Greatly Increased Use of Fly Ash in Hydraulic Cement Concrete (HCC) for Pavement Layers and Transportation Structures - Volume I

Final Report to Research Consortium led by Purdue University and funded by FHWA (March 2012)

Prepared by
Karthik H. Obla, PhD, PE, Colin L. Lobo and Haejin Kim, PhD

Prime Award No. DTFGH61-09-H-00005
Subaward No. 4108-30885

The National Ready Mixed Concrete Association (NRMCA) was involved in 2 phases of this project.

Phase I – Fly ash Use Survey

The purpose of this phase is to evaluate the past, current and future trends of use of fly ash in concrete and restrictions to its use. The American Coal Ash Association[1] (ACAA) conducts an annual survey of fly ash production and use. Typically on an annual basis out of the 70 million tons of fly ash generated, about 40% is beneficially utilized. Out of the fly ash that is beneficially used about 50% is used in cement and concrete applications. Table 1a has been developed based on fly ash use as reported by ACAA, slag cement use as reported by the Slag Cement Association[2] and cement use as reported by the US Geological Survey[3]. Ready mixed concrete production is estimated from cement shipments reported by USGS. Several other assumptions as stated in Table 1a are made to derive the fly ash volume used in ready mixed concrete. Table 1a shows that even though concrete volume had decreased, fly ash and fly ash+slag cement use had steadily increased and stood at 12% and 16% respectively of the total cementitious content in 2008. These percentages should not be confused to percent of cementitious materials used in typical concrete mixtures.

Even though ready mixed concrete forms the single largest market for fly ash it can still offer the largest potential for increased fly ash utilization. There is a large body of research and literature[4-6] on the development and use of High-Volume Fly Ash (HVFA) concrete but actual use still is much lower. In order to clarify some of the assumptions and corroborate the findings made in Table 1a a survey of ready mixed concrete producers was conducted to determine:

1. Average amounts of cement, fly ash, slag cement, and silica fume used in a cubic yard of ready mixed concrete. This will serve as a bench mark for future comparisons.
2. Differences between the percent of supplementary cementitious materials (SCM) use between companies
3. Primary reasons for not using more fly ash. This will help devise programs for enhancing fly ash use in ready mixed concrete.

The survey was based on excel and is reproduced in Appendix A.1. The survey findings are as follows:

Survey Respondents

A total of 57 companies/divisions responded constituting total ready mixed concrete production in 2010-11 (12 months) of 35 million yd^3 which was 13% of total production for that period. The breakdown of survey respondents is: 53% of the companies produced less than 250,000 yd^3, 32% between 250,000 and 1 million yd^3, and 16% of the companies produced more than 1 million yd^3. The average reported production per respondent was 610,000 yd^3. Table 1b shows the minimum, maximum and percentile breakdown of production amounts. The respondents cover a broad range of production.

Use of SCMs

About 98% of the companies had used fly ash in some of their concrete over that time period. It does not mean that fly ash was used in all the concrete produced. Similarly 61% of the companies had used slag cement and 39% of the companies used silica fume. 9% of the companies used blended cement. 61% of the companies reported using blended cement and/or more than one SCM but not necessarily in the same concrete mixture.

Quantity of SCMs used

The average reported portland cement consumption was 457 lb per yd^3 produced; blended cement was 2.7 lb/yd^3; fly ash was 83 lb/yd^3; slag cement was 18 lb/yd^3; silica fume was 0.2 lb/yd^3. These numbers do not reflect typical concrete mixture proportions being used. Rather for each specific material (for example slag cement) they are arrived at by dividing the total material consumed annually by all respondents by the total annual concrete produced by all respondents. In the discussions below the fly ash and total SCM was calculated after assuming that the blended cement had on average 70% portland cement, 10% fly ash, and 30% total SCM (this includes the 10% fly ash). Table 1b shows the minimum, maximum and percentile breakdown of portland cement, fly ash and total SCM used. Figure 1 shows the cumulative distribution function of the total SCM use. When the 20^{th} and 80^{th} percentile numbers are compared it is clear that there is a 2-3 times increase in the amount of fly ash and total SCM used between companies.

SCM Use by company size

No trends can be observed in average portland cement, and/or SCM usage when companies are differentiated based on their production levels. Table 1c shows the average portland cement, fly ash, and total SCM consumption for companies producing less than 250,000 yd^3, between 250,000 and 1 million yd^3, and over 1 million yd^3. The averages for “all” production are also provided. The average portland cement content was consistently around 455 lb/ yd^3 and average total SCM content was consistently around 102 lb/yd^3. Smaller producers used more slag cement as compared to fly ash but this may be a result of the regional availability and companies responding to the survey.

Breakdown of concrete production based on SCM use

Producers were asked to state how much of their production was with straight portland cement etc. It is not clear how many companies were tracking these numbers; therefore there is some uncertainty associated with responses to this question. Data analysis reveals that 34% of all ready mixed concrete produced was with straight portland cement; 2.2% with blended cement only, 56% with fly ash as the only SCM, 5.1% with slag cement as the only SCM, 0.1% was with silica fume as the only SCM, and 2.8% was with more than one SCM (ternary mixtures).

Reasons that limit use of fly ash

Producers were asked to rank the reasons for not substantially increasing the use of fly ash with "1" being extremely important and "6" being least important. Table 1d illustrates the average ratings. Restrictive specifications and concrete performance issues ranked as the most important reasons (average rating of 2.5), followed by customer objection (2.9), variable fly ash properties (3.9) and finally fly ash availability and use of other SCMs (4.6). Lack of fly ash availability may be a localized concern in some areas. Use of other SCMs is not considered as an important reason. Use of other SCMs like slag cement also helps improve concrete performance and makes concrete more sustainable. In a slightly different way of analyzing these data, producer rankings 1, and 2 were compiled together as "strongly agree", 3-4 were termed "agree" and 5-6 were termed "neutral". Table 1d illustrates that by this approach the rankings are the same as before with restrictive specifications and performance issues ranked as the most important reasons for limiting use. There was no correlation between how producers responded to this question and their production numbers, and/or extent of SCM use.

Opportunities for Increasing the use of fly ash

Producers were also asked to list the various opportunities that exist to substantially increase the use of fly ash. Individual comments from the survey are captured in Appendix A.2. A vast majority of them listed education of specifiers and owners on the benefits of use of SCMs as the most important reason; some of them listed cost and performance issues such as setting time and early age strength; a few listed lack of availability but that might again be a localized phenomenon.

Conclusions

If the overall average SCM use increases to the currently reported 80th percentile level in Table 1b that would lead to an increase in SCM use from 102 lb to 144 lb per cubic yard produced, i.e. an increase of 42 lb. If all of this increase is attributed to increase in fly ash use and if the annual ready mixed concrete production were to recover to the pre 2008 recession level of 460 million yd^3 that would increase the beneficial use of fly ash by an additional 14 million tons. This represents an increase of fly ash utilization from 40%, currently, to 61%. For all ready mixed concrete produced SCM use will then constitute 26% of the total cementitious content as opposed to the current levels of 18%. In order to accomplish this, it is suggested that a series of seminars with the target audience of specifying engineers, contractors and concrete producers be conducted with the following goals:

1. Replace specification restrictions on SCM dosages with concrete performance requirements.
2. Share laboratory/field data showing acceptable concrete performance with higher amounts of SCMs
3. Share best practices for successfully incorporating higher amounts of SCMs and achieving concrete performance requirements

It may be useful to include presentations by concrete producers who are already at the 80% percentile in terms of use of SCMs.

Phase II – Development of an Activation Energy Database and Strength-Maturity Relationship

One of the primary reasons provided for not using HVFA concrete is its slower setting characteristics and rate of strength development, especially at early ages. This can be addressed to some extent through the effective use of chemical admixtures and proportions and characteristics of other ingredients when developing and producing concrete mixtures. In an earlier research study[7] it was clearly shown that even though laboratory or field cured measured strengths at early ages of HVFA concrete mixtures are low the actual strengths in the structure is higher. This is because the greater mass of concrete in most structures entraps more heat generated by the hydration reactions of cementitious materials. Higher in-place concrete temperatures allow for faster rate of strength gain in the structure than indicated by strength of standard-cured or field-cured cylinders.

Maturity techniques have been developed and used to predict the concrete strength in the structure. The strength of in-place concrete in the structure is estimated by monitoring its temperature history over time, calculating the accumulated maturity, and by obtaining an estimated strength from the pre-determined strength-maturity relationship that is unique to that set of materials and the mixture. Maturity concepts are well established for concrete mixtures containing only portland cement. Not much work has been done with HVFA concrete mixtures containing chemical admixtures. The Arrhenius and Nurse-Saul maturity functions are commonly used to calculate the maturity index. The Arrhenius maturity function is considered to be more accurate and it requires the use of a mixture-specific activation energy to yield accurate results. Activation energy parameters for HVFA have not been established to any degree of accuracy. This phase of the project therefore focuses on developing an activation energy database comprising of typical fly ashes and portland cements used commercially. The activation energy quantifies the temperature sensitivity of the concrete mixture. The activation energy of each of the concrete mixture is established using the procedure outlined in ASTM C1074-11[8].

Trial Concrete Mixtures

The physical and chemical properties of the three fly ashes and the two cements used in this study are provided in Table 2. An ASTM C494[8] Type F polycarboxylate based super plasticizer and a Type C accelerating admixture were used.

Before starting on the activation energy testing several trial mixtures were prepared to finalize the most optimal HVFA concrete mixture combination that will yield adequate early age strengths and workability.

Table 3 shows the concrete mixture proportions and test results:

- Mixture 1 is the control mixture with low alkali Type I cement (Cement A) and no fly ash.

- Mixture 2 is the HVFA concrete mixture containing 50% fly ash (fly ash FAA) designed to attain higher early age strength by using a low w/cm (low mixing water content and high cementitious content). Mixture 2 attained about 3000 psi at 2 days and 3800 psi at 4 days. This rate of strength gain is adequate for most applications. Mixture 2 could be used for vertical elements but it was determined that the consistency was very sticky. This was likely due to the high paste volume and the use of a low water content and high HRWRA. Mortar mixtures were evaluated by varying proportions to improve the workability. To improve this in Mixture 3 cement replacement with fly ash was done on a volume basis while maintaining the total paste volume equal to that of the control concrete Mixture 1. This led to the development of HVFA Mixture 3.
- Mixture 3 is a HVFA mixture. The fly ash was at 50% volume of total cementitious (approximately 40% by weight). Mixture 3 had a lower mixing water content and HRWR admixture dosage level than Mixture 2 and similar workability. Comparing the strength at early age of 2 and 4 days of this mixture to Mixture 2 it is clear that the fly ash does not appear to be contributing much to strength gain. At a 45°F curing temperature (by placing the cylinders in a refrigerator maintained at 45°F) the 2 day compressive strengths was 1700 psi.
- Mixture 4 is a modification of Mixture 3 by using 30 oz/cwt of a Type C non-chloride accelerating admixture. This caused an increase in the 2 and 4 day strengths for concrete cured at 73°F and at the 45°F curing temperature, compared to Mixture 3.
- In Mixture 5 a Type III cement from a different source replaced the Type I cement used in Mixture 4. Using the Type III cement yielded a significantly higher compressive strengths for specimens cured at 73°F and at 45°Fas indicated in Table 3. The measured strengths at early age of Mixture 5 are even higher than the control Mixture 1. The use of a Type III cement and higher dosage of a Type C accelerating admixture will increase materials cost and may only be necessary in fast-track construction applications.

Experimental work for Determination of Activation Energy (AE)

In this portion of the study, for determining the activation energy of HVFA mixtures, mortar mixtures were used by proportioning the mortar to have a fine aggregate-to-cement ratio equal to the coarse aggregate-to-cement ratio of the concrete. This is as recommended in ASTM C1074. The mortar mixture with 50% fly ash is equivalent to concrete Mixture 4 (Table 3) since it yielded acceptable early age strengths.

<u>Variables</u>

Table 4 summarizes the variables for the 14 mortar mixtures used in the determination of the activation energy. The variables were as follows:

- Two portland cements – Cement B (low alkali) and Cement C (high alkali);
- Three fly ashes – Fly ash A (Class F, low calcium); Fly ash B (Class F, intermediate calcium), and Fly ash C (Class C, high calcium);
- Fly ash quantity - 35% and 50% of cementitious materials by volume;

The w/cm of the mortar mixtures was varied – the w/cm of the control mixture was 0.43; and 0.39 and 0.34 for the 35% and 50% fly ash mixtures, respectively.

<u>Procedures</u>

Mortar mixtures were mixed and the cubes were molded in accordance with ASTM C109[9]. Mortar cubes were conditioned in lime-saturated water baths maintained at 3 different temperatures - 45°F, 73°F, 100°F. All ingredient materials for mortar mixtures were conditioned at the respective temperatures for 24 hours before mixing. For the 73°F condition, the standard curing room was used; for the higher temperature, the specimens were stored in a room maintained at 100°F; and for the 45°F condition, the specimens were stored in a refrigerator maintained at that temperature.

A total of 18 cubes were made for each batch – two 2 in. cubes at each of 7 test ages, 1 cube with embedded temperature sensor, and 3 extra cubes. A temperature sensor placed in the water bath as a back-up record of curing temperature. Compressive strength was measured at equivalent ages (73°F) of early age (less than 1 day), 1, 2, 4, 8, 16, 32 days. This should not be confused with chronological test ages. Equivalent age represents the age at a reference curing temperature (73°F) that results in the same maturity as under the actual curing temperature. To estimate the chronological test age for the temperature conditions of 45°F and 100°F, an initial approximation of activation energy based on past experience was used. The early age (less than 1 day) was chosen by estimating when a compressive strength in the range of 600-1000 psi would be achieved. Typically this strength level is attained at an equivalent age of 12 hours and was used as a starting point.

Results and Discussion

Tables 5a-c summarize the mortar mixture proportions and test results of fresh mortar mixtures with the low alkali cement at curing temperatures 73°F, 100°F and 45°F, respectively. Tables 6a-c summarizes the mortar compressive strength results of corresponding mixtures. Figure 2, 3, 4 illustrate the compressive strength test results of low alkali cement mixtures conditioned in 73°F, 100°F, and 45°F respectively. In the following discussion, the fly ash quantity in the mixtures is on the basis of volume of cementitious materials.

From Figure 2 (73°F) the following observations are made:

1. The control mixture, Mix 1, had the fastest rate of strength gain at early age as expected and the rate slowed considerably by 16 days.
2. For the fly ash mixtures with 35% fly ash, the faster rate of strength gain at early ages was evident with the FAA fly ash. The strength of this mixture exceeded that of the control mixture by 18 days. The strength of the mixtures with fly ashes FAB and FAC exceeded that of the control mixture after 80 days. Later age strength for the fly ash mixtures is ranked from highest to lowest with fly ashes FAA, FAB and FAC.
3. For the mixtures with 50% fly ash, there was little difference between the mixtures at early ages. These mixtures had a slower rate of strength gain compared to the control mixture and exceeded it by 28 days. Ranking later age strength followed the same trend for highest to lowest: FAA, FAB and FAC.
4. Two of the mixtures (0.43PC and 0.34FAA50) had to be repeated because the early age strength measured exceeded the target range of 600-1000 psi. The repeat mixtures (0.43PC-R and 0.34FAA50-R) show compressive strength test results very close to the original mixtures thus confirming good repeatability.

Figure 3 illustrates strength curves for mortars maintained at 100°F. The strength of 35% and 50% fly ash mixtures exceeded that of the control mixture within 4-6 days. The mixture with the

FAA fly ash had higher later age strength than the mixtures with the FAB and FAC fly ashes. The higher curing temperature caused an accelerated rate of strength development for the fly ash mixtures compared to the control mixture. Later age (>90 days) data shows the fly ash mixtures had a mortar strength almost 3000 to 4000 psi higher than the control mixture. Ultimate strengths of the fly ash mixtures appear to be less affected by higher temperature compared to the control mixture without fly ash.

Figure 4 illustrates strength curves for mortars maintained at 45°F. The strength of the 35% FAA and FAC mixtures exceeded the control mixture after 1 year. The strength of the50% FAC and FAA mixture exceeded that of the control mixture after 200 days and 1 year respectively. Both the FAB mixtures were lagging behind the control even after 1 year. The lower curing temperature resulted in a slower rate of strength development for the fly ash mixtures as compared to the control mixture.

Tables 5d-f summarize the mortar mixture proportions and test results of fresh mortar mixtures with the high alkali cement at curing temperatures 73°F, 100°F and 45°F, respectively. Tables 6d-f summarizes the mortar compressive strength results of corresponding mixtures. Figure 5, 6, 7 illustrate the compressive strength test results of high alkali cement mixtures conditioned in 73°F, 100°F, and 45°F respectively. In the following discussion, the fly ash quantity in the mixtures is on the basis of volume of cementitious materials.

From Figure 5 (73°F) the following observations are made:

1. The control mixture had the fastest rate of strength gain at early age as expected and the rate slowed considerably by 8 days
2. For the fly ash mixtures with 35% fly ash, the faster rate of strength gain at early ages was evident with the FAA fly ash. The strength of this mixture exceeded that of the control mixture by 33 days. The strength of the mixtures with fly ashes FAB and FAC exceeded that of the control mixture after 45 days. Later age strength for the fly ash mixtures is ranked from highest to lowest with fly ashes FAA, FAB and FAC.
3. For the 50% fly ash dosage the FAA and FAB fly ash mixtures showed a faster strength gain and had exceeded the control mixture by 25 days. The FAC mixture had exceeded the control by about 90 days. Later age data shows the FAA, FAB mixtures with a better strength gain as compared to FAC mixture.
4. One mixture (0.43PC) had to be repeated because the early age strength measured exceeded the target range of 600-1000 psi. The repeat mixtures (0.43PC-R) shows compressive strength test results very close to the original mixtures thus confirming good repeatability

Figure 6 illustrates strength curves for mortars maintained at 100°F. The strength of 35% FAA and FAC mixtures had exceeded the control mixture by 11 days. The 35% FAB mixture also exceeded the control mixture by 16 days. Later age strength for the fly ash mixtures is ranked from highest to lowest with fly ashes FAA, FAC and FAB. All of the 50% fly ash mixtures exceeded the control mixture by 7 days and by 90 days had over 2000 psi higher strength as compared to the control mixture.

Figure 7 illustrates strength curves for mortars maintained at 45°F. Even after 1 year all of the fly ash mixtures were lagging behind the control mixture.

In some of the mortar mixtures the dosage of the Type F HRWRA used considerably exceeded the manufacturer's recommended dosage. This caused some retardation. These mixtures were repeated. It was decided, however, that the strengths measured were appropriate to use in the analysis. More details of the repeated mixtures are discussed in Appendix B.

Charts in Appendix C illustrate different comparisons of the mortar test results. The following conclusions can be drawn from those plots:

1. A *cross-over* effect is observed in these charts, where the later age strengths of the specimens cured at cooler temperatures are higher than that of specimens cured at warmer temperatures. This effect is observed for the control 0.43PC, and to a lesser extent for the 0.39FAA35 and 0.39FAB35 mixtures. It was not observed for the rest of the fly ash mixtures even when testing was extended to over 1 year.
2. For the control 0.43PC mixture the strengths of the specimens cured at 43°F exceeded that of specimens cured at 73°F after 80 days. For all the fly ash mixtures even after 400 days of curing at 43°F the strengths were similar to the 28 day strengths of specimens cured at 73°F.
3. Alkali content of fly ash does not seem to influence the rate of strength development of fly ash mixtures. The high and low alkali cement mixtures for the control as well as the fly ash mixtures showed similar strengths at different curing temperatures except for the 0.39FAA35 and 0.39FAB35 mixtures cured at cooler temperatures, in which case the high alkali cement mixtures showed higher strengths.

Determination of Activation Energy

The Activation Energy (AE) was determined for all 14 mixtures - 7 with low alkali cement and 7 with high alkali cement. For each mixture after the completion of the mortar cube testing the compressive strength and equivalent age data at each of the three temperatures were fitted with a hyperbolic function in accordance with ASTM C1074. The hyperbolic function is

$$S = S_u \frac{k(t - t_0)}{1 + k(t - t_0)}$$

Where:
S = average cube compressive strength at age t,
t = test age,
S_u = limiting strength,
t_0 = age when strength development is assumed to begin, and
k = rate constant

The solver process of Microsoft Excel software was used to calculate the best-fit values of S_u, t_0, and k through a regression analysis. For each mixture the rate constants were plotted against temperature and fitted with the Arrhenius equation, from which the AE was estimated. Using the calculated AE values for each mixture the strength-to-equivalent age for the 3 temperatures were plotted.

