | 15% FA4 | 20% FA2 | 15% FA2 | 25% FA2 | 15% FA1 | 25% FA1 |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| A | 0.40 | 0.50 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.70 | 0.70 | 0.70 | 0.75 | 0.75 |
| B | 0.40 | 0.46 | 0.54 | 0.51 | 0.54 | 0.51 | 0.47 | 0.47 | 0.51 | 0.57 | 0.55 | 0.55 | 0.64 | 0.66 | 0.63 | 0.67 | 0.62 |
| C | 0.34 | 0.43 | 0.51 | 0.45 | 0.51 | 0.45 | 0.39 | 0.39 | 0.51 | 0.51 | 0.51 | 0.51 | 0.56 | 0.60 | 0.53 | 0.64 | 0.56 |
| Batch ID | F6 | G2 | G3 | H3 | H4 | H2 | H2 | H3 | C3 | C4 | C5 | C6 | N5 | M8 | E5 | E6 | G5 |
| Control ID | | G1 | G1 | H2 | H2 | H2 | H2 | H2 | C1 | C1 | C1 | C1 | N1 | M1 | E1 | E1 | G4 |
| DAYS | | | | | | | | | | | | | | | | | |
| 14 | 0.0063% | 0.0407% | 0.0033% | 0.0720% | 0.0197% | 0.0603% | 0.0273% | 0.0273% | 0.0163% | 0.1077% | 0.0960% | 0.0703% | 0.0713% | 0.1387% | 0.0483% | 0.1573% | 0.0797% |
| 28 | 0.0037% | 0.0440% | 0.0040% | 0.0623% | 0.0223% | 0.0680% | 0.0273% | 0.0273% | 0.0157% | 0.1193% | 0.1080% | 0.0793% | 0.0743% | 0.1567% | 0.0570% | 0.1670% | 0.0840% |
| 56 | 0.0113% | 0.0483% | 0.0073% | 0.0700% | 0.0247% | 0.0707% | 0.0287% | 0.0287% | 0.0153% | 0.1330% | 0.1133% | 0.0843% | 0.0807% | 0.1877% | 0.0607% | 0.1763% | 0.0910% |
| 84 | 0.0113% | 0.0500% | 0.0083% | 0.0670% | 0.0207% | 0.0713% | 0.0293% | 0.0293% | 0.0167% | 0.1600% | 0.1250% | 0.0910% | 0.0827% | 0.1997% | 0.0623% | 0.1783% | 0.0927% |
| 112 | 0.0130% | 0.0510% | 0.0080% | 0.0717% | 0.0227% | 0.0753% | 0.0300% | 0.0283% | 0.0173% | 0.1703% | 0.1297% | 0.0933% | 0.0823% | 0.2033% | 0.0623% | 0.1800% | 0.0927% |
| 168 | 0.0133% | 0.0510% | 0.0083% | 0.0743% | 0.0233% | 0.0703% | 0.0283% | 0.0283% | 0.0163% | 0.1760% | 0.1327% | 0.0960% | 0.0817% | 0.2030% | 0.0623% | 0.1810% | 0.0937% |
| 252 | 0.0127% | 0.0523% | 0.0093% | 0.0780% | 0.0273% | 0.0740% | 0.0300% | 0.0300% | 0.0180% | 0.1803% | 0.1370% | 0.0967% | 0.0817% | 0.2013% | 0.0617% | 0.1837% | 0.0960% |
| 336 | 0.0180% | 0.0557% | 0.0107% | 0.0817% | 0.0300% | 0.0760% | 0.0313% | 0.0313% | 0.0190% | 0.1853% | 0.1390% | 0.0987% | 0.0873% | 0.2097% | 0.0660% | 0.1857% | 0.0977% |
| Norm 1Yr | 0.0255% | 0.0542% | 0.0104% | 0.0554% | 0.0204% | 0.0918% | 0.0379% | 0.0230% | 0.0230% | 0.0873% | 0.0655% | 0.0465% | 0.0910% | 0.1574% | 0.0688% | 0.1827% | 0.0961% |