This is depicted in Figures 8 and 9 for low alkali cements and Figures 12 and 13 for high alkali cements. Figures 8 and 12 are for the low alkali and high alkali cement control mixtures, respectively. Each of these figures has 3 plots depicted as a, b, c. In Figure 8, plot 8a shows the strength vs. age results (for age up to 20 days) for all 3 curing temperatures and the hyperbolic curve fit. Plot 8b shows the logarithm of rate constant vs. inverse of curing temperature in degree Kelvin. The fitted line is the Arrhenius curve fit. The slope of this line is the activation energy. Plot 8c shows the strength vs. equivalent age results (for equivalent age up to 20 days) for all 3 curing temperatures. For the fly ash mixtures in the interest of space only the strength-equivalent age plots are shown in Figures 9, and 13 for the low alkali and high alkali cement mixtures respectively.

Tables 7a and 9a summarize the hyperbolic curve fit data for the low alkali and high alkali mixtures respectively. Generally one would expect t_0 to be similar to the final setting time but Tables 7a, and 9a show some zero values. For these mixtures the curve fit had suggested a negative t_0 value and since that is not physically possible a zero value is assumed. S_u values also are slightly lower than the actual later age strengths measured in some cases. However this also is acceptable as long as the hyperbolic curve fits are good for the first 7 days and the overall coefficient of determinations (R^2) values are good. It can be seen that the hyperbolic function gives good correlations with R^2 values between 0.94 and 1.00 for all 42 cases (14 mixtures x 3 curing temperatures). For comparison, curve fits of the strength age data for each case was also done using the logarithmic function and the R^2 values are listed in the last column of Tables 7a and 9a. It can be seen that for the control Mixture (0.43PC) and for the mixtures containing Fly ash FAC (Class C fly ash) the hyperbolic function gave better R^2 values. For the mixtures containing Fly ash FAA and FAB (Class F fly ashes) the logarithmic function gave better R^2 values for low alkali cement mixtures. Since in our case the hyperbolic function gave overall good curve fits for all mixtures (R^2 values of 0.94 to 1.00) it was decided to use the hyperbolic function for all mixtures.

Tables 7b and 9b summarize the AE values determined from the curve fits for the logarithm of rate constant (k) vs. inverse of temperature plots. The R^2 values ranging 0.94-1.00indicate a good fit. Using these AE values the strength vs. equivalent age plots for the 3 curing temperatures were illustrated in Figures 8c, 9, Figures 12c and 13. Ideally the strength vs. equivalent age plots for all 3 curing temperatures should plot on a straight line. Some variation may be acceptable. Unfortunately the variation is too high. For the control mixtures (Figures 8C and 12c) the strength vs. equivalent age for the hot temperature was much lower whereas for the fly ash mixtures (Figures 9 and 13) the strength vs. equivalent age for the cold temperature was much lower. Different methods were tried to reduce the variation in the strength vs. equivalent age plots for the 3 curing temperatures. Eventually, the following approach was used for each mixture:

1. The measured 28 day strength at the control curing temperature (73°F) was set as the value of the ultimate strength, S_u for all 3 curing temperatures.
2. 70% of this S_u value was calculated. For all 3 curing temperatures only test results up to this strength level were included in the analysis.

3. t_0, k, and AE values were determined using the best fit with the hyperbolic function discussed earlier. The log of rate constant (k) was plotted against inverse of temperature and this slope of this fitted line is reported as the estimate of the activation energy.

The above process is depicted in Figures 10 and 11 for low alkali cements and Figures 14 and 15 for high alkali cements. Figures 10 and 14 are for the low alkali and high alkali cement control mixtures, respectively. Each of these figures has 3 plots depicted as a, b, c. In Figure 10, Plot 10a illustrates the strength vs. age results for all 3 curing temperatures and the hyperbolic curve fit to the data. Only strength test results up to 70% of the S_u value were used in the analysis. Plot 10b plots the logarithm of rate constant (k) vs. inverse of curing temperature in degree Kelvin and the line fit. The slope of this line is used to calculate the activation energy. Plot 10c shows the strength vs. equivalent age results (for equivalent age up to 7 days) for all 3 curing temperatures. For the fly ash mixtures in the interest of space only the strength-to-equivalent age plots are illustrated in Figures 11 and 15 for the low alkali and high alkali cement mixtures respectively.

Using the modified analysis, Tables 8a and 10a summarize the hyperbolic curve fit data for the low alkali and high alkali mixtures, respectively. The values of t_0 determined from this analysis are more reasonable than those in Table 7a with the prior analysis.. The values of S_u are lower than the actual measured later age strengths. However this was considered to be acceptable as long as the hyperbolic curve fits are good for the first 7 days and the overall coefficient of determinations (R^2) values are good. It can be seen that the hyperbolic function indicate a good fit with R^2 values between 0.91 and 1.00 for all 42 cases.

Table 8b and 10b summarize the activation energy values determined from the curve fits from the plots of the logarithm of rate constant (k) vs. inverse of temperature. Using these derived values of activation energy, the strength vs. equivalent age plots for the 3 curing temperatures were drawn (Figures 10c, 11, and Figures 14c and 15). It can be seen that with this modified analysis the curves for 3 different curing temperatures converge together as should be expected.

Significance of the Activation Energy Values Calculated

For any concrete mixture the rate of strength development increases as concrete temperature increases. The activation energy values provide a relative indicator of the rate of hydration and strength gain characteristics of cementitious systems dependent on temperature. A higher value of the activation energy has a lower rate of strength gain at lower temperature and this rate increases as temperature rises. Lower values of activation energy indicate that the cementitious materials are less temperature sensitive. This can be observed in age conversion factors calculated from the AE of the various mixes listed in Table 8b and 10b. Age conversion factors of a mixture at a specific temperature can be seen as the ratio of strength of that mixture at that temperature to the strength at a reference (datum) temperature, which is commonly 73°F.

So for the low alkali 0.43PC mixture (Table 8b) at 41°F the strength is only 40% of the strength at 73°F which means that in order to attain the 2 day strength at 73°F one would have to cure the specimen at 41°F for 5 days (2/0.40). The low alkali 0.43PC mix had an AE of 34,981 J/mol. The fly ash mixtures made with low alkali cement have up to 50% higher AE values. For the 0.39FAA35 mixture at 41°F the strength is only 24% of the strength at 73°F which means that in order to attain the 2 day strength at 73°F one would have to cure the specimen at 41°F for 8.3

days. The AE values of mixtures made with the high alkali cement in general were lower for the 0.39FAA35 and 0.39FAB35 mixtures; for the rest of the mixtures it was similar. The AE values were up to 25% higher for the 50% low alkali cement fly ash mixtures and 50% higher for the 50% high alkali cement fly ash mixtures when compared to their respective control mixtures. No particular trends between AE values and cement or fly ash properties could be discerned. The age conversion factor is used to convert the temperature history of the concrete in the field into an equivalent age at 73°F and based on a predetermined strength-equivalent age relationship the strength is estimated.

Development of Concrete Strength-Maturity Relationship

Concrete testing was conducted on the 50% fly ash (by volume) mixtures with low and high CaO fly ash in conjunction with low and high alkali cements (total of 4 concrete mixtures). Table 11 shows the mixture proportions and test results. Mixtures 1 and 2 used low alkali cement (Cement B) and were the concrete equivalents of mortar Mixtures 0.34FAA50 and 0.34FAC50 respectively in Table 5a. Therefore they will be referred to as 0.34FAA50LAC, and 0.34FAC50LAC respectively. Mixtures 3 and 4 used high alkali cement (Cement C) and were the concrete equivalents of mortar mixtures 0.34FAA50 and 0.34FAC50 respectively in Table 5d. Therefore they will be referred to as 0.34FAA50HAC, and 0.34FAC50HAC respectively. Concrete slump (ASTM C143), temperature (C1064), density (C138), air content (C231), and compressive strength (C39) was measured. The w/cm was 0.34 for all the mixtures and a target concrete slump of 4 to 8 in. was attained through the use of a HRWR. All concrete mixtures were non air entrained. A 30 oz/cwt of a non-chloride Type C accelerating admixture was also used. The water content from the admixture was subtracted from the mixing water. Two concrete cylinders (4 in. x 8 in.) were tested in compression at equivalent ages of 1, 2, 4, 7, 14, 28 days and temperature was monitored in one additional cylinder.

As noted in the mortar mixtures the concrete mixtures containing fly ash FAA required a higher Type F admixture dosage as compared to the concrete mixtures containing fly ash FAC. But the admixture dosages were not excessive (<10 oz/cwt. as compared to 20 to 32 oz/cwt for corresponding mortar mixtures).

The two concrete mixtures with high alkali cement had higher strengths compared to the two mixtures with the low alkali cement at all ages except at 1 day. The 1 day strength of the 0.34FAC50HAC mixture was 161 psi indicating severe retardation of that mixture. For both cement types the concrete mixtures containing the high CaO fly ash showed higher strengths at all ages except at 1 day. Figure 16a-d illustrates the strength vs. equivalent age at 73°F for the four concrete mixtures with the hyperbolic curve fit (indicated as best-fit within the figure). The equivalent age was calculated by the Arrhenius equation with the selected AE value obtained from the mortar study. The R^2 values were higher than 0.95. The best fit equations for the 4 mixtures are provided below:

0.34FAA50LAC: $$S = 6774 \times \frac{0.023(t-0.0)}{1+0.023(t-0.0)}$$

0.34FAC50LAC: $$S = 9608 \times \frac{0.015(t-1.5)}{1+0.015(t-1.5)}$$

0.34FAA50HAC: $S = 9125 \times \frac{0.020(t-0.0)}{1+0.020(t-0.0)}$

0.34FAC50HAC: $S = 10423 \times \frac{0.018(t-22.2)}{1+0.018(t-22.2)}$

Where t = equivalent age at 73.4°F (23°C).
The above best fit equations can be used predicting in-place compressive strengths using maturity if the corresponding mixtures are used. A temperature sensor is recorded inside the structure. The time, and temperature data recorded is converted to equivalent at 73.4°F using the AE for that mixture. Using the above concrete Strength-Maturity equation the strength is predicted.

Acknowledgements

The authors would like to extend their sincere thanks to Mr. Soliman Ben-Barka and Mr. Stuart Sherman who conducted the test program at the NRMCA Research Laboratory and Mr. Colin L. Lobo, Ph.D., P.E. for his review of this report. The authors would like to thank WR Grace, Boral Materials Technologies Inc., and Separation Technologies LLC for the materials provided. Funding for the study was provided by the Federal Highway Administration through a research consortium led by Purdue University.

References

1. US Slag Cement Shipments, Slag Cement Association, http://www.slagcement.org/News/Shipments.html
2. ACAA Coal Combustion Product (CCP) Production & Use Survey Report, American Coal Ash Association, http://www.acaa-usa.org/
3. Cement Statistics and Information, US Geological Survey, http://minerals.usgs.gov/minerals/pubs/commodity/cement/
4. Sivasundaram, V., Carette, G. G., and Malhotra, V. M., "Properties of Concrete Incorporating Low Quantity of Cement and High Volumes of Low-Calcium Fly Ash," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete—Proceedings, Third International Conference*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, 1989, pp. 45-71.
5. Naik, T. R., and Singh, S. S., "Superplasticized Structural Concrete Containing High Volumes of Class C Fly Ash," *ASCE Journal of Energy Engineering*, V. 117, No. 2, Aug. 1991, pp. 87-95.
6. Obla, Karthik, Hill, Russell, and Martin Ross, "HVFA Concrete – An Industry Perspective", Concrete International, Vol. 25, No. 8, 2003, pp. 49-54.
7. Obla K., Upadhyaya S., Goulias D., Schindler A.K., and Carino N., "New Technology Based Approach to Advance Higher Volume Fly ash Concrete with Acceptable Performance," Final Report, August 2008, http://www.nrmca.org/research_engineering/Lab.htm
8. ASTM C39, C138, C143, C231, C494, C1064, C1074, Annual Book of ASTM Standards, Vol. 4.02, Concrete and Aggregates, ASTM International, www.astm.org.
9. ASTM C109, C185, C1437, Annual Book of ASTM Standards, Vol. 4.01, Cement; Lime; and Gypsum, ASTM International, www.astm.org.

Table 1a Fly Ash and Slag Cement Use in Ready Mixed Concrete (RMC)

Year	RMC Volume (Million yd^3)	PC (Million tons)	FA (Million tons)	FA (%)	SL (Million tons)	FA+SL (%)	PC (lb/yd^3)	FA (lb/yd^3)	SL (lb/yd^3)
2001	406.1	91.4	11.0	10.5	2.6	13.1	450	54	13
2003	404.3	91.0	11.1	10.6	3.3	13.8	450	55	17
2005	458.3	103.1	13.5	11.3	3.9	14.5	450	59	17
2006	456.8	102.8	13.7	11.4	4.0	14.8	450	60	18
2007	414.6	93.3	12.4	11.4	3.7	14.8	450	60	18
2008	351.7	79.1	11.4	12.2	3.3	15.8	450	65	19

Note. PC= Portland cement, FA= Fly ash, SL = Slag cement

Assumptions:

75% of all cement (including blended cement) is used in RMC - blended cement is 2.5% of total cement consumption (USGS) and assumed to contain 30% SCM on average

Fly ash use is derived from ACAA survey. Ready mixed concrete is assumed to consume 88% of the value reported under Concrete/Concrete Products /Grout of the ACAA survey and 10% of the value reported under Blended Cement/ Raw Feed for Clinker of the ACAA survey

Slag use is determined from the Slag Cement Association use reports

Table 1b Percentile Breakdown, Average, Minimum, and Maximum Amounts of Concrete Production, Fly ash and SCM Use

Survey Participants	20%ile	50%ile	80%ile	Average	Min	Max
Annual Concrete Volume, yd^3	58,547	197,535	733,356	610,400	13,000	5,216,519
Annual fly ash used, lb/yd^3	39	75	100	83	0	170
Annual SCM used, lb/yd^3	62	94	144	102	28	198
Annual fly ash used, %	7	13	18	15	0	27
Annual SCM used, %	12	17	24	18	3	33

Table 1c Average Portland Cement, fly ash, SCM usage based on Company Production Levels

	<250,000 yd^3	250 to 1 Million yd^3	>1 Million yd^3	All
Annual portland cement used, lb/yd^3	451	466	454	457
Annual fly ash used, lb/yd^3	62	86	85	83
Annual SCM used, lb/yd^3	106	99	104	102

Table 1d Analysis of Company Responses of Causes Preventing Increased Use of Fly ash

Causes	Avg. Rating	Strongly Agree	Agree	Neutral
Fly ash supply - not available or inconsistent	4.6	14%	18%	68%
Fly ash properties are variable	3.9	18%	38%	45%
Use other SCMs (slag, etc)	4.6	16%	20%	64%
Concrete performance issues - setting time, strength gain, etc	2.5	52%	36%	13%
Specifications restrict use	2.5	57%	29%	14%
Customers object to use	2.9	38%	48%	14%

Table 2 Chemical and Physical Characteristics of Portland Cements and Fly ashes

Item	Cement A	Cement B	Cement C	FA-A	FA-B	FA-C
NRMCA Sample ID	**143**	**078**	**067**	**FAA**	**FAB**	**FAC**
Silicon oxide (SiO_2), %	20.59	19.49	19.34	60.5	53.38	38.71
Aluminum oxide (Al_2O_3), %	4.76	4.93	5.95	29.1	19.05	19.15
Iron oxide (Fe_2O_3), %	1.96	3.74	1.94	2.9	4.8	6.49
Sum of SiO_2, Al_2O_3, Fe_2O_3, %				92.5	77.23	64.35
Calcium oxide (CaO), %	63.77	64.24	62.3	0.7	15.09	23.51
Magnesium oxide (MgO), %	2.68	1.04	2.93	-	3.09	5.29
Sulfur trioxide (SO_3), %	3	3.18	3.89	0	0.63	1.36
Sodium Oxide (Na_2O), %	0.13	0.19	0.24	0.12	0.65	1.64
Potassium Oxide (K_2O), %	0.25	0.36	1.06	0.64	1.03	0.58
Loss of Ignition, %	2.61	2.34	1.46	1.3	0.28	0.3
Fineness 45 m sieve, % retained	-	-	-	27.2	27.23	12.3
Blaine (Specific Surface) $m^{2/}kg$	379	388	369	-	-	-
Relative Density	3.15	3.15	3.15	2.14	2.47	2.63
Strength Activity Index with Portland Cement at 7 days, % Control	-	-	-	80.4	84.6	84
Strength Activity Index with Portland Cement at 28 days, % Control	-	-	-	88.5	102.7	-
Water Requirement, % Control	-	-	-	100.4	93.8	93
Autoclave Expansion %	-	-	-	-0.06	-0.01	0.03
Total Alkali (as Na_2O eq), %	0.29	0.42	0.94	0.54	1.33	2.02
Available Alkali (as Na_2O), %	-	-	-	0.50	0.61	-
Tricalcium Silicate (C_3S), %	60	66	53	-	-	-
Dicalcium silicate (C_2S), %	14	6	16	-	-	-
Tricalcium Aluminate (C_3A), %	9	7	12	-	-	-
Tetracalcium Aluminoferrite (C_4AF), %	6	11	6	-	-	-

FAA = Sample Source: Brandon shore, MD; FAB = Sample Source: Big Brown, TX (from Boral); FAC = Sample Source: Muskogee (from Lafarge through Purdue).
Cement A, B, and C were supplied by W.R. Grace

Table 3 Summary of Concrete Trial Mixtures

Calculated Batch Quantities	Mix1	Mix2	Mix3	Mix4	Mix5
Cement A, lb/yd^3	619	380	389	387	
Type III cement, lb/yd^3					388
Fly ash FAA, lb/yd^3		380	265	263	264
Fly ash, %	0	50	41	40	40
Coarse Agg. (No.57), lb/yd^3	2056	2089	2089	2075	2080
Fine Aggregate, lb/yd^3	1243	1100	1260	1278	1281
Mixing Water, lb/yd^3	265	233	223	221	222
w/cm	0.43	0.31	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	4.0	11.5	9.2	7.9	8.0
ASTM C494 Type C, oz/cwt	-	-	-	30.0	30.0
Fresh Concrete Properties					
ASTM C143, Slump, in.	8.00	9.00	7.50	7.75	6.75
ASTM C231, Air, %	2.3	0.5	1.2	1.2	1.6
ASTM C138, Density, lb/ft^3	155.7	155.7	157.3	156.9	157.3
ASTM C1064, Temperature, °F	68	68	71	71	71
Hardened Conc. Properties					
Compressive Strength, psi					
2days	4,631	2,965	3,025	3,895	6,029
4d	6,467	3,767	-	-	-
6d	-	-	4,617	5,424	7,274
2d at 45F	-	-	1,685	2,132	3,281
6d at 45F	-	-	3,945	4,567	6,285

Type F polycarboxylate based super plasticizer (Advacast 575), Type C accelerating admixture (Darset HES) provided by W.R. Grace

Table 4 Characteristics of Mortar Mixtures for Activation Energy Measurement

Portland Cement	w/cm	Fly Ash Dosage	Fly Ash Source		
			FAA	FAB	FAC
Cement B (low alkali)	0.43	0%			
	0.39	35%	☑	☑	☑
	0.34	50%	☑	☑	☑
Cement C (high alkali)	0.43	0%			
	0.39	35%	☑	☑	☑
	0.34	50%	☑	☑	☑

Note: Target flow = 105-115 per C109 attained with a dosage of Type F admixture.

Table 5a Summary of Mortar Test Result @ Control-73ºF (Low alkali cement)

Batch Quantities	Mix1	Mix2	Mix3	Mix4	Mix5	Mix6	Mix7	Mix1R	Mix5R
	0.43PC	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**	**0.43PC-R**	**0.34FAA50-R**
Cement B, lb/yd^3	620	454	444	439	384	373	368	620	384
Fly ash, lb/yd^3	0	166	187	198	261	292	307	0	261
Fly ash, % by Mass	0	26.8	29.6	31.1	40.5	43.9	45.5	0	40.5
Fly ash, % by Vol.	0	35	35	35	50	50	50	0	50
Fine Aggregate, lb/yd^3	2060	2060	2060	2060	2060	2060	2060	2060	2060
Mixing Water, lb/yd^3	266	242	246	248	219	226	229	266	219
w/cm	0.43	0.39	0.39	0.39	0.34	0.34	0.34	0.43	0.34
ASTM C494 Type F, oz/cwt	4.0	5.8	4.9	2.7	18.0	4.0	2.6	4.0	18.0
ASTM C494 Type C, oz/cwt	-	-	-	-	30.0	30.0	30.0	-	30.0
Fresh Mortar Properties									
ASTM C1437, Flow, %	114	105	112	106	112	106	112	107	107
ASTM C185, Density, lb/ft^3	138.2	137.1	134.6	136.3	137.2	133.5	138.1	138	139.5
ASTM C185, Air, %	7.7	8.6	10.8	7.3	6.4	9.8	7.1	6.1	4.9

Note: FAA, FAB, FAC are different fly ash sources

Table 5b Summary of Mortar Test Result @ Hot-100ºF (Low alkali cement)

Batch Quantities	Mix8	Mix9	Mix10	Mix11	Mix12	Mix13	Mix14
	0.43PC	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**
Cement B, lb/yd^3	620	454	444	439	384	373	368
Fly ash, lb/yd^3	0	166	187	198	261	292	307
Fly ash, % by Mass	0	26.8	29.6	31.1	40.5	43.9	45.5
Fly ash, % by Vol.	0	35	35	35	50	50	50
Fine Aggregate, lb/yd^3	2060	2060	2060	2060	2060	2060	2060
Mixing Water, lb/yd^3	266	242	246	248	219	226	229
w/cm	0.43	0.39	0.39	0.39	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	4.0	9.6	4.0	2.7	19.8	4.0	2.6
ASTM C494 Type C, oz/cwt	-	-	-	-	30.0	30.0	30.0
Fresh Mortar Properties							
ASTM C1437, Flow, %	108	107	109	114	106	105	115
ASTM C185, Density, lb/ft^3	137.2	136.7	134.9	137.9	139	134.5	139.2
ASTM C185, Air, %	6.7	8.9	10.6	6.2	5.2	9.1	6.3

Note: FAA, FAB, FAC are different fly ash sources

Table 5c Summary of Mortar Test Result @ Cold-45ºF (Low alkali cement)

Batch Quantities	**Mix15**	**Mix16**	**Mix17**	**Mix18**	**Mix19**	**Mix20**	**Mix21**
	0.43PC	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**
Cement B, lb/yd^3	620	454	444	439	384	373	368
Fly ash, lb/yd^3	0	166	187	198	261	292	307
Fly ash, % by Mass	0.0	26.8	29.6	31.1	40.5	43.9	45.5
Fly ash, % by Vol.		35	35	35	50	50	50
Fine Aggregate, lb/yd^3	2060	2060	2060	2060	2060	2060	2060
Mixing Water, lb/yd^3	266	242	246	248	219	226	229
w/cm	0.43	0.39	0.39	0.39	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	4.7	11.2	2.8	1.8	4.0	4.4	2.2
ASTM C494 Type C, oz/cwt	-	-	-	-	30.0	30.0	30.0
Fresh Mortar Properties							
ASTM C1437, Flow, %	114	115	109	120	110	113	114
ASTM C185, Density, lb/ft^3	136.7	137.1	136.2	137.1	138.9	134.1	137.2
ASTM C185, Air, %	7.0	8.6	9.7	6.7	5.2	9.4	7.7

Note: FAA, FAB, FAC are different fly ash sources

Table 5d Summary of Mortar Test Result @ Control-73ºF (High alkali cement)

Calculated Batch Quantities	**Mix22**	**Mix22R**	**Mix23**	**Mix24**	**Mix25**	**Mix26**	**Mix27**	**Mix28**
	0.43PC	**0.43PC**	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**
Cement C, lb/yd^3	620	620	454	444	439	384	373	368
Fly ash, lb/yd^3	0	0	166	187	198	261	292	307
Fly ash, % by Mass	0	0	27	30	31	40	44	45
Fly ash, % by Vol.			35	35	35	50	50	50
Fine Aggregate, lb/yd^3	1246	1246	1244	1245	1245	1245	1245	1245
Mixing Water, lb/yd^3	266	266	242	246	248	219	226	229
w/cm	0.43	0.43	0.39	0.39	0.39	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	11.3	11.3	15.0	6.0	3.6	31.5	5.2	3.5
ASTM C494 Type C, oz/cwt	-	-	-	-	-	30.0	30.0	30.0
Fresh Mortar Properties								
Temperature, °F	81	80	78	78	78	78	76	76
ASTM C1437, Flow, %	106	107	107	124	122	106	107	105
ASTM C185, Density, lb/ft^3	140.9	138.9	137.9	137.1	138.2	139.8	136	140.4
ASTM C185, Air, %	4.9	5.0	5.0	6.1	5.7	3.8	7.8	5.2

Note: FAA, FAB, FAC are different fly ash sources

Table 5e Summary of Mortar Test Result @ Hot-100ºF (High alkali cement)

Calculated Batch Quantities	Mix29	Mix30	Mix31	Mix32	Mix33	Mix34	Mix35
	0.43PC	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**
Cement C, lb/yd^3	620	454	444	439	384	373	368
Fly ash, lb/yd^3		166	187	198	261	292	307
Fly ash, % by Mass	0.0	26.8	29.6	31.1	40.5	43.9	45.5
Fly ash, % by Vol.		35	35	35	50	50	50
Fine Aggregate, lb/yd^3	1246	1245	1245	1245	1245	1245	1245
Mixing Water, lb/yd^3	266	242	246	248	219	226	229
w/cm	0.43	0.39	0.39	0.39	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	4.0	16.1	4.0	2.8	45.3	4.0	6.0
ASTM C494 Type C, oz/cwt	-	-	-	-	30.0	30.0	30.0
Fresh Mortar Properties							
Temperature, °F	98	97	94	97	87	95	93
ASTM C1437, Flow, %	107	107	119	114	105	106	117
ASTM C185, Density, lb/ft^3	139.4	139.1	137.8	140	139.1	139.4	140.4
ASTM C185, Air, %	4.9	4.1	5.7	4.4	4.3	5.4	5.2

Note: FAA, FAB, FAC are different fly ash sources

Table 5f Summary of Mortar Test Result @ Cold-45ºF (High alkali cement)

Calculated Batch Quantities	Mix36	Mix37	Mix38	Mix39	Mix40	Mix41	Mix42
	0.43PC	**0.39FAA35**	**0.39FAB35**	**0.39FAC35**	**0.34FAA50**	**0.34FAB50**	**0.34FAC50**
Cement C, lb/yd^3	620	454	444	439	384	373	368
Fly ash, lb/yd^3		166	187	198	261	292	307
Fly ash, % by Mass	0.0	26.8	29.6	31.1	40.5	43.9	45.5
Fly ash, % by Vol.		35	35	35	50	50	50
Fine Aggregate, lb/yd^3	1246	1245	1245	1245	1245	1245	1245
Mixing Water, lb/yd^3	266	242	246	248	219	226	229
w/cm	0.43	0.39	0.39	0.39	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	6.7	11.5	8.3	1.9	28.8	4.4	2.2
ASTM C494 Type C, oz/cwt	-	-	-	-	30.0	30.0	30.0
Fresh Mortar Properties							
Temperature, °F	67	63	66	64	72	67	64
ASTM C1437, Flow, %	106	105	105	122	108	112	114
ASTM C185, Density, lb/ft^3	137.8	138	133.9	135.7	137.5	132.7	136.6
ASTM C185, Air, %	5.9	7.5	8.3	7.4	5.8	10.0	7.8

Note: FAA, FAB, FAC are different fly ash sources

Table 6a Summary of Mortar Strength Result @ Control-73ºF (Low alkali cement)

Mix1		Mix1R		Mix2		Mix3		Mix4		Mix5		Mix5R		Mix6		Mix7	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
0.44	1325	0.31	506	0.38	994	0.38	369	0.44	613	0.44	1325	0.79	2613	0.40	975	0.38	406
1.00	3781	0.77	3325	0.75	2856	0.75	2006	0.88	2100	0.88	2700	1.25	3438	0.81	2456	0.76	1944
1.83	5556	1.25	4563	1.33	4169	1.33	3300	1.79	3688	1.83	4331	2.83	5013	1.81	4219	1.76	3869
4.00	6650	3.00	6788	3.00	5625	3.00	4728	3.13	4706	3.17	5050	8.00	6388	2.98	5131	2.93	5044
		16.00	8375	8.00	7031	8.00	6213	8.00	6088	8.00	6200	10.02	6743	7.94	6350	7.76	6488
		32.00	8625	32.00	9219	32.00	8325	32.00	8125	31.08	9125	16.00	7563	33.01	8875	31.97	8750
		90.06	9000	98.02	11438	98.00	9625	97.08	8813	97.13	11375	32.00	9500	96.08	10313	95.04	10563
				177.81	11875	177.77	10438	176.86	8938	176.91	12750	169.88	12000	175.85	10563	174.81	10750
				276.04	12875	276.00	11350	275.08	9625	275.13	12850	268.08	12900	274.06	11750	273.01	11000

Table 6b Summary of Mortar Strength Result @ Hot-100ºF (Low alkali cement)

Mix8		Mix9		Mix10		Mix11		Mix12		Mix13		Mix14	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
0.156	286	0.19	550	0.19	300	0.22	216	0.22	98	0.22	411	0.25	312
0.313	2250	0.38	2550	0.38	1969	0.31	1063	0.44	1713	0.44	1781	0.50	1569
0.771	4581	0.83	4331	0.85	3631	0.88	3494	0.88	3725	0.88	3581	1.00	3969
1.250	5538	1.42	5275	1.50	4638	1.81	4975	1.88	4738	1.92	4738	2.00	5350
2.813	6194	2.98	6438	3.00	5588	14.64	8000	3.81	5900	3.83	6075	16.00	9500
8.088	6788	13.13	8938	6.00	6700	88.04	10125	14.00	9188	14.00	9125	84.21	10875
88.083	7625	88.13	11313	13.13	7969			84.08	12250	84.13	11000		
				88.17	9813								

Table 6c Summary of Mortar Strength Result @ Cold-45ºF (Low alkali cement)

Mix15		Mix16		Mix17		Mix18		Mix19		Mix20		Mix21	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
0.74	825	0.75	379	6.00	3306	3.76	2719	1.75	1575	0.87	491	1.00	425
1.26	1763	1.73	1756	12.00	4597	7.00	4163	3.10	2925	1.75	1856	2.00	950
2.70	4081	12.78	5381	28.67	5763	14.00	5588	7.00	4338	3.74	3825	4.00	2756
10.00	6731	28.77	6344	68.94	6513	29.79	6638	14.01	5475	7.00	4831	8.00	4781
28.75	8063	68.75	7188	105.96	6800	62.77	7100	31.85	6438	14.00	5800	16.00	6419
82.05	9125	107.96	7875	446.79	8450	102.00	7875	71.00	7100	32.80	6688	34.83	7750
107.96	9250	448.80	9250			442.83	9250	101.00	7475	70.83	7432	71.08	8375
167.90	9250							441.83	9125	100.00	7625	95.04	8375
										440.83	8750	435.83	9750

Table 6d Summary of Mortar Strength Result @ Control-73ºF (High alkali cement)

Mix22		Mix22R		Mix23		Mix24		Mix25		Mix26		Mix27		Mix28	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
1.0	5259	0.55	1413	0.55	1206	0.55	1150	0.55	419	0.55	400	0.55	1056	0.57	269
2.0	6063	0.95	4500	0.95	3294	1.03	3300	1.01	2133	0.95	2631	0.95	2638	0.95	1425
4.0	6750	3.00	6188	3.00	4750	3.00	5063	3.04	4375	4.15	5069	4.17	5125	4.21	5325
8.0	7613	8.00	7344	8.02	6663	8.03	6222	8.00	6106	8.00	5944	8.01	6388	8.04	6150
22.2	8250	16.00	7438	16.00	7338	16.00	6969	16.00	7031	15.97	6925	15.98	7475	16.00	6431
31.9	8313	40.04	8250	40.01	8688	40.10	8125	40.07	7813	34.01	8438	34.03	8500	34.07	7438
223.6	9650	204.21	9500			106.09	9750	106.07	8813					100.05	8500
								204.24	9400						

Table 6e Summary of Mortar Strength Result @ Hot-100ºF (High alkali cement)

Mix29		Mix30		Mix31		Mix32		Mix33		Mix34		Mix35	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
0.33	1335	0.38	1556	0.30	1156	1.08	2968	0.96	3006	0.50	2106	0.31	474
0.75	5088	0.93	3863	0.98	3781	1.25	4350	1.25	3588	1.00	3794	0.50	1631
3.00	6444	3.00	5306	2.00	4575	2.27	5050	2.29	4719	2.00	4950	1.25	4281
5.96	6906	5.99	6100	4.13	5313	5.02	6231	5.14	6044	4.98	6706	2.26	6038
12.22	7156	13.18	8125	8.13	6413	11.26	7360	10.06	8813	8.01	8000	5.08	7500
93.02	8375			27.06	8250	20.19	8375	20.04	9750	15.96	9250	10.03	8688
				93.11	8875	92.10	9563			92.08	10750	72.09	10188

Table 6f Summary of Mortar Strength Result @ Cold-45ºF (High alkali cement)

Mix36		Mix37		Mix38		Mix39		Mix40		Mix41		Mix42	
Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi	Age days	Strength psi
1.73	2069	1.77	1513	2.00	1575	2.19	1169	1.75	869	1.85	1363	2.01	875
2.99	4281	3.06	3275	4.00	3225	5.02	2950	3.02	2038	3.74	3238	3.99	2713
5.00	6038	6.90	5000	8.00	4856	8.90	4025	7.01	3944	7.50	4944	7.99	4725
11.06	7390	13.00	6363	17.06	5738	17.06	4674	13.98	4669	15.06	5319	16.03	5194
28.79	8000	29.84	6738	33.06	6438	62.15	6063	31.91	5144	32.18	6050	33.81	6288
82.05	9375	68.79	7188	68.94	7313			397.80	7500	71.04	6181	71.01	6506
390.80	10375	398.80	8125	396.80	8000					392.80	8250	391.80	8000

Table 7a Strength vs Age Curve Fit Parameters for Low Alkali Cement Mixtures based on ASTM C1074

Mixture ID	Curing Condition	t_0 (hr)	S_u (psi)	k (hr^{-1})	R^2 – Hyperbolic*	R^2 – Log age+
0.43PC	Hot-97F	3.4	7,361	2.533	1.00	0.79
	Control-76F	6.2	8,953	1.097	1.00	0.89
	Cold-40F	9.5	9,390	0.290	1.00	0.96
0.39FAA35	Hot-98F	0.0	10,781	0.636	0.97	0.98
	Control-76F	0.0	11,797	0.282	0.96	0.99
	Cold-41F	0.0	8,775	0.107	0.98	0.98
0.39FAB35	Hot-97F	0.1	9,391	0.569	0.97	0.98
	Control-75F	0.0	10,440	0.242	0.97	0.99
	Cold-41F	0.0	7,872	0.107	0.94	0.98
0.39FAC35	Hot-97F	3.5	9,667	0.659	0.98	0.98
	Control-75F	1.9	9,172	0.327	0.99	0.96
	Cold-41F	0.0	8,750	0.117	0.97	0.96
0.34FAA50	Hot-98F	0.0	12,115	0.310	0.97	0.99
	Control-76F	0.0	12,258	0.194	0.95	1.00
	Cold-45F	0.0	8,342	0.141	0.97	0.98
0.34FAB50	Hot-97F	0.0	11,038	0.388	0.99	0.99
	Control-75F	0.0	10,785	0.273	0.97	0.99
	Cold-45F	11.0	8,121	0.220	0.98	0.95
0.34FAC50	Hot-98F	4.6	10,826	0.592	1.00	0.97
	Control-75F	0.0	10,759	0.254	0.98	0.98
	Cold-43F	19.6	9,496	0.130	0.99	0.95

* Coefficient of Determination for Hyperbolic strength age function
\+ Coefficient of Determination for Strength log-age function

Table 7b Activation Energies Determined for Low Alkali Cement Mixtures based on ASTM C1074

Mixture ID	R^2	Activation Energy (J/mol)	Age Conversion Factor				
			41°F	59°F	73°F	95°C	113°C
0.43PC	1.00	48,837	0.28	0.58	1.00	2.17	3.95
0.39FAA35	0.99	40,273	0.35	0.63	1.00	1.89	3.10
0.39FAB35	0.98	37,421	0.37	0.66	1.00	1.81	2.86
0.39FAC35	1.00	39,760	0.35	0.64	1.00	1.88	3.06
0.34FAA50	0.95	18,847	0.61	0.81	1.00	1.35	1.70
0.34FAB50	0.94	13,685	0.70	0.86	1.00	1.24	1.47
0.34FAC50	0.96	34,835	0.40	0.67	1.00	1.74	2.66

Table 8a Strength vs Age Curve Fit Parameters for Low Alkali Cement Mixtures based on modified ASTM C1074 approach

Mixture ID	Curing Condition	t_0 (hr)	S_u (psi)	k (hr^{-1})	R^2 – Hyperbolic*	R^2 – Log age+
0.43PC	Hot-97F	3.2	8,500	1.802	1.00	1.00
	Control-76F	6.4	8,500	1.263	1.00	1.00
	Cold-40F	12.2	8,500	0.399	1.00	0.99
0.39FAA35	Hot-98F	2.8	9,000	1.241	0.98	0.99
	Control-76F	3.7	9,000	0.681	0.98	0.99
	Cold-41F	4.3	9,000	0.124	0.99	1.00
0.39FAB35	Hot-97F	2.7	8,100	0.980	0.98	0.99
	Control-75F	6.2	8,100	0.586	0.98	0.99
	Cold-41F	0.0	8,100	0.105	0.96	0.99
0.39FAC35	Hot-97F	4.4	8,000	1.073	1.00	1.00
	Control-75F	5.6	8,000	0.504	0.99	0.99
	Cold-41F	15.1	8,000	0.167	1.00	0.99
0.34FAA50	Hot-98F	0.0	8,900	0.628	0.98	0.97
	Control-76F	0.0	8,900	0.430	0.99	0.98
	Cold-45F	0.0	8,900	0.123	0.97	0.99
0.34FAB50	Hot-97F	3.3	8,500	0.835	0.99	0.99
	Control-75F	3.7	8,500	0.575	1.00	1.00
	Cold-45F	10.9	8,500	0.205	0.99	0.99
0.34FAC50	Hot-98F	5.4	8,500	1.000	1.00	0.98
	Control-75F	6.6	8,500	0.563	1.00	1.00
	Cold-43F	20.9	8,500	0.161	1.00	0.95

* Coefficient of Determination for Hyperbolic strength age function
+ Coefficient of Determination for Strength log-age function

Table 8b Activation Energies for Low Alkali Cement Mixtures based on modified ASTM C1074 approach

Mixture ID	R^2	Activation Energy (J/mol)	Age Conversion Factor				
			41°F	59°F	73°F	95°C	113°C
0.43PC	1.00	34,981	0.40	0.67	1.00	1.74	2.67
0.39FAA35	0.99	53,717	0.24	0.55	1.00	2.34	4.53
0.39FAB35	0.98	52,384	0.25	0.55	1.00	2.29	4.36
0.39FAC35	1.00	42,890	0.32	0.62	1.00	1.97	3.34
0.34FAA50	0.95	40,886	0.34	0.63	1.00	1.91	3.16
0.34FAB50	0.94	35,328	0.39	0.67	1.00	1.75	2.70
0.34FAC50	0.96	43,592	0.32	0.61	1.00	1.99	3.41

Table 9a Strength vs Age Curve Fit Parameters for High Alkali Cement Mixtures based on ASTM C1074