A - alkali content of cement, Na2O equiv. percent

B - alkali content of batch contributed by cement (A x fractional proportion of cement) percent

C - alkali content of batch, cement plus mineral admixture (PC alk% x FP + FA alk% x FP x .17)

PC - portland cement; FP - fraction proportion in batch; FA - fly ash

Appendix B: Fly Ash Batches (Cont'd)

| Alkali Content | 35% FA1 | 25% FA2 | 25% FA3 | 25% FA4 | IP18% | IP18% | IP20% | IP22% | 25% FA1 | 35% FA1 | 25% FA1 | 35% FA1 | 25% FA1 | 35% FA1 | 35% FA2 | 35% FA3 | 35% FA4 |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| A | 0.75 | 0.75 | 0.75 | 0.75 | 0.64 | 0.64 | 0.64 | 0.64 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 |
| B | 0.57 | 0.67 | 0.64 | 0.63 | 0.60 | 0.60 | 0.60 | 0.59 | 0.75 | 0.68 | 0.75 | 0.68 | 0.68 | 0.75 | 0.75 | 0.70 | 0.70 |
| C | 0.49 | 0.56 | 0.56 | 0.56 | 0.52 | 0.52 | 0.51 | 0.50 | 0.69 | 0.60 | 0.69 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| Batch ID | G9 | M4 | M5 | M6 | C6 | L8 | L7 | M7 | H6 | H7 | I2 | I3 | I3 | L2 | L3 | L4 | L4 |
| Control ID | G4 | M1 | M1 | M1 | L1 | L1 | L1 | M1 | H5 | H5 | I1 | I1 | I1 | L1 | L1 | L1 | L1 |
| DAYS | 14 | 0.0303% | 0.0777% | 0.0783% | 0.0690% | 0.1037% | 0.0683% | 0.0423% | 0.0537% | 0.1203% | 0.0700% | 0.0943% | 0.0530% | 0.0800% | 0.0730% | 0.0597% | 0.0597% |
| 28 | 0.0313% | 0.0883% | 0.0860% | 0.0760% | 0.1180% | 0.0837% | 0.0533% | 0.0603% | 0.1343% | 0.0793% | 0.1127% | 0.0623% | 0.0623% | 0.0973% | 0.0880% | 0.0730% | 0.0730% |
| 56 | 0.0330% | 0.0973% | 0.0917% | 0.0817% | 0.1207% | 0.0870% | 0.0600% | 0.0660% | 0.1427% | 0.0857% | 0.1217% | 0.0673% | 0.0673% | 0.1007% | 0.0913% | 0.0757% | 0.0757% |
| 84 | 0.0383% | 0.1030% | 0.0960% | 0.0847% | 0.1257% | 0.0953% | 0.0587% | 0.0703% | 0.1410% | 0.0823% | 0.1227% | 0.0687% | 0.0687% | 0.1067% | 0.0943% | 0.0780% | 0.0780% |
| 112 | 0.0390% | 0.1053% | 0.0973% | 0.0867% | 0.1270% | 0.0973% | 0.0603% | 0.0717% | 0.1427% | 0.0860% | 0.1250% | 0.0703% | 0.0703% | 0.1080% | 0.0967% | 0.0793% | 0.0793% |
| 168 | 0.0403% | 0.1070% | 0.0977% | 0.0877% | 0.1263% | 0.1013% | 0.0637% | 0.0730% | 0.1457% | 0.0893% | 0.1260% | 0.0693% | 0.0693% | 0.1130% | 0.1000% | 0.0843% | 0.0843% |
| 252 | 0.0433% | 0.1090% | 0.0990% | 0.0887% | 0.1260% | 0.1053% | 0.0680% | 0.0747% | 0.1507% | 0.0943% | 0.1317% | 0.0747% | 0.0747% | 0.1197% | 0.1050% | 0.0890% | 0.0890% |
| 336 | 0.0447% | 0.1110% | 0.1003% | 0.0907% | 0.1317% | 0.1050% | 0.0657% | 0.0767% | 0.1543% | 0.0983% | 0.1373% | 0.0787% | 0.0787% | 0.1180% | 0.1033% | 0.0893% | 0.0893% |
| Norm 1Yr | 0.0439% | 0.0443% | 0.0400% | 0.0361% | 0.1591% | 0.0900% | 0.0560% | 0.0310% | 0.1792% | 0.1142% | 0.1385% | 0.0793% | 0.0793% | 0.1015% | 0.0889% | 0.0768% | 0.0768% |