Mixture ID	Curing Condition	t_0 (hr)	S_u (psi)	k (hr^{-1})	R^2 – Hyperbolic*	R^2 – Log age+
0.43PC	Hot-97F	6.6	7,583	3.655	0.96	0.79
	Control-76F	8.8	8,445	1.388	0.94	0.86
	Cold-43F	20.2	9,964	0.336	0.97	0.89
0.39FAA35	Hot-96F	0.0	8,386	0.681	0.95	0.98
	Control-76F	0.0	8,791	0.426	0.97	0.98
	Cold-43F	18.4	8,125	0.259	0.98	0.85
0.39FAB35	Hot-97F	0.0	8,620	0.537	0.96	0.97
	Control-75F	0.0	8,973	0.376	0.95	0.98
	Cold-43F	13.2	7,858	0.189	0.99	0.90
0.39FAC35	Hot-97F	0.0	9,238	0.507	0.96	0.96
	Control-75F	5.0	8,991	0.292	0.98	0.96
	Cold-44F	24.8	6,443	0.200	0.99	0.96
0.34FAA50	Hot-98F	0.0	11,053	0.329	0.97	0.98
	Control-76F	0.0	9,177	0.238	0.96	0.98
	Cold-44F	11.0	7,216	0.140	0.96	0.94
0.34FAB50	Hot-97F	0.0	10,621	0.434	0.98	0.97
	Control-75F	0.0	9,056	0.324	0.99	0.99
	Cold-44F	16.4	7,353	0.228	0.93	0.91
0.34FAC50	Hot-98F	5.5	10,167	0.677	1.00	0.93
	Control-75F	11.3	8,131	0.427	0.98	0.94
	Cold-43F	29.8	7,480	0.197	0.97	0.91

* Coefficient of Determination for Hyperbolic strength age function
\+ Coefficient of Determination for Strength log-age function

Table 9b Activation Energies Determined for High Alkali Cement Mixtures based on ASTM C1074

Mixture ID	R^2	Activation Energy (J/mol)	Age Conversion Factor				
			41°F	59°F	73°F	95°C	113°C
0.43PC	1.00	56,945	0.22	0.53	1.00	2.46	4.96
0.39FAA35	0.98	23,213	0.54	0.77	1.00	1.44	1.92
0.39FAB35	1.00	25,167	0.52	0.75	1.00	1.49	2.03
0.39FAC35	0.95	21,991	0.56	0.78	1.00	1.42	1.86
0.34FAA50	1.00	20,457	0.58	0.79	1.00	1.38	1.78
0.34FAB50	1.00	15,294	0.67	0.84	1.00	1.27	1.54
0.34FAC50	1.00	29,127	0.46	0.72	1.00	1.59	2.27

Table 10a Strength vs Age Curve Fit Parameters for High Alkali Cement Mixtures based on modified ASTM C1074 approach

Mixture ID	Curing Condition	t_0 (hr)	S_u (psi)	k (hr^{-1})	R^2 – Hyperbolic*	R^2 – Log age+
0.43PC	Hot-97F	6.1	8,000	2.746	0.96	0.84
	Control-76F	10.4	8,000	2.034	0.98	0.88
	Cold-43F	31.3	8,000	0.780	1.00	0.96
0.39FAA35	Hot-96F	0.1	8,400	0.800	0.91	0.96
	Control-76F	1.8	8,400	0.510	0.97	0.96
	Cold-43F	20.6	8,400	0.260	1.00	0.99
0.39FAB35	Hot-97F	0.1	7,700	0.900	0.92	0.96
	Control-75F	6.2	7,700	0.752	0.97	0.95
	Cold-43F	18.2	7,700	0.215	0.99	0.98
0.39FAC35	Hot-97F	0.0	7,500	1.007	0.94	0.99
	Control-75F	10.1	7,500	0.578	1.00	0.99
	Cold-44F	10.9	7,500	0.124	0.96	0.98
0.34FAA50	Hot-98F	0.0	8,200	0.595	0.99	1.00
	Control-76F	8.6	8,200	0.308	0.97	0.98
	Cold-44F	0.0	8,200	0.093	0.88	0.94
0.34FAB50	Hot-97F	2.2	8,200	0.871	0.99	0.99
	Control-75F	3.0	8,200	0.452	0.98	0.99
	Cold-44F	13.2	8,200	0.180	0.94	0.94
0.34FAC50	Hot-98F	6.9	7,200	1.685	0.98	1.00
	Control-75F	13.0	7,200	0.714	1.00	0.99
	Cold-43F	33.9	7,200	0.238	0.98	0.95

* Coefficient of Determination for Hyperbolic strength age function
+ Coefficient of Determination for Strength log-age function

Table 10b Activation Energies for High Alkali Cement Mixtures based on modified ASTM C1074 approach

Mixture ID	R^2	Activation Energy (J/mol)	Age Conversion Factor				
			41°F	59°F	73°F	95°C	113°C
0.43PC	0.98	30,897	0.44	0.71	1.00	1.63	2.38
0.39FAA35	1.00	27,395	0.49	0.73	1.00	1.54	2.16
0.39FAB35	0.93	35,635	0.39	0.67	1.00	1.76	2.72
0.39FAC35	0.98	51,982	0.25	0.56	1.00	2.28	4.31
0.34FAA50	1.00	44,695	0.31	0.60	1.00	2.03	3.51
0.34FAB50	1.00	37,781	0.37	0.65	1.00	1.82	2.89
0.34FAC50	1.00	45,843	0.30	0.60	1.00	2.07	3.63

Table 11 Yield Adjusted Concrete Mixture Proportions and Test Results

Calculated Batch Quantities	**Mix1**	**Mix2**	**Mix3**	**Mix4**
Low Alkali cement (Cement B), lb/yd^3	385	367		
High Alkali cement (Cement C), lb/yd^3			389	371
Fly ash (FAA), lb/yd^3	261		264	
Fly ash (FAC), lb/yd^3		307		310
Fly ash, % by Mass	40.4	45.5	40.4	45.5
Fly ash, % by Volume	50	50	50	50
Coarse Agg. (No.57), lb/yd^3	2065	2056	2086	2077
Fine Aggregate, lb/yd^3	1248	1242	1261	1255
Mixing Water, lb/yd^3	220	229	222	231
w/cm	0.34	0.34	0.34	0.34
ASTM C494 Type F, oz/cwt	7.0	1.7	9.9	4.7
ASTM C494 Type C, oz/cwt	30.0	30.0	30.0	30.0
Fresh Concrete Properties				
ASTM C143, Slump, in.	8.00	6.00	7.00	3.75
ASTM C231, Air, %	1.6	2.5	1.9	2.2
ASTM C138, Density, lb/ft^3	155.3	156.1	156.9	157.7
ASTM C1064, Temperature, °F	72	72	75	75
Hardened Concrete Properties				
ASTM C39, Compressive Strength, psi				
1 day	2,736	2559	3542	161
3 days	4,136	5278	5323	5329
7 days	5,034	6758	6620	7309
14 days	5,790	7784	7773	8762
28 days	6,760	9027	9061	9897

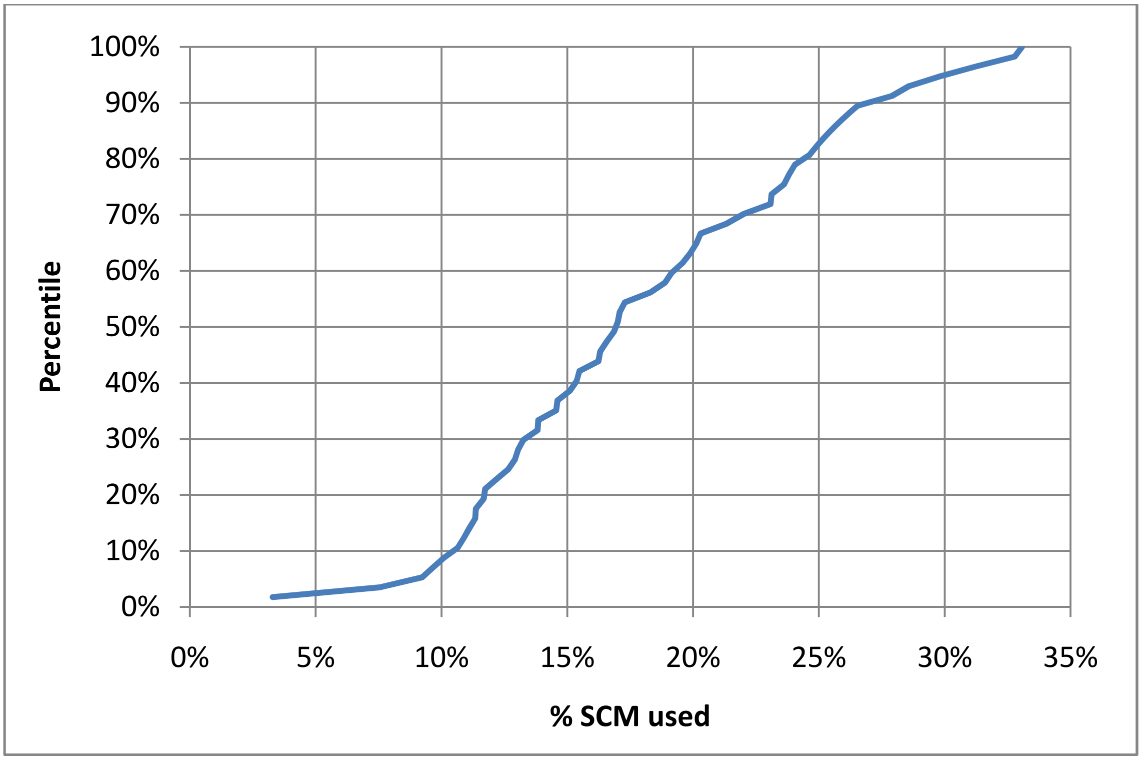
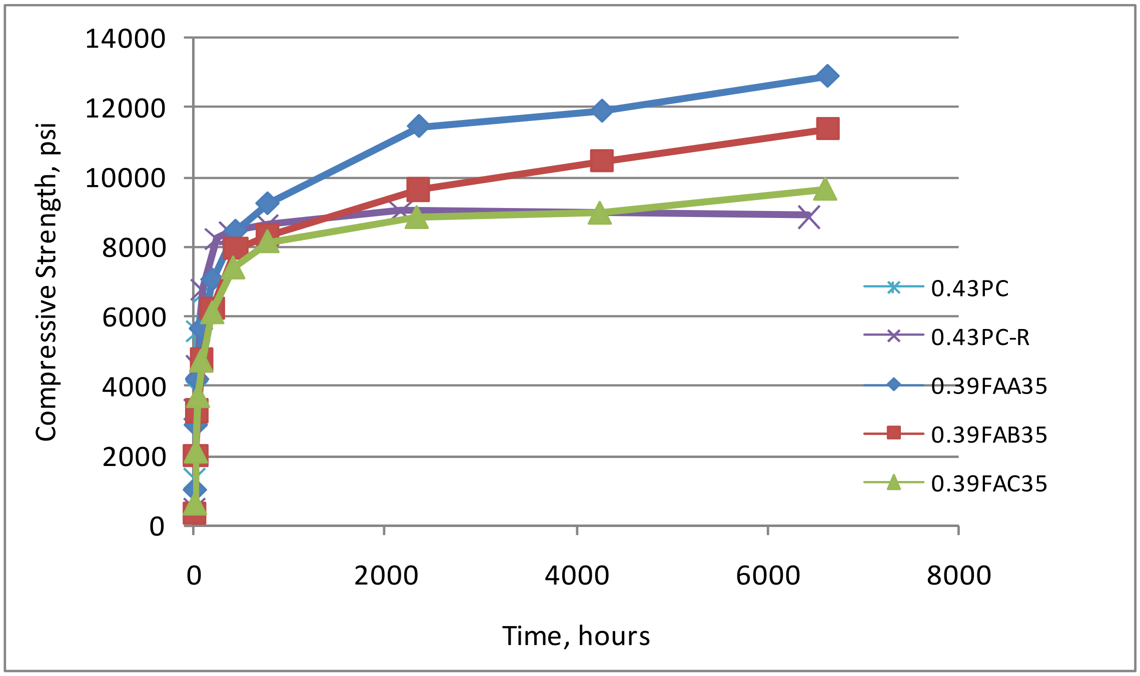
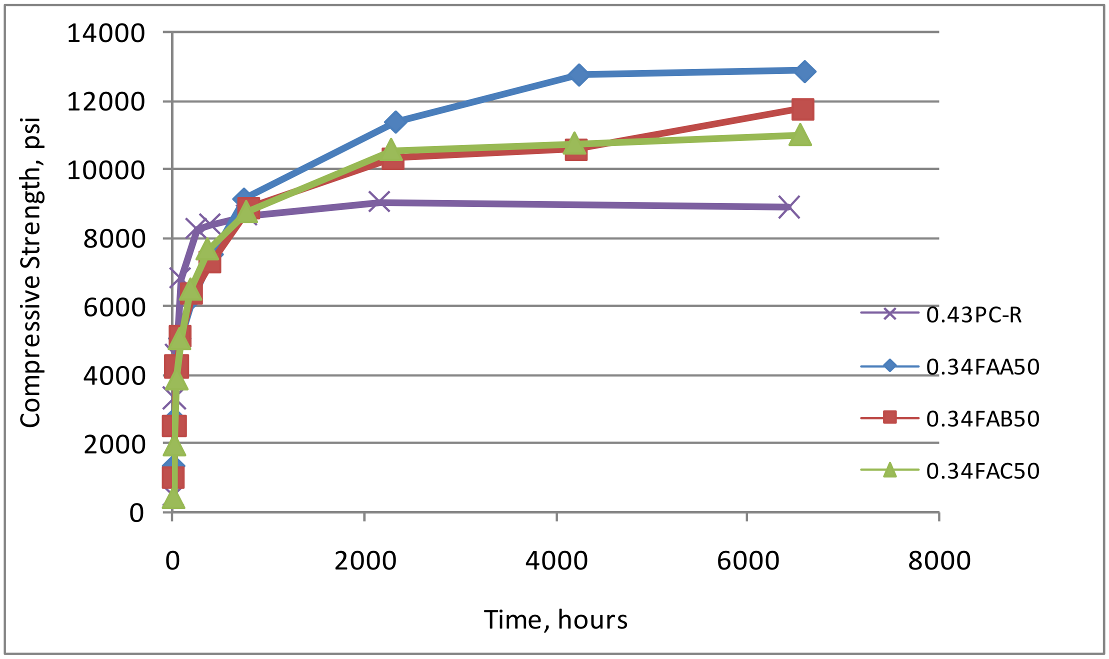


Figure 1. Percentile Distribution of SCM Used by Companies

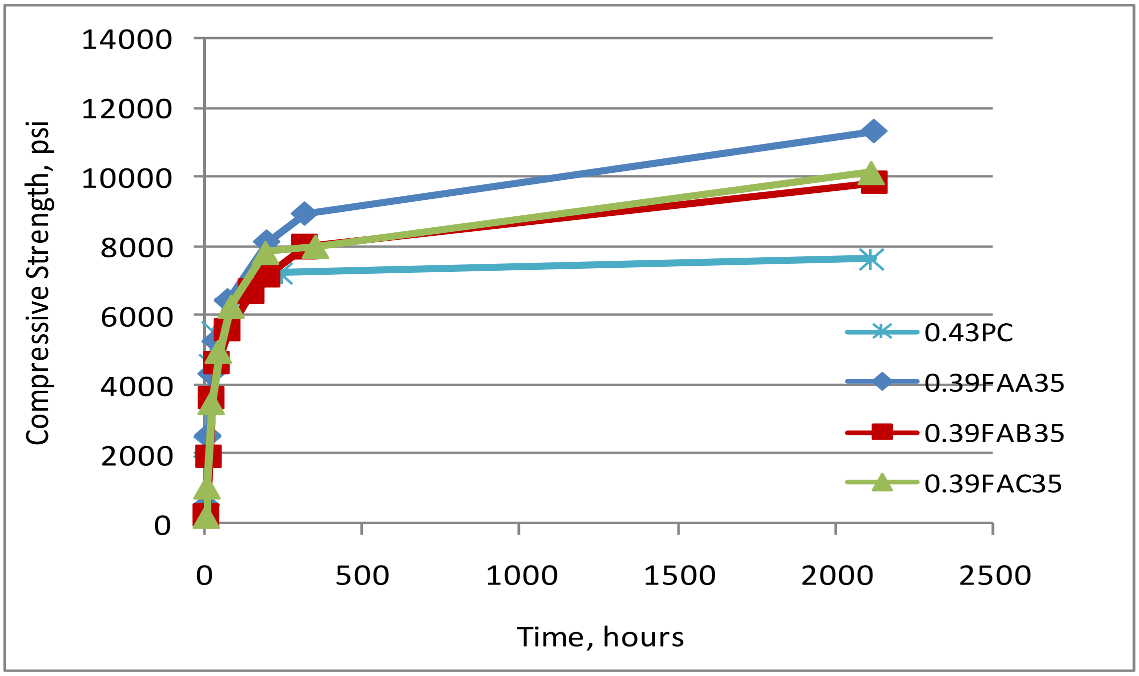


(a)

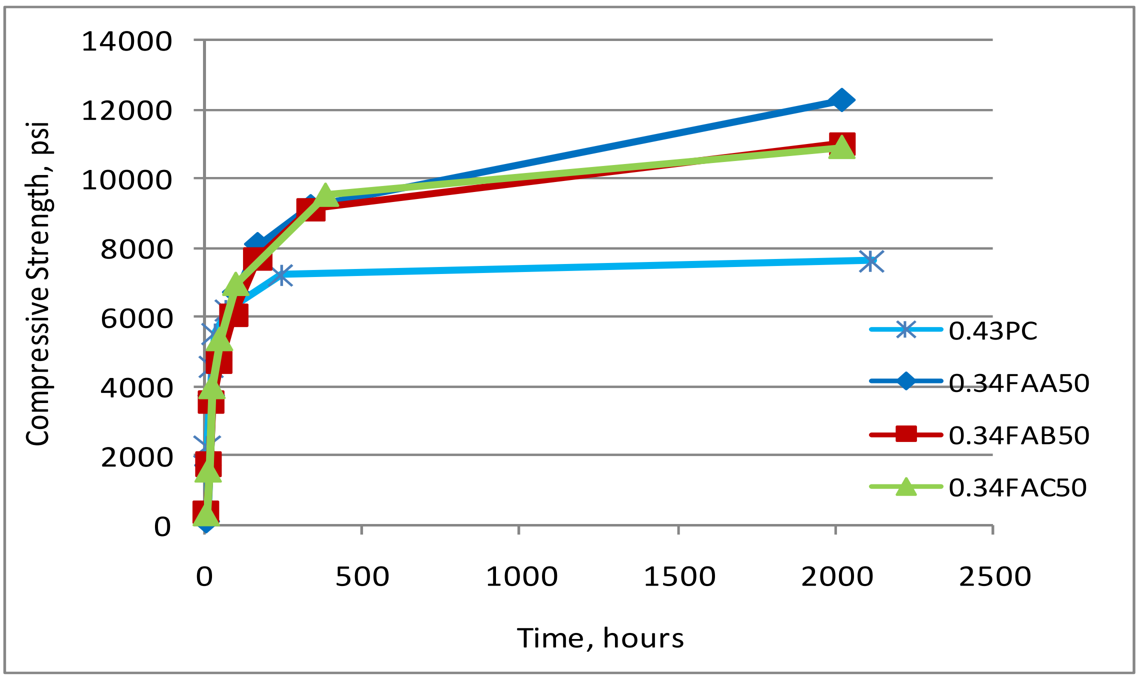


(b)

Figure 2a-b. Compressive strength test results of the low alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Control-73°F

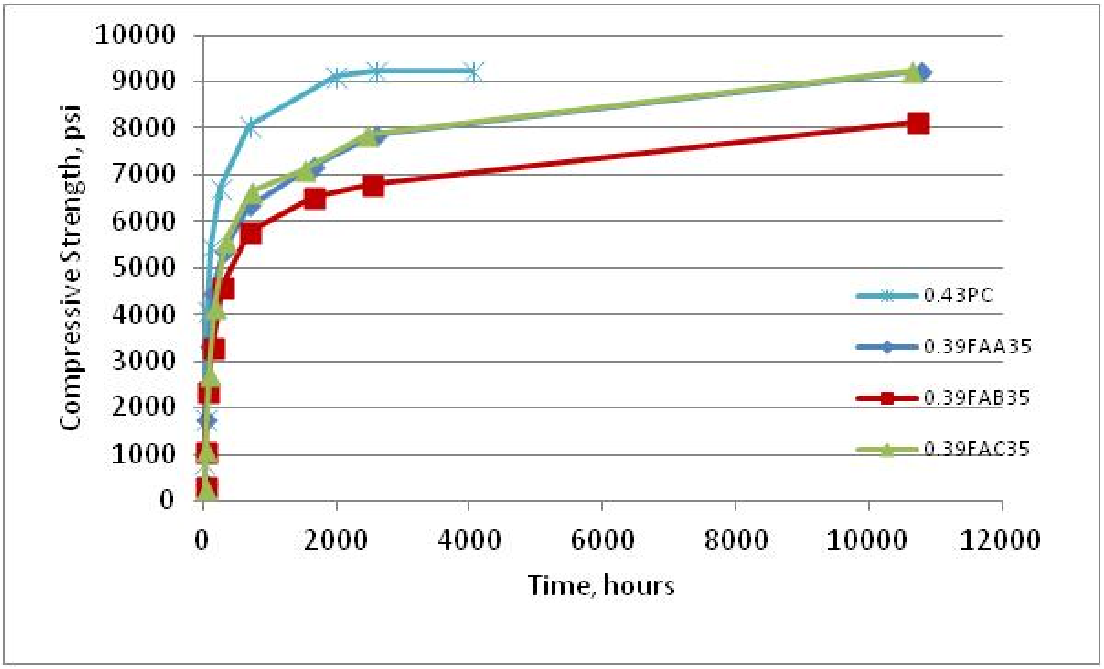


(a)

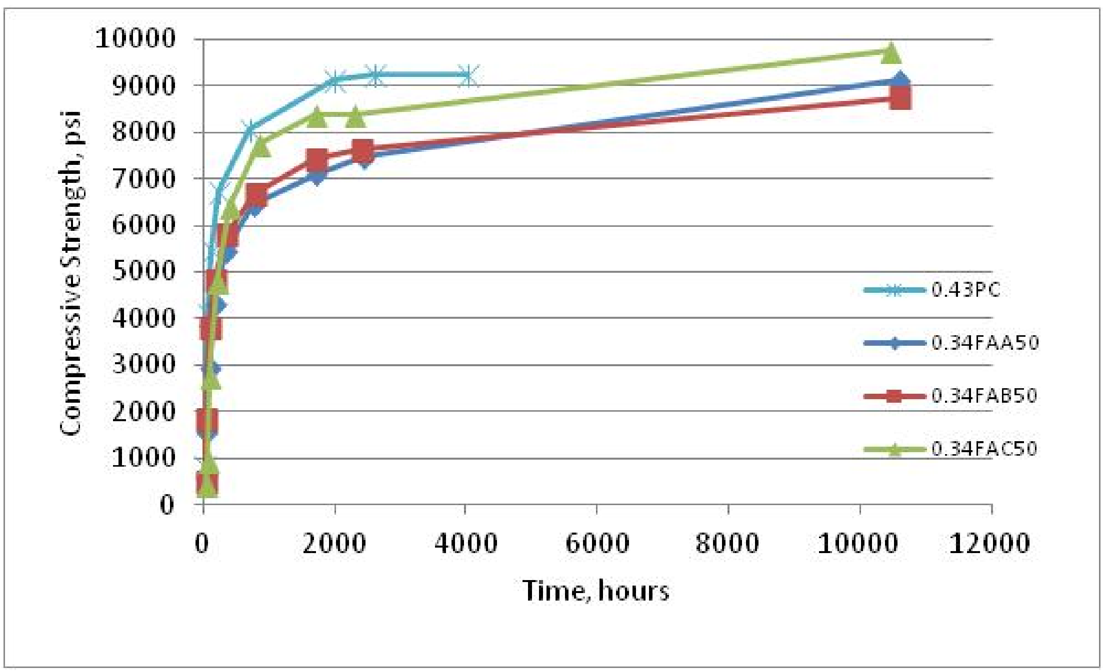


(b)

Figure 3a-b. Compressive strength test results of the low alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Hot-100°F

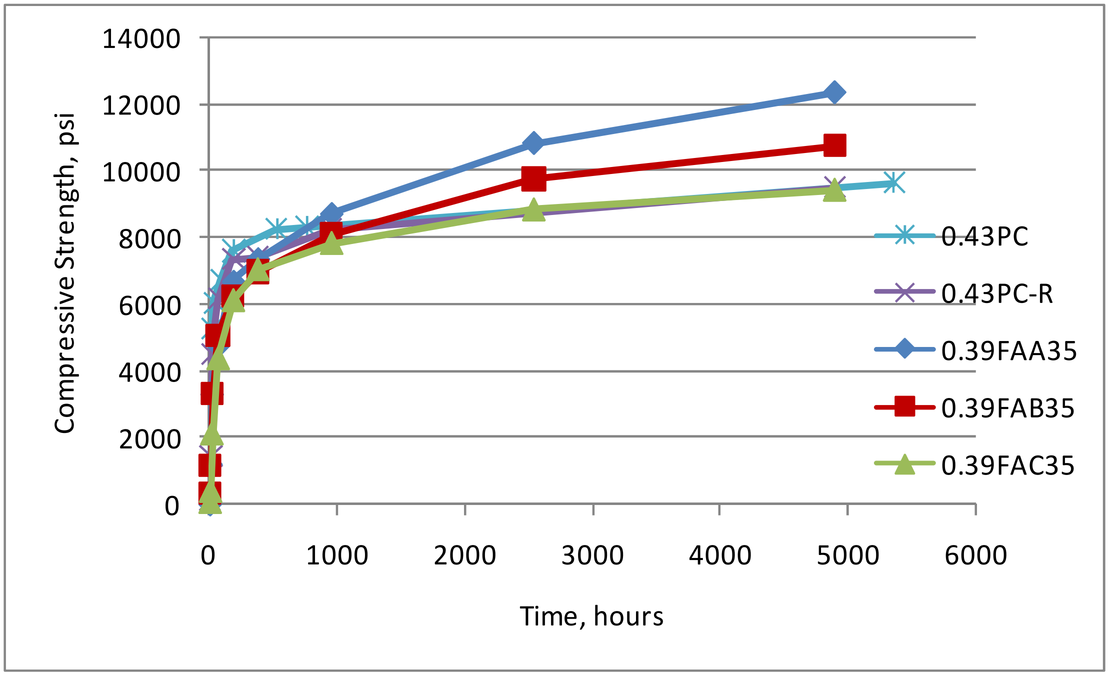


(a)

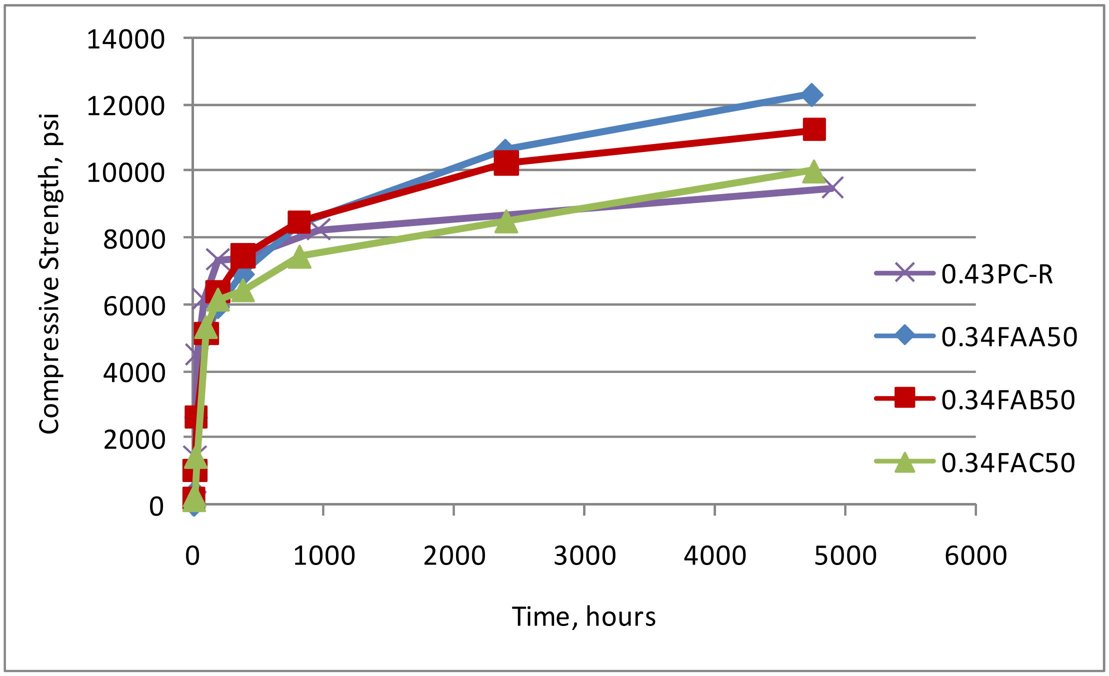


(b)

Figure 4a-b. Compressive strength test results of the low alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Cold-45°F

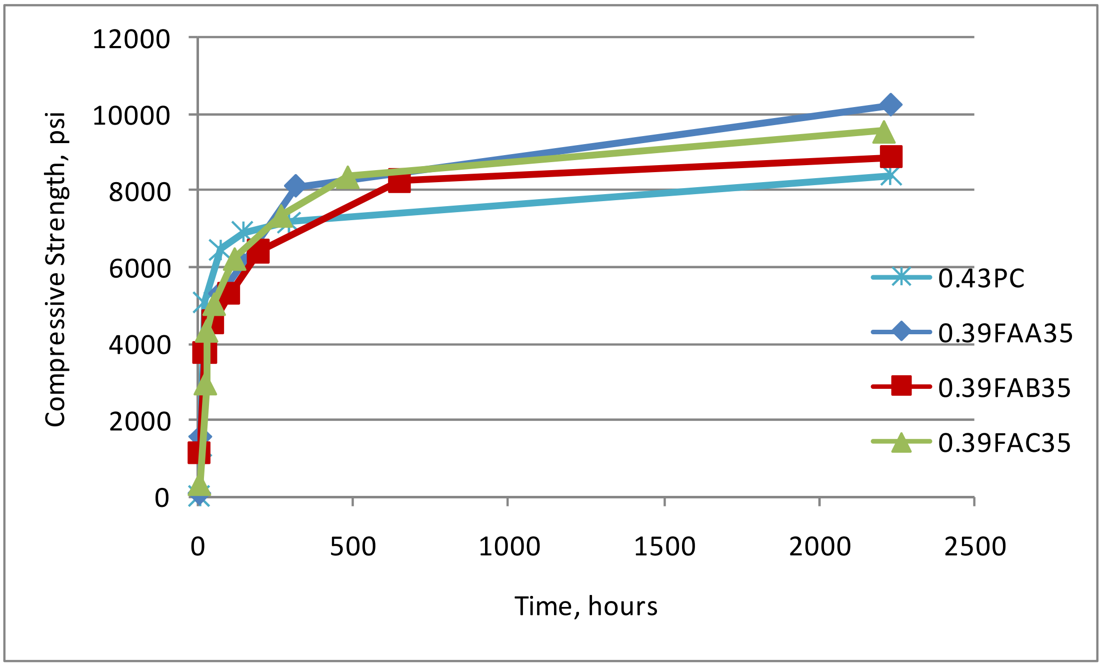


(a)

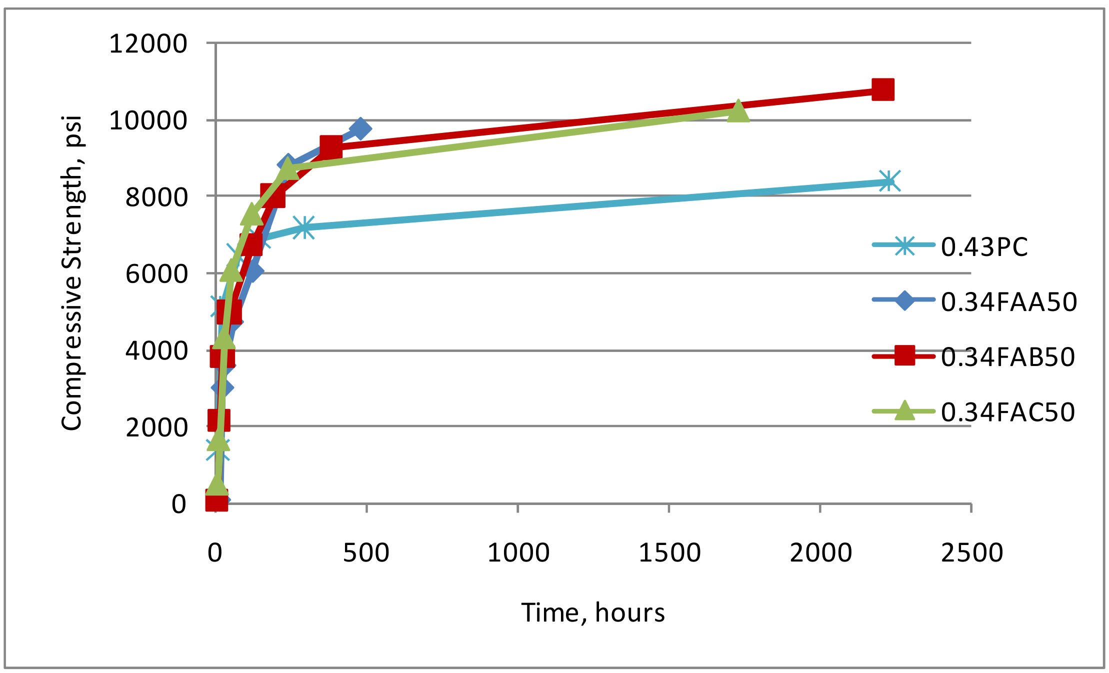


(b)

Figure 5a-b. Compressive strength test results of the high alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Control-73°F

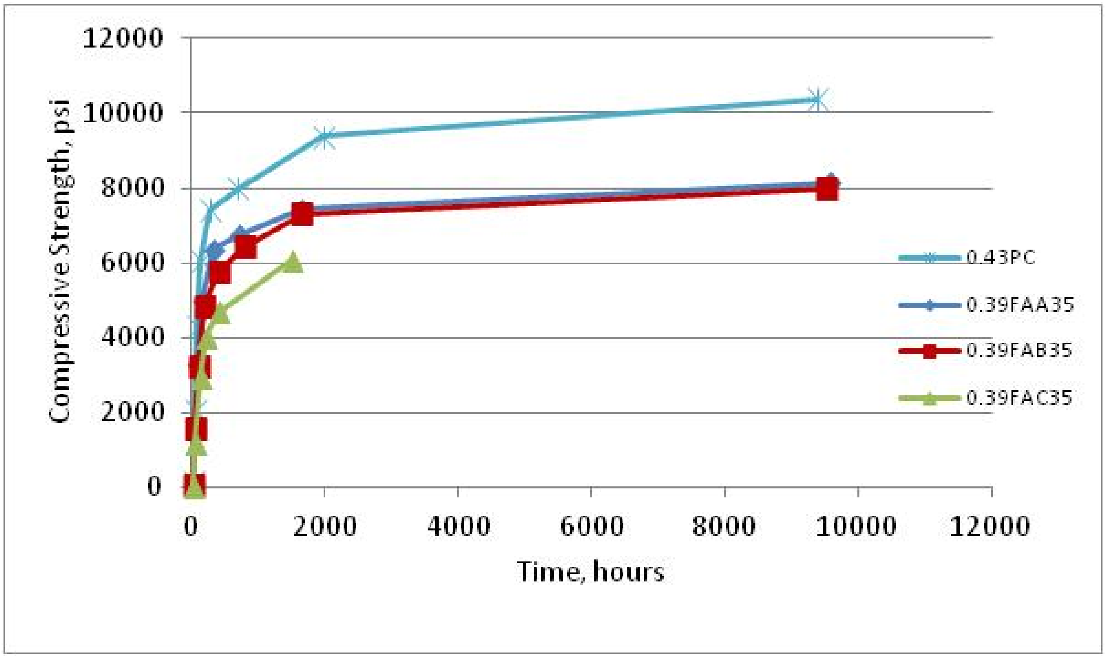


(a)

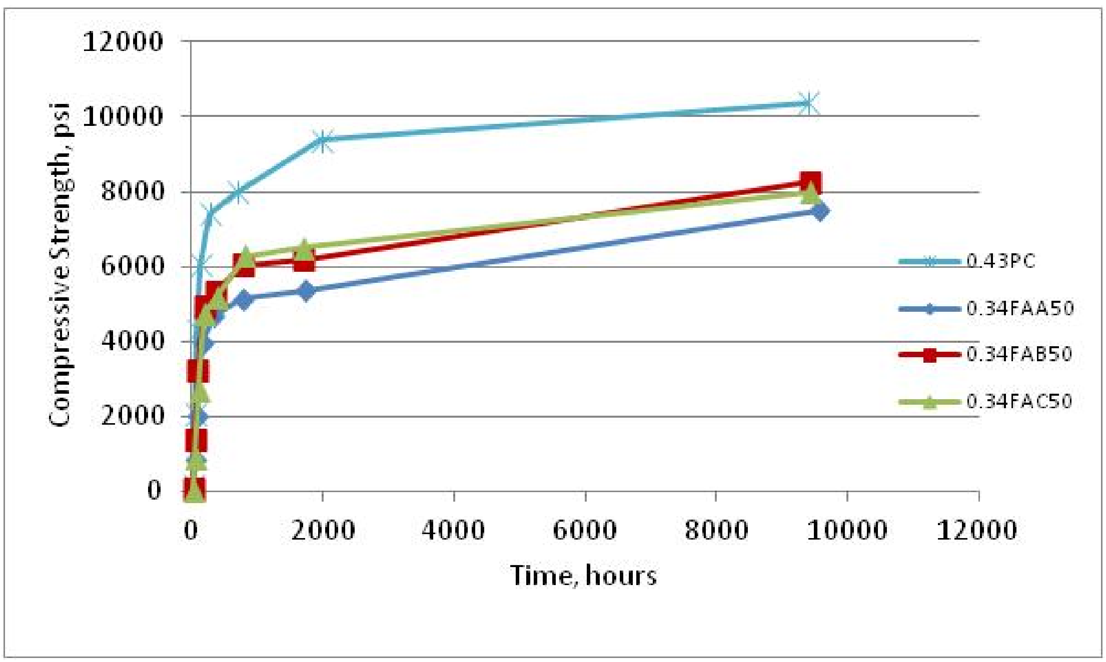


(b)

Figure 6a-b. Compressive strength test results of the high alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Hot-100°F

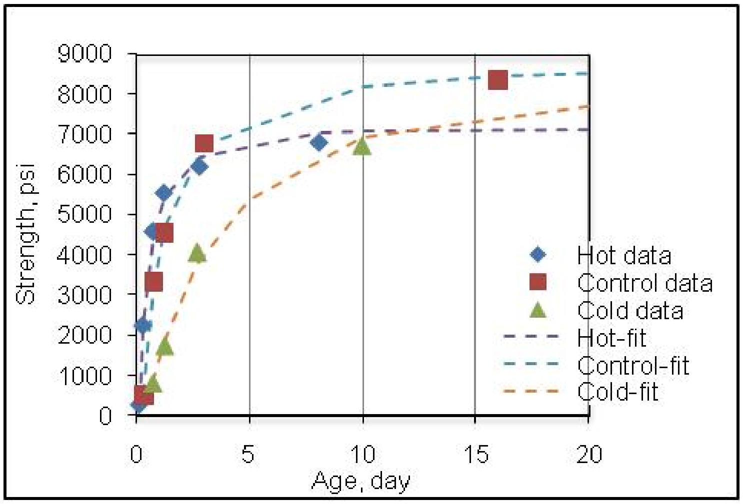


(a)

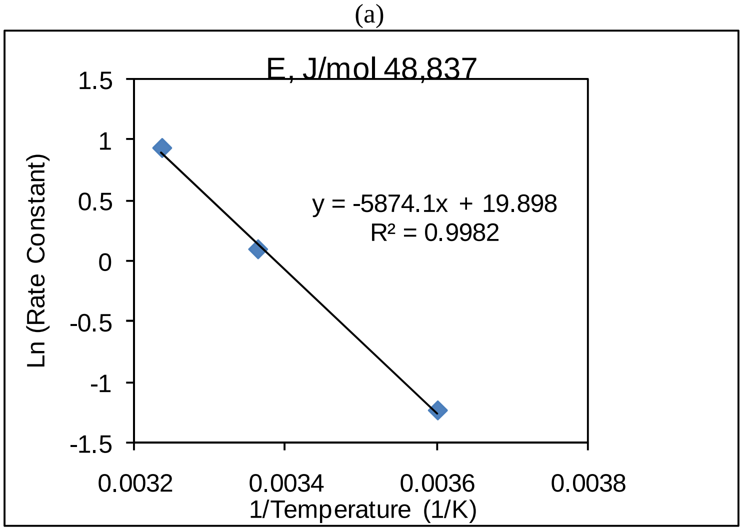


(b)