A - alkali content of cement, Na2O equiv. percent

B - alkali content of batch contributed by cement (A x fractional proportion of cement) percent

C - alkali content of batch, cement plus mineral admixture (PC alk% x FP + FA alk% x FP x .17)

PC - portland cement; FP - fraction proportion in batch; FA - fly ash

APPENDIX C: SLAG BATCHES

| Alkali Content | 35% S1 | 20% S1 | 35% S1 | 50% S1 | 20% S1 | 35% S1 | 50% S1 | 20% S1 | 35% S1 | 50% S1 | 35% S1 | 50% S1 | 50% S1 | 50% S1 |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| A | 0.50 | 0.60 | 0.60 | 0.60 | 0.60 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.92 | 0.92 | 0.92 |
| B | 0.40 | 0.52 | 0.48 | 0.41 | 0.52 | 0.64 | 0.56 | 0.49 | 0.56 | 0.66 | 0.66 | 0.57 | 0.57 | 0.57 |
| C | 0.33 | 0.48 | 0.39 | 0.30 | 0.48 | 0.60 | 0.49 | 0.37 | 0.49 | 0.60 | 0.60 | 0.46 | 0.46 | 0.46 |
| Batch ID | G10 | D2 | D3 | D4 | N2 | D6 | D7 | D8 | M2 | I4 | I5 | J5 | J5 | L5 |
| Control ID | G1 | D1 | D1 | D1 | N1 | D5 | D5 | D5 | M1 | I1 | I1 | J1 | J1 | L1 |
| DAYS | 14 | 0.0087% | 0.0103% | 0.0093% | 0.0607% | 0.1477% | 0.0227% | 0.0077% | 0.0300% | 0.0337% | 0.0103% | 0.0110% | 0.0110% | 0.0320% |
| 28 | 0.0103% | 0.0417% | 0.0107% | 0.0100% | 0.1167% | 0.1940% | 0.0297% | 0.0087% | 0.0460% | 0.0627% | 0.0183% | 0.0193% | 0.0193% | 0.0420% |
| 56 | 0.0150% | 0.0623% | 0.0167% | 0.0147% | 0.2173% | 0.2337% | 0.0423% | 0.0147% | 0.0790% | 0.0950% | 0.0247% | 0.0217% | 0.0217% | 0.0465% |
| 84 | 0.0170% | 0.0690% | 0.0197% | 0.0173% | 0.2700% | 0.2460% | 0.0490% | 0.0177% | 0.1117% | 0.1060% | 0.0277% | 0.0317% | 0.0317% | 0.0565% |
| 112 | 0.0190% | 0.0713% | 0.0200% | 0.0173% | 0.2860% | 0.2470% | 0.0517% | 0.0190% | 0.1200% | 0.1190% | 0.0303% | 0.0287% | 0.0287% | 0.0585% |
| 168 | 0.0197% | 0.0703% | 0.0190% | 0.0170% | 0.2893% | 0.2450% | 0.0510% | 0.0183% | 0.1280% | 0.1280% | 0.0310% | 0.0307% | 0.0307% | 0.0670% |
| 252 | 0.0217% | 0.0713% | 0.0220% | 0.0197% | 0.2913% | 0.2457% | 0.0538% | 0.0213% | 0.1327% | 0.1460% | 0.0397% | 0.0373% | 0.0373% | 0.0705% |
| 336 | 0.0247% | 0.0737% | 0.0283% | 0.0257% | 0.2947% | 0.2487% | 0.0583% | 0.0257% | 0.1357% | 0.1500% | 0.0427% | 0.0373% | 0.0373% | 0.0690% |
| Norm 1Yr | 0.0240% | 0.0960% | 0.0369% | 0.0335% | 0.1388% | 0.3035% | 0.0712% | 0.0313% | 0.0541% | 0.1512% | 0.0430% | 0.0368% | 0.0368% | 0.0593% |

A - alkali content of cement, Na2O equiv. percent

B - alkali content of batch contributed by cement (A x fractional proportion of cement) percent

C - alkali content of batch, cement plus mineral admixture (PC alk% x FP + slag alk% x FP x .50)

PC - portland cement; FP - fraction proportion in batch

APPENDIX D: SILICA FUME BATCHES

| Alkali Content | 3% SF1 | 7% SF1 | 7% SF1 | 3% SF1 | 7% SF1 |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|
| A | 0.60 | 0.60 | 0.60 | 0.75 | 0.75 | 0.75 | 0.75 | 0.92 | 0.92 | 0.92 |
| B | 0.60 | 0.59 | 0.59 | 0.74 | 0.73 | 0.73 | 0.73 | 0.89 | 0.89 | 0.89 |
| C | 0.58 | 0.56 | 0.56 | 0.73 | 0.70 | 0.70 | 0.70 | 0.86 | 0.86 | 0.86 |
| Batch ID | L7 | C8 | N3 | G7 | G8 | M3 | I6 | J6 | L6 | |
| Control ID | | C1 | N1 | G4 | G4 | M1 | I1 | J1 | L1 | |
| DAYS | | | | | | | | | | |
| 14 | 0.0440% | 0.0093% | 0.0077% | 0.1293% | 0.0140% | 0.0250% | 0.0197% | 0.0213% | 0.0240% | |
| 28 | 0.0730% | 0.0117% | 0.0123% | 0.1827% | 0.0190% | 0.0313% | 0.0313% | 0.0330% | 0.0433% | |
| 56 | 0.1023% | 0.0150% | 0.0150% | 0.2123% | 0.0275% | 0.0467% | 0.0490% | 0.0477% | 0.0703% | |
| 84 | 0.1097% | 0.0167% | 0.0247% | 0.2250% | 0.0305% | 0.0780% | 0.0580% | 0.0607% | 0.1217% | |
| 112 | 0.1117% | 0.0197% | 0.0283% | 0.2267% | 0.0325% | 0.0880% | 0.0673% | 0.0713% | 0.1383% | |
| 168 | 0.1093% | 0.0183% | 0.0307% | 0.2267% | 0.0350% | 0.0990% | 0.0723% | 0.0803% | 0.1603% | |
| 252 | 0.1103% | 0.0193% | 0.0343% | 0.2290% | 0.0355% | 0.1050% | 0.0920% | 0.0983% | 0.1747% | |
| 336 | 0.1140% | 0.0233% | 0.0387% | 0.2300% | 0.0400% | 0.1097% | 0.0977% | 0.1067% | 0.1777% | |
| Norm 1Yr | 0.1378% | 0.0282% | 0.0180% | 0.2263% | 0.0394% | 0.0440% | 0.0985% | 0.1052% | 0.1530% | |

A - alkali content of cement, Na2O equiv. percent

B - alkali content of batch contributed by cement (A x fractional proportion of cement) percent

C - alkali content of batch, cement plus mineral admixture (PC alk% x FP + SF alk% x FP)

PC - portland cement; FP - fraction proportion in batch; SF - silica fume