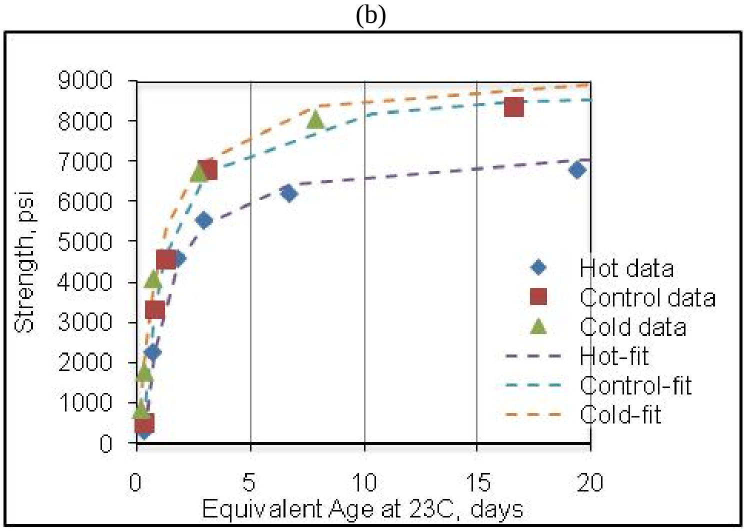
Figure 7a-b. Compressive strength test results of the high alkali cement control mortar mixture vs (a) 35% fly ash; (b) 50% fly ash
All mixtures cured at Cold-45°F



(a)

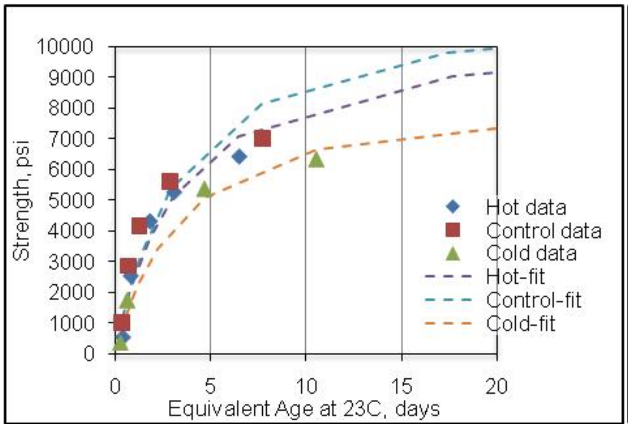


(b)

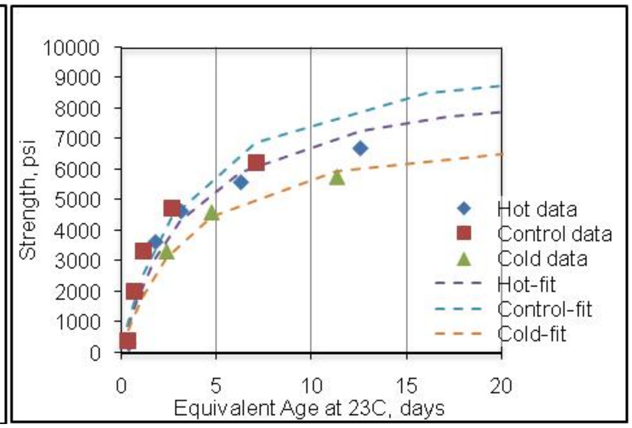


(c)

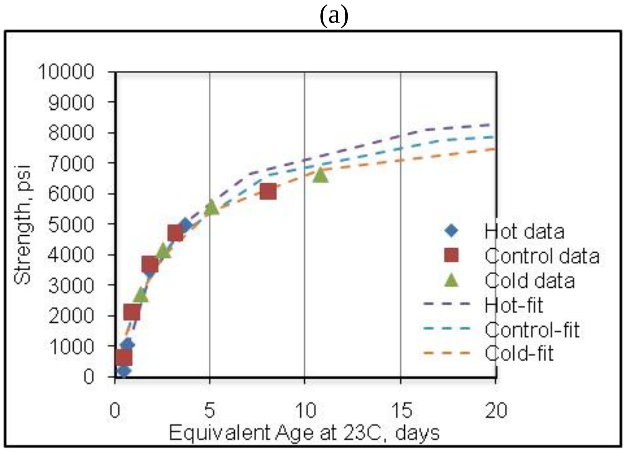
Figure 8. Strength-age plot (a), Plot to compute activation energy based on ASTM C1074 (b) and Strength-equivalent age plot (c) for Low Alkali Portland Cement B Mixture



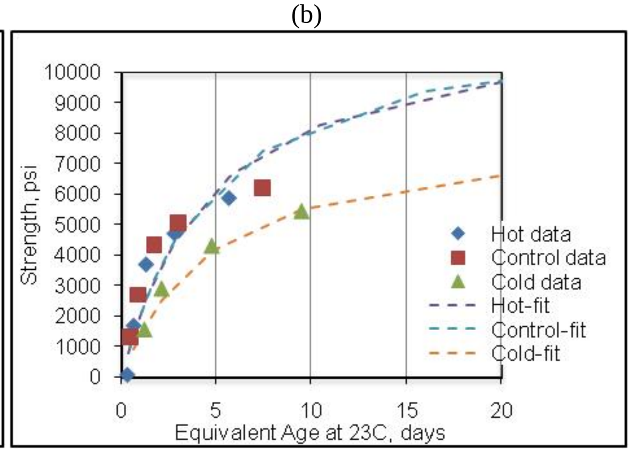
(a)



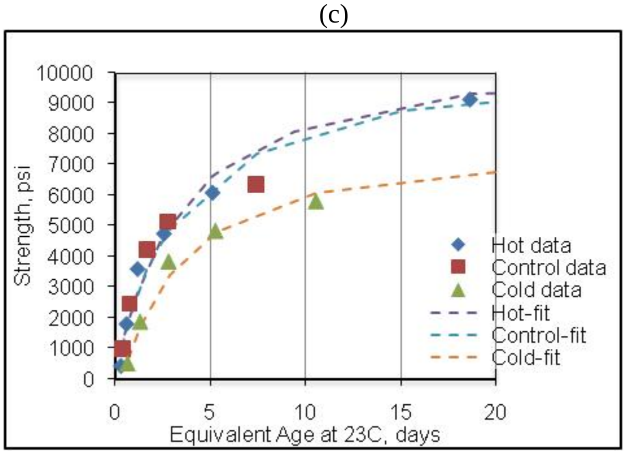
(b)



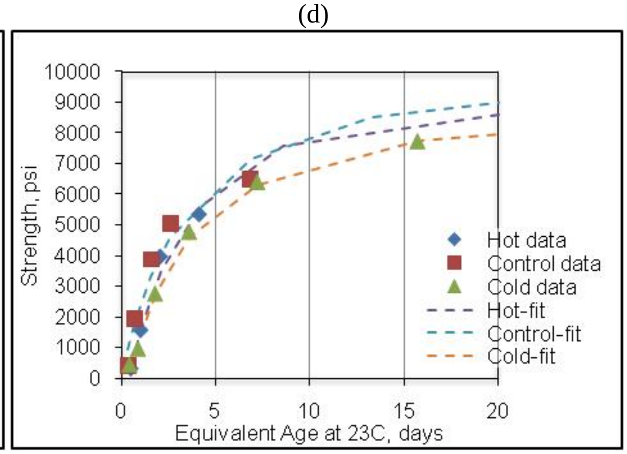
(c)



(d)

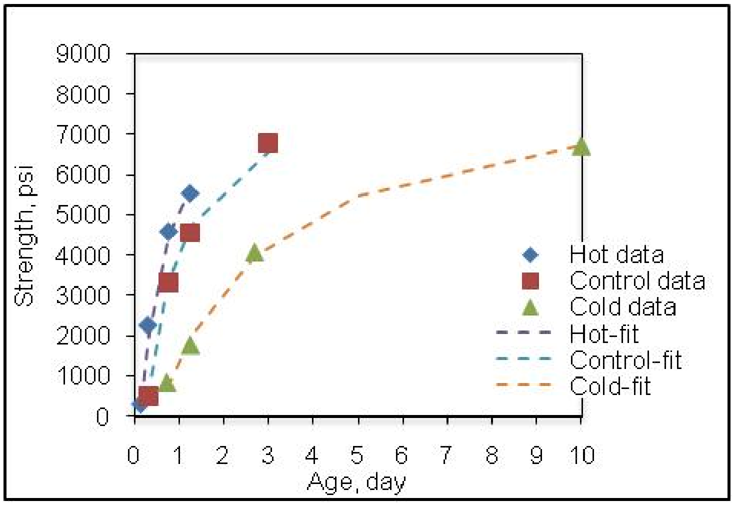


(e)

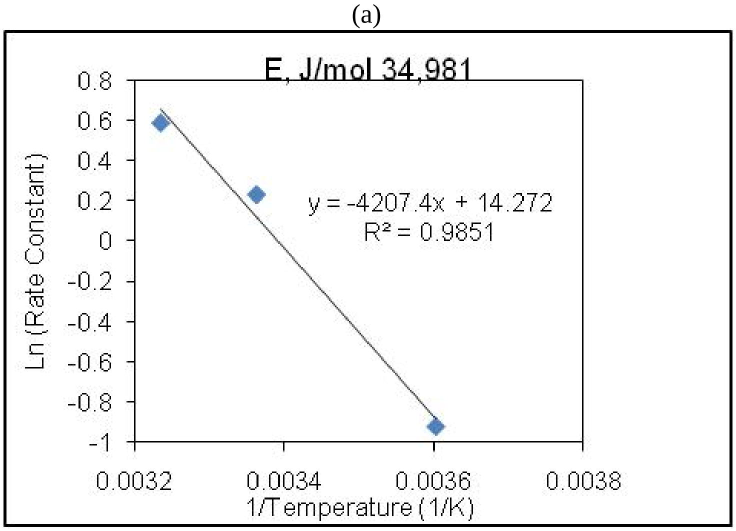


(f)

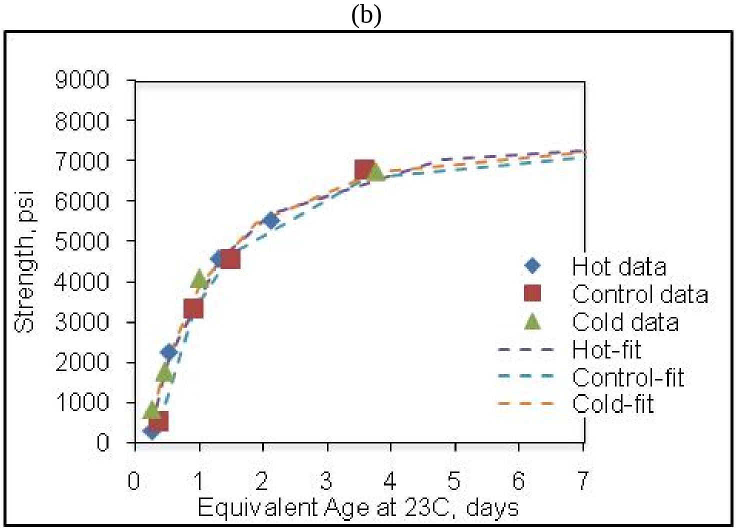
Figure 9. Strength-equivalent age plot for Low Alkali Cement B Mixtures based on ASTM C1074 (a) 0.39FAA35 (b) 0.39FAB35 (c) 0.39FAC35 (d) 0.39FAA50 (e) 0.39FAB50 (f) 0.39FAC50



(a)



(b)



(c)

Figure 10. Strength-age plot (a), Plot to compute activation energy based on modified ASTM C1074 (b) and Strength-equivalent age plot (c) for Low Alkali Portland Cement B Mixture

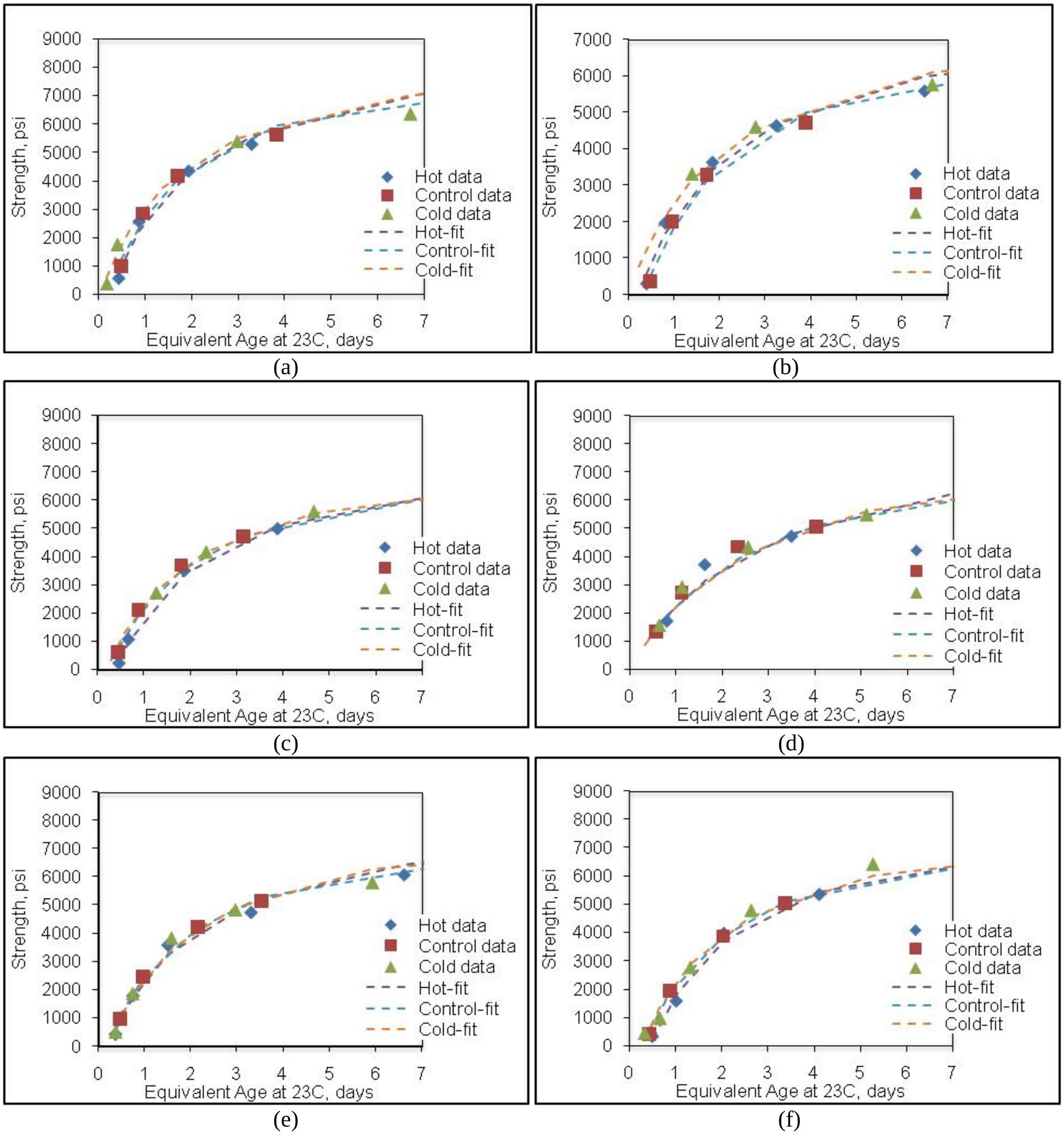
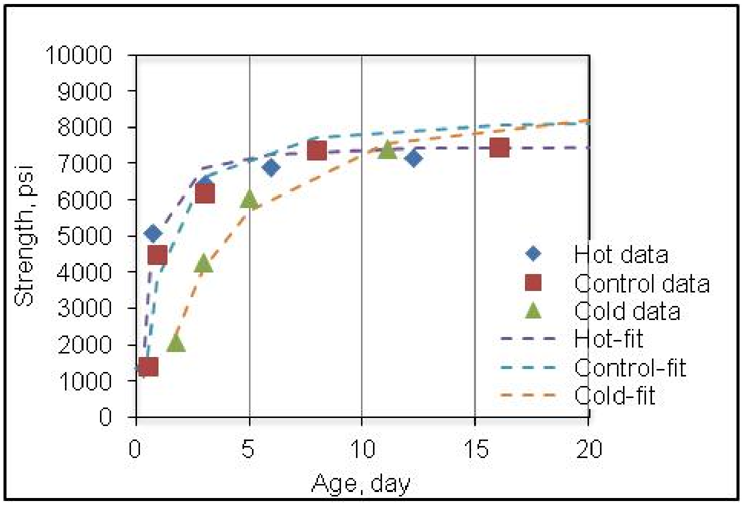
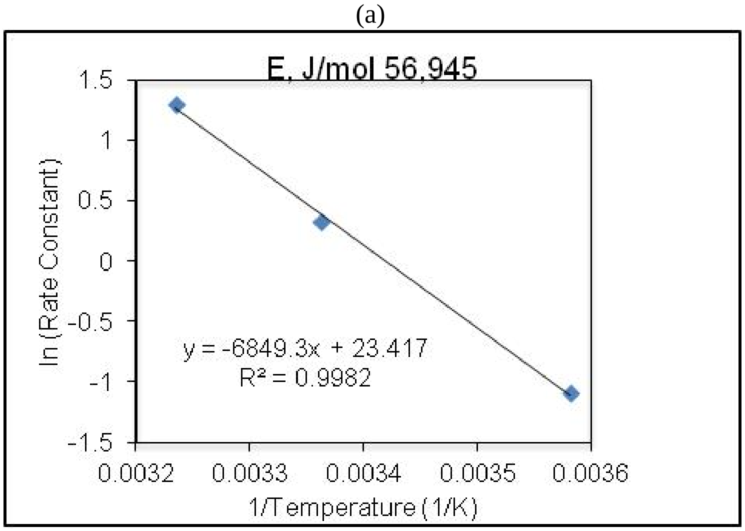


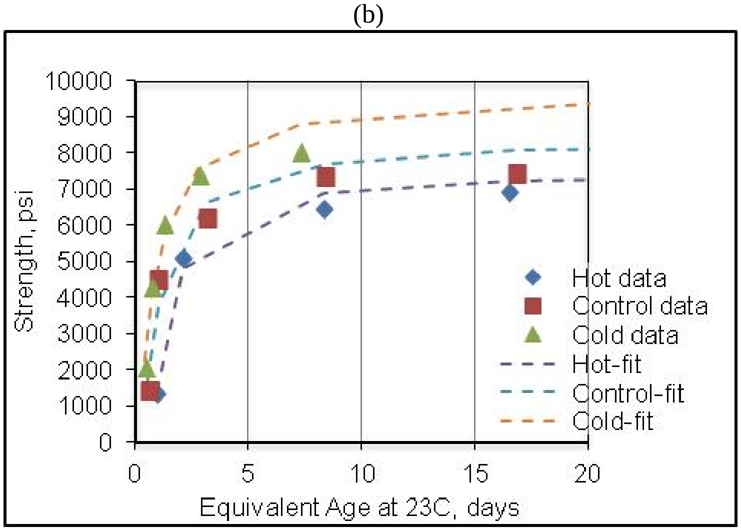
Figure 11. Strength-equivalent age plot for Low Alkali Cement B Mixtures based on modified ASTM C1074 (a) 0.39FAA35 (b) 0.39FAB35 (c) 0.39FAC35 (d) 0.39FAA50 (e) 0.39FAB50 (f) 0.39FAC50



(a)



(b)



(c)

Figure 12. Strength-age plot (a), Plot to compute activation energy based on ASTM C1074 (b) and Strength-equivalent age plot (c) for High Alkali Portland Cement Mixture

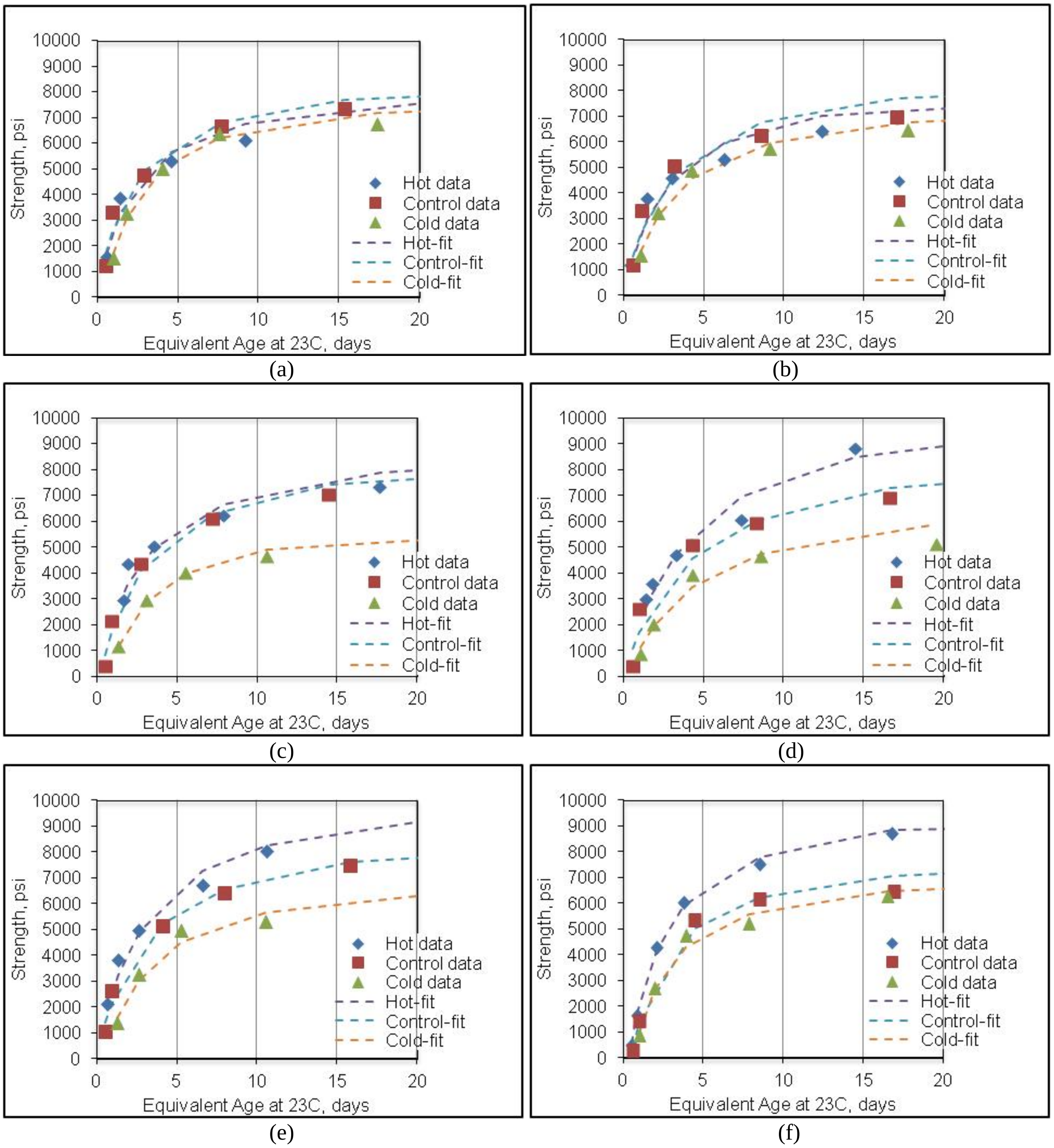
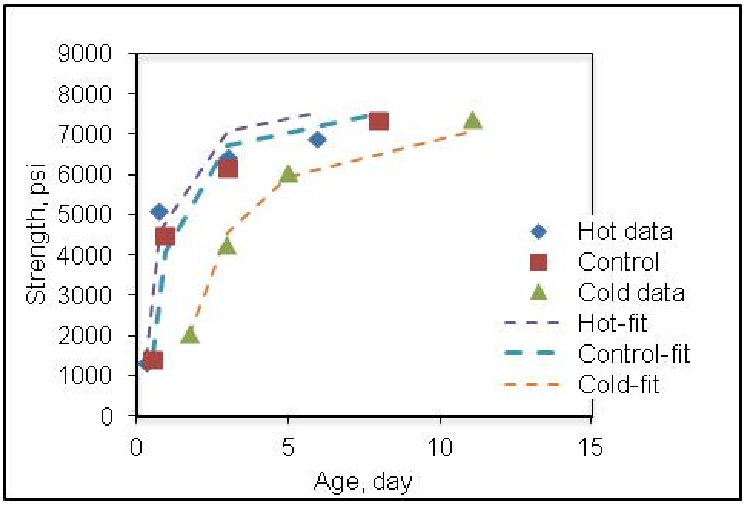
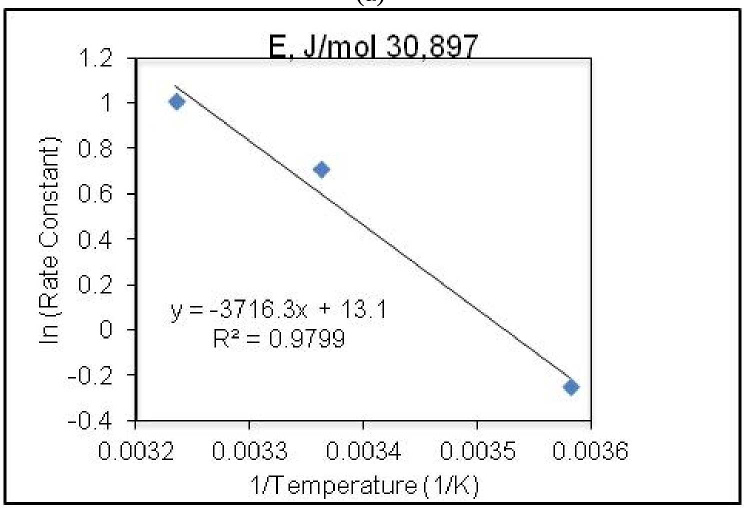


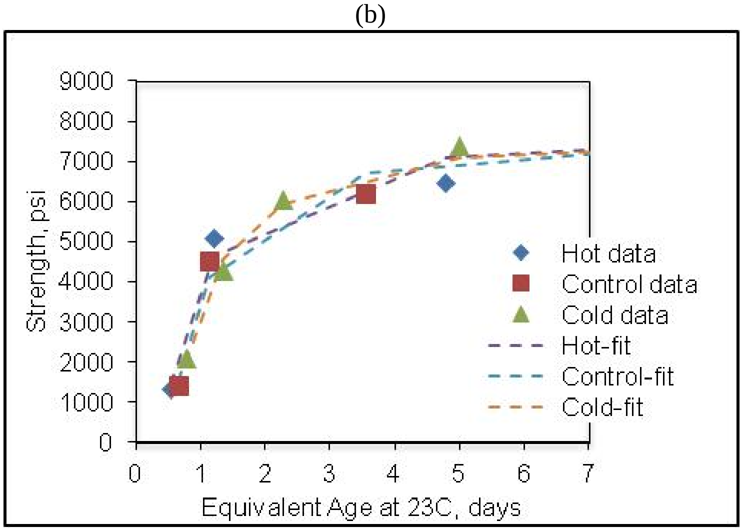
Figure 13. Strength-equivalent age plot for High Alkali Cement Mixtures based on ASTM C1074 (a) 0.39FAA35 (b) 0.39FAB35 (c) 0.39FAC35 (d) 0.39FAA50 (e) 0.39FAB50 (f) 0.39FAC50



(a)

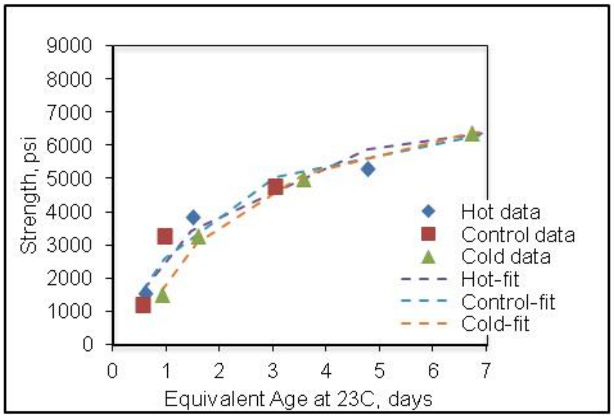


(b)

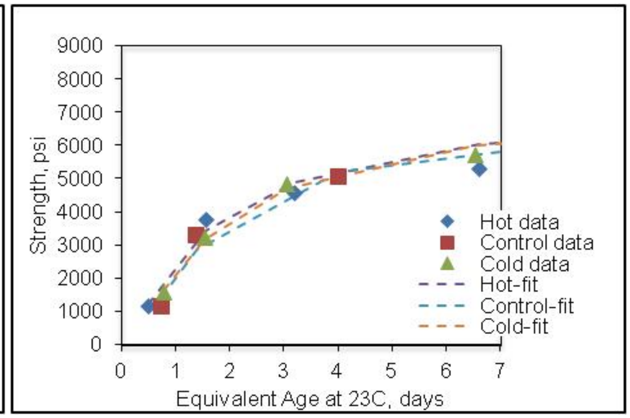


(c)

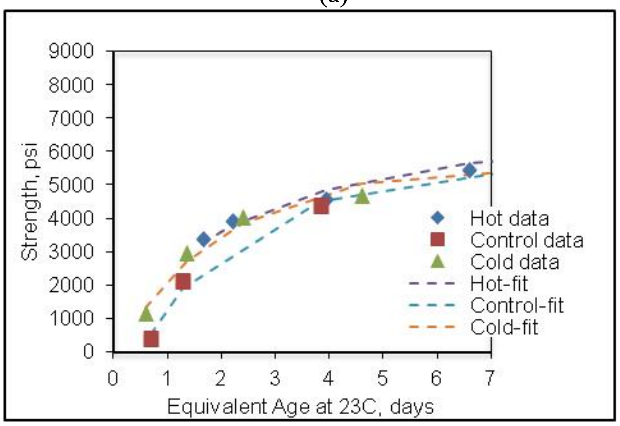
Figure 14. Strength-age plot (a), Plot to compute activation energy based on modified ASTM C1074 (b) and Strength-equivalent age plot (c) for High Alkali Portland Cement Mixture



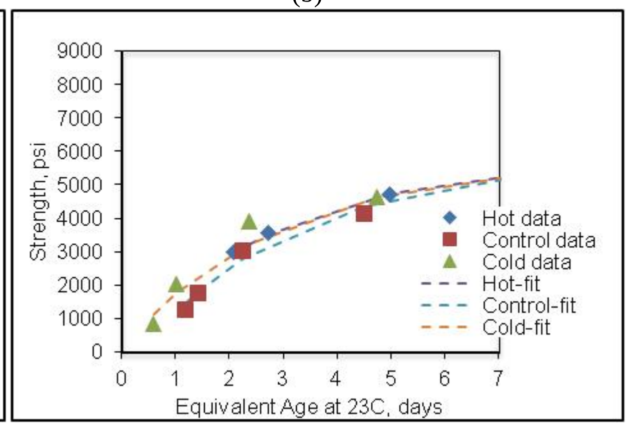
(a)



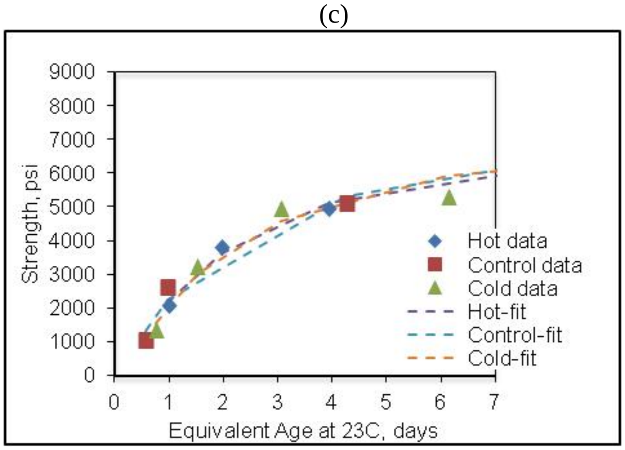
(b)



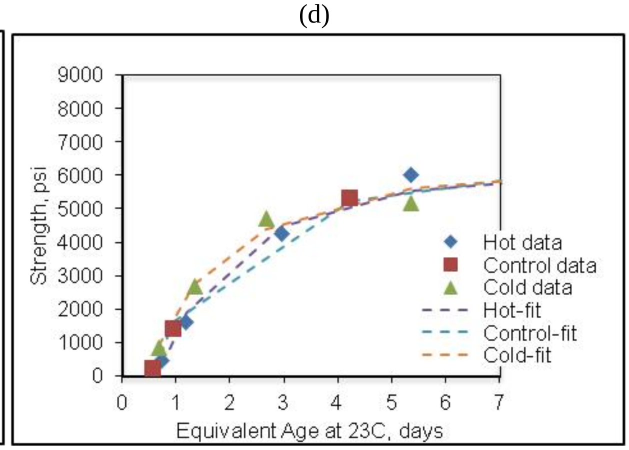
(c)



(d)

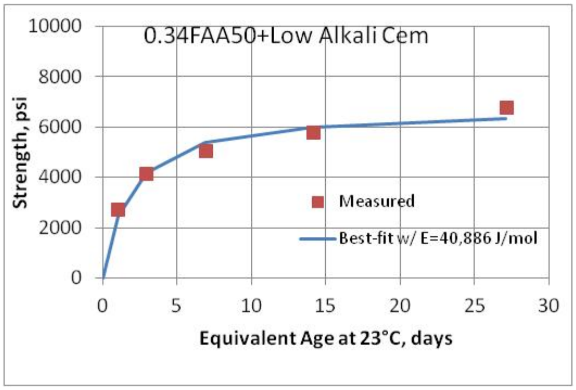


(e)

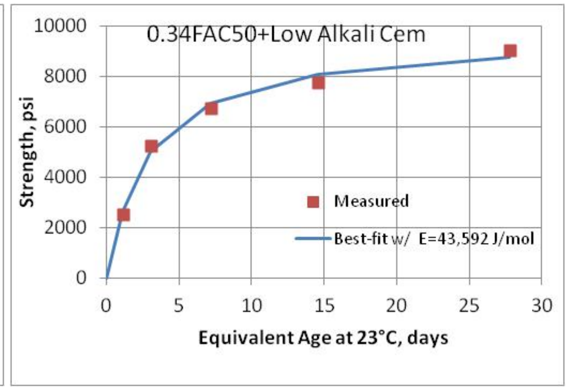


(f)

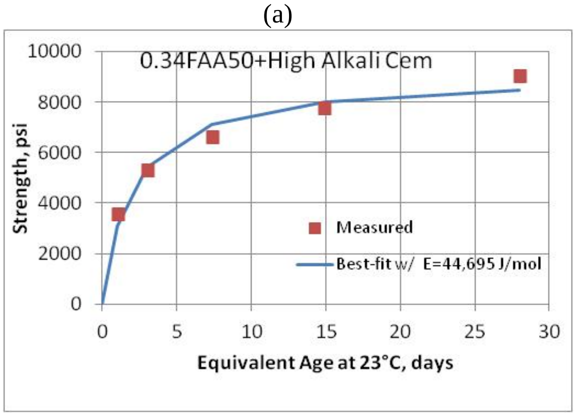
Figure 15. Strength-equivalent age plot for High Alkali Cement Mixtures based on modified ASTM C1074 (a) 0.39FAA35 (b) 0.39FAB35 (c) 0.39FAC35 (d) 0.39FAA50 (e) 0.39FAB50 (f) 0.39FAC50



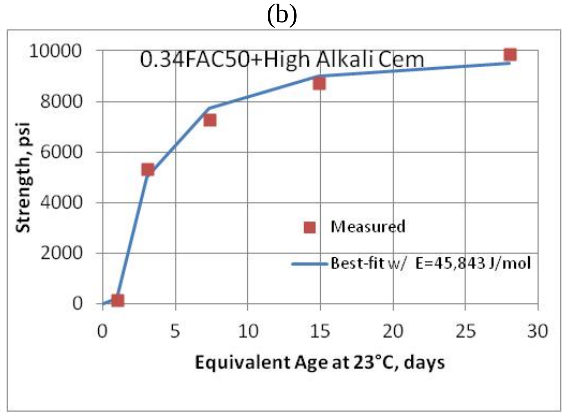
(a)



(b)



(c)



(d)

Figure 16a-d. Compressive strength vs equivalent age plots for Concrete Mixtures (a) 0.34FAA50LAC; (b) 0.34FAC50LAC; (c) 0.34FAA50HAC; (d) 0.34FAC50HAC

Appendix A.1 Supplementary Cementitious Materials (SCM) Use Survey

As part of a funded research project on increased fly ash utilization in hydraulic cement concrete, NRMCA is tasked with conducting a survey to better understand SCM use. SCM can consist of fly ash meeting ASTMC618/AASHTO M295, slag cement meeting C989, and silica fume meeting C1240. Report portland cement conforming to ASTM C150/AASHTO M85; blended cement conforming to ASTM C595/AASHTO M240 or ASTM C1157. This survey should be completed by the concrete producer for calendar year 2011 (use 2010 data if 2011 is not available). This survey only pertains to SCM used in all concrete supplied by a ready mixed concrete producer. Do not include SCM use for non-concrete applications. You are requested to answer as many questions as possible without guessing. The data you report will be kept confidential and only the overall nationwide survey results will be shared with all survey participants and other researchers.		
1	Name	
2	Company/Division Name	
3	Email id	
4	Annual Concrete Volume (cyds)	
5	Annual portland cement used (tons)	
6	Annual blended cement used (tons)	
7	Annual fly ash used (tons)	
8	Annual slag cement used (tons)	
9	Annual silica fume used (tons)	
10	**Breakdown percentage of concrete produced - All of it should add up to 100**	
10.1	Percent with portland cement only, %	
10.2	Percent with blended cement only, %	
10.3	Percent with fly ash, %	
10.4	Percent with slag cement, %	
10.5	Percent with silica fume, %	
10.6	Percent with more than one SCM (ternary), %	

The following questions pertain only to fly ash use

11	**In your view what are the reasons why you don't substantially increase the use of fly ash? Rank them from 1 to 6 in the order of importance with 1=most important**	
11.1	Fly ash supply - not available or inconsistent	
11.2	Fly ash properties are variable	
11.3	Use other SCMs (slag, etc)	
11.4	Concrete performance issues - setting time, strength gain, etc	
11.5	Specifications restrict use	
11.6	Customers object to use	
12	**What opportunities exist to substantially increase use of fly ash? List one or more items below.**	
13	**Comment - state any assumptions or details about reported data.**	

Appendix A.2 Compilation of Responses to Question #12 of SCM Use Survey

ID	What opportunities exist to substantially increase use of fly ash? List one or more items
1	It would be used more if it is not percieved as a hazzardous material by the EPA and the classification issue gets resolved. It would be used more if it is required, instead of being listed as an option.
2	Teach engineers and architects the benefits of using SCM's as so they will allow it on more projects.
4	LEED Projects, Flowable fill Mix Designs,
5	Commercial Specs
7	1) Improved specifications that don't restrict the % of fly ash allowed (i.e. 15% max) 2) Continued availability of beneficiated ash that allows for more consistent concrete performancd
8	educate engineers municipal and private, flyash was not permitted in Wind power turbine foundations so ..much for green energy….
9	green movement and specifications. we will always want to use as much ash as possible except where cold weather limits us. (durability, set time, strength gain)
10	Cell fill (High Replacement) / Specified green mixes
12	Unfortunately the use of Fly Ash in the North West could see a decrease. Both of our local plants are currently shut down due to natural gas prices and they are both scheduled to be shut down by 2019 if not sooner.
13	Specification limitation to 15% common….Wider exceptance to ACI limitations would help.
16	Acceptance of high volume fly ash mixes. Emerging technology creating modified fly ash products.
17.1	We use the maximum quantities as allowed by spec writers.
17.2	None currently. Supply is very limited.
20	More LEED projects and increased use in residential jobs in "Green" type mixes.
22	Educate specifiers and owners
23.1	Many opportunities exist, we just need to push them as an industry. LEED may help us achieve this as straight portland cement is starting to be looked at as non-environmentally friendly.
23.2	LEED Project Requirements. Sustainability Initiatives. Durability
24	set times need to be decreased, design and engineering fields need to be educated on the benefits of higher % cement replacement
25	The green building iniative, Usage of fly ash in warmer temp for slab on grade applications. Slower set time
27	LEED complaint construction and other "Green" Building systems. 2011 saw a change in sources of fly ash and shortages. Generally % fly ash was reduced for a significant portion of the year but not removed from the mix designs completely.
28	If the specifiers will allow a higher percent of fly ash replacement. We would actively develop usable mixes with higher fly ash content
29	New government specifications are calling for higher volumes of SCM in the 30-40% range on most projects.
30	1. Residential Concrete. 2. Commercial Floors.
32	An increase in specified acceptance age. For example 56 days in lieu of 28 days.
33	Floors, walls, footings
34	Increased density to mitigate salt intrusion form marine environment, need to educate the end user of the benefits andof the need to increase the ultimate strength test date beyond 28 days. Normally designers and contracters are VERY reluctant to permit higher than "normal" ratios of FA to Cem. i think based on old steriotyical though processes. We ahve had difficulty in pushing the higher ratio mixes.
35	The specs for green uses have increased. We do raise the levels of Fly Ash in our concrete in the warmer summer months upto 25% of cementitous content in our standard mixes and in specialty mixes for state highway work and other mixes. But generally it's no more than

	15%.
36	Educate contractors, specifiers and owners (including governmental agencies) on benefits of fly ash, dispel incorrect performance assumptions, and get specifications updated to allow for the use of more fly ash.
38	Set time with ash to be equal with all cement mixes
40	More focus on sustainability & green building. Designers yielding to the pressure of LEEDs-type projects.
41	infrastructure projects; flowable fill, CLSM, grouts ….
43	(1) Relax specification restrictions (2) Where feasible, have specifiers increase the strength acceptance age to 56 or 90 days for mixes with higher percentages of fly ash
44	Talk to more architects and engineers about the usage. Restricitive specs are the biggest reason to not include SCM.
45	Projects with severe ASR problems can utilize a higher quantity of some types of Fly Ash. As well as more backfill opportunities.
49	Reduction of concrete early strength, Reduction in Cost
50	Until there is a savings to use Fly Ash, it is going to be difficult to increase usage. Furthermore, supply has been getting tighter, and tighter, which has proven to be problematic when Fly Ash is specified in a project--we have actually had instances where supply has forced projects to be delayed until Fly Ash was available. Another issue, recently, has been with Fly Ash being on the news as part of the group of by-products the Federal EPA wants to classify as hazardous waste, customers are afraid to have Fly Ash mixes, particularly in residential applications, out of fear they will face future liability as a result.
51	Spec change is by far biggest for us. Education of specifiers and promotion of LEED?
52	New highranges designed to increase the strength efficiency of fly ash. Air entraining agents that provide a stable air content
54	Supply and consistant quality
55	The opportunities are changing gradually. The biggest problem we see is that a lot of the engineers in our area are still "old school" in the fact that they believe that straight bag mixes are the only way to make quality concrete.
56	LEED pushes for more fly ash but the Northwest availability is totally cut off between March to June due to hydroelectric power being so much cheaper than coal burned power that coal burning power plants totally shutdown.

Appendix B. Repetition of some Mortar Mixtures

A close look at Table 5 indicates that the following mortar mixtures (see Table B.1) had Type F admixture dosage that was greater than 12 oz/cwt. (typical manufacturer recommended dosage is 2-7 oz/cwt.).

Table B.1 Mortar Mixtures to be Repeated

Mixture ID, Curing Condition	Admixture Dosage, oz/cwt	Cement type
Mix5 (0.34FAA50), 73F	18	Low alkali
Mix12 (0.34FAA50), 100F	20	Low alkali
Mix23 (0.39FAA35), 73F	15	High alkali
Mix26 (0.34FAA50), 73F	32	High alkali
Mix30 (0.39FAA35), 100F	16	High alkali
Mix33 (0.34FAA50), 100F	45	High alkali
Mix40 (0.34FAA50), 45F	29	High alkali

The following observations can be made:

1. Out of 42 mixtures 7 mixtures had Type F admixture dosages greater than 12 oz/cwt.
2. All of the 7 mixtures had fly ash FAA
3. 5 out of these 7 mixtures had high alkali cement.
4. For similar conditions the 50% FAA mix had much higher Type F dosage as compared to the 35% FAA mix which is understandable due to the much lower water contents.
5. Higher mixing temperatures lead to slightly higher admixture dosages.

The manufacturer communicated that higher admixture dosages can be used if needed without any degradation in strength results. Nevertheless it was decided to repeat all of above mixtures except Mixture 23 and 30. Mixture 23, 30 did not excessively high dosages and at the same time it was decided that at least two mixtures for each temperature should be repeated (6 mixtures in all). The repetitions were done with the following objectives:

1. To confirm again whether the originally recorded admixture dosages were correct
2. If the recorded admixture dosages were indeed correct to confirm whether the high admixture dosages led to poorer strength performance.

The repeat mixtures were conducted with the following criteria:

- Use a total of 12 oz/cwt type F admixture
- Try to hit the lowest flow (95) that is workable to make cubes well
- If flow is below 95 then, add slightly more water to hit the minimum flow (95).
- Test two cubes each age at 1, 2, 4, 8, 16, 28 days (equivalent ages at 73F) - as verification test the cubes will be tested during the business hours.

In Table B.2 the repeated mixtures' flow values, w/cm, admixture dosages, and mix temperatures are provided along with those values for the original mixtures.

Table B.2 Fresh Mortar Properties of Repeated Mortar Mixtures

Mix ID	**Cement Type**	**Curing Condition**	**Mix #**	**Flow %**	***w/cm* ratio**	**F-admix. oz/cwt**	**Temp °F**
FAA50	LAC	Control-75F	Mix5	112	0.34	18	75
			Mix5R	111	0.36	12	73
FAA50	HAC	Control-75F	Mix26	106	0.34	31.5	78
			Mix26R	96	0.35	12	76
FAA50	LAC	Hot-100F	Mix12	106	0.34 (0.35$^+$)	19.8	Not measured
			Mix12R	117	0.38	12	81
FAA50	HAC	Hot-100F	Mix33	105	0.34 (0.36$^+$)	45.3	87
			Mix33R	91	0.40	12	88
FAA50	HAC	Cold-45F	Mix40	108	0.34 (0.35$^+$)	28.8	72
			Mix40R	92	0.37	12	69

LAC = Low Alkali Cement
HAC = High Alkali Cement
$^+$ *w/cm* ratio including water portion of the type F admixture

The strength development for each mixture and its repeat is plotted in Figure B.1. The curing temperatures for some of the mixtures and their repeats are plotted in Figure B.2.

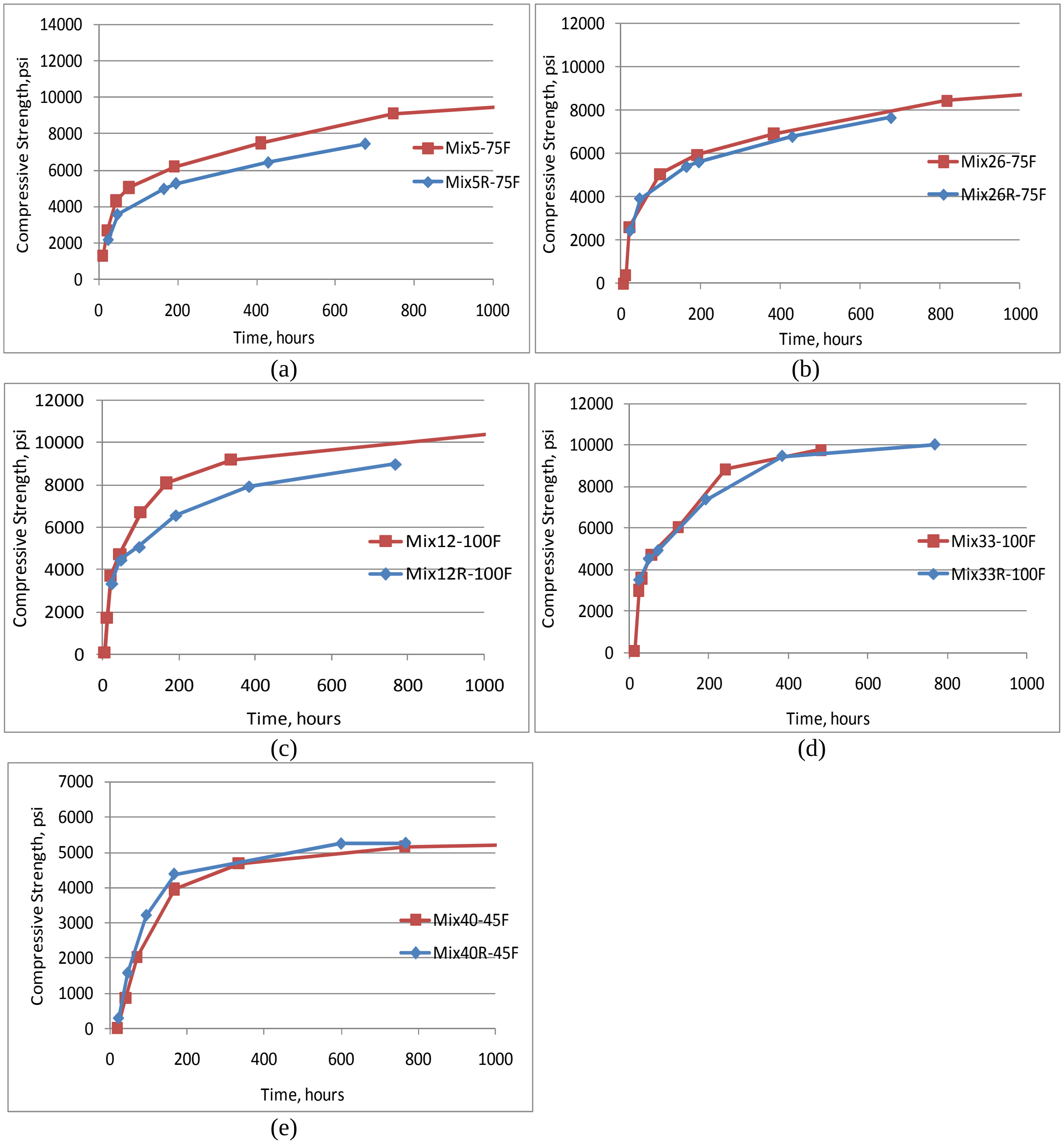
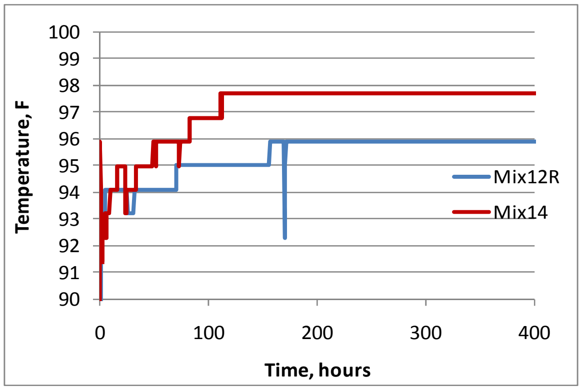
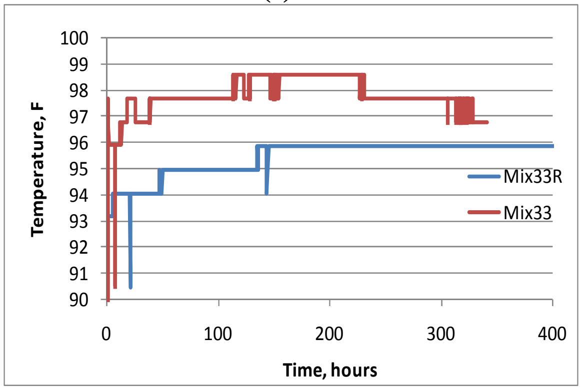


Figure B.1. Compressive strength test result of Repeated Mortar Mixture

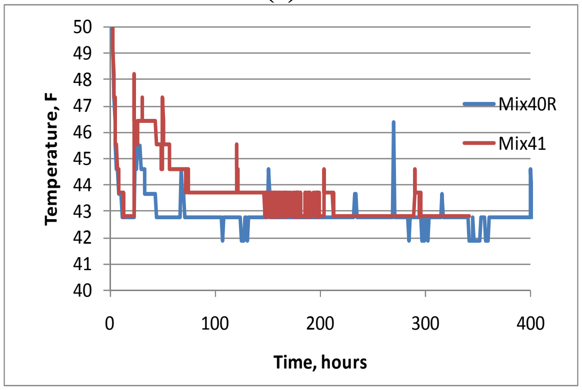


Note. Mixture 12 I-button failed to function. Mixture 14 I-button cube was in the same curing environment as Mixture 12.

(a)



(b)



Note. Mixture 40 I-button failed to function. Mixture 41 I-button cube was in the same curing environment as Mixture 40.

(c)

Figure B.2. Curing Temperature History Comparisons of Repeat Mortar and Original Mortar Mixtures

From Table B.1 and Figure B.1 the following observations can be made:

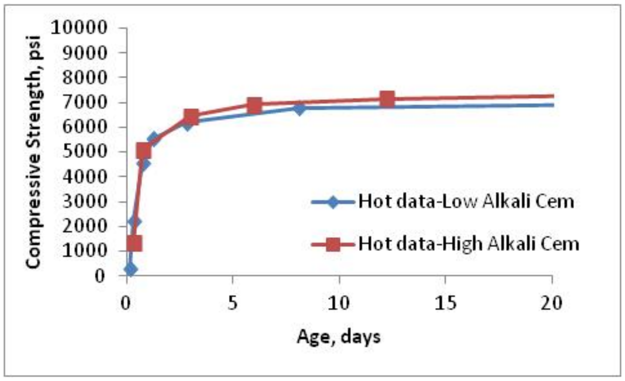
- When compared to Mixture 5 Mixture 5R had a slightly higher w/cm (0.36 vs 0.34), a lower admixture dosage (12 vs 18 oz/cwt.) and had similar flow. It is clear that for Mixture 5 the originally recorded admixture dosage was correct. As illustrated in Figure

8 (a) Mixture 5R had lower strength than Mixture 5 probably due the higher w/cm. Therefore there is no indication of strength degradation due to higher admixture dosage of Mixture 5.

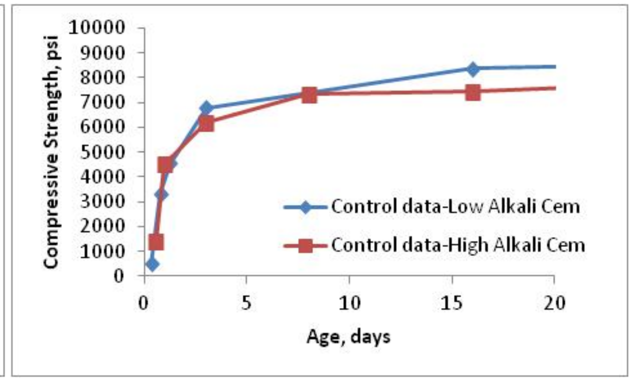
- When compared to Mixture 26 Mixture 26R had a slightly higher w/cm (0.35 vs 0.34), a significantly lower admixture dosage (12 vs 31 oz/cwt.) and had lower flow (96 vs 106). It is clear that for Mixture 26 the originally recorded admixture dosage even though significantly higher than manufacturer recommendation was correct. It is possible that with increasing admixture dosages the workability enhancement is less efficient. As illustrated in Figure 8 (b) Mix26R had slightly lower strength than Mix26 mainly as a result of the slightly higher w/cm. Therefore there is no indication of strength degradation due to higher admixture dosage of Mixture 26.
- When compared to Mixture 12 Mixture 12R had a higher w/cm (0.38 vs 0.35), a lower admixture dosage (12 vs 19.8 oz/cwt.) and had higher flow (117 vs 106). It is clear that for Mixture 12 the originally recorded admixture dosage was correct. As illustrated in Figure 8 (c) Mix12R had lower strength than Mix12 mainly as a result of the slightly higher w/cm ratio. Therefore there is no indication of strength degradation due to higher admixture dosage of Mixture 12. Figure 9 shows that the repeat mixtures were cured at 2-3 F lower temperature than the original mixture but apparently that did not have a significant effect on the strength development.
- When compared to Mixture 33 Mixture 33R had a higher w/cm (0.40 vs 0.36), a significantly lower admixture dosage (12 vs 45.3 oz/cwt.) and had lower flow (91 vs 105). It is clear that for Mixture 33 the originally recorded admixture dosage even though significantly higher than manufacturer recommendation was correct. As illustrated in Figure 8 (d) Mix33R had the same strength as Mix 33. The higher w/cm of Mix 33R would have suggested a decrease in strength of 1000 to 1500 psi. Since this was not observed it is likely that Mixture 33 had a strength degradation of 1000 to 1500 psi as a result of the very high admixture dosage. Figure 9 shows that the repeat mixtures were cured at 2-3 F lower temperature than the original mixture. That small temperature differential is unlikely to help explain the strength anomaly.
- When compared to Mixture 40 Mixture 40R had a higher w/cm (0.37 vs 0.35), a significantly lower admixture dosage (12 vs 28.8 oz/cwt.) and had lower flow (92 vs 108). It is clear that for Mixture 40 the originally recorded admixture dosage even though significantly higher than manufacturer recommendation was correct. As illustrated in Figure 8 (e) Mix40R had the same strength as Mix 40. The higher w/cm of Mix 40R would have suggested a decrease in strength of about 800 psi. Since this was not observed it is likely that Mixture 40 had a strength degradation of about 800 psi as a result of the very high admixture dosage. Figure 9 shows that the repeat mixtures were cured at almost the same temperature as the original mixture and hence cannot explain the observed strength anomaly.

For mixtures 33 and 40 it was decided to use the originally measured strength in activation energy calculations because even though there was some strength degradation due to the higher admixture dosage it was not possible to cast mixtures at the lower w/cm with low HRWR dosage. The repeat mixtures had to be cast at a higher w/cm in spite of the HRWR dosage being at 12 oz/cwt. (manufacturer recommended value of 2-7 oz/cwt). Increasing the HRWR dosage any further may result in lower w/cm but the potential strength increase due to the lower w/cm is likely to be balanced by strength degradation due to the higher HRWR dosage.

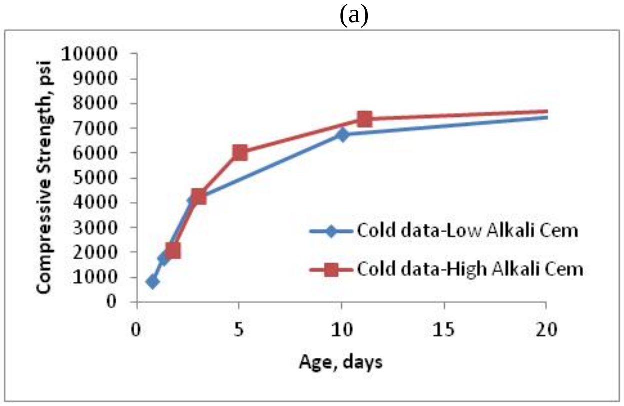
Appendix C. Compressive Strength Test Results of Mortar Mixtures



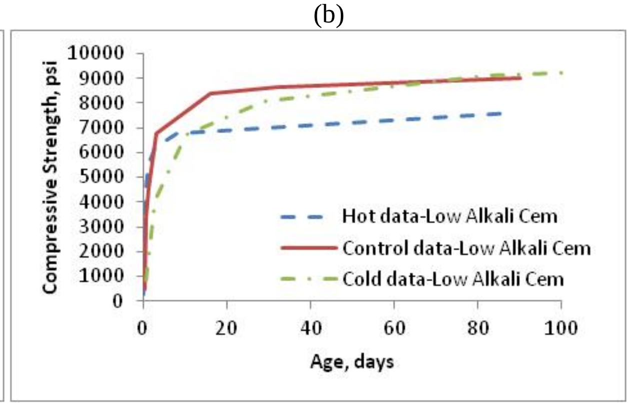
(a)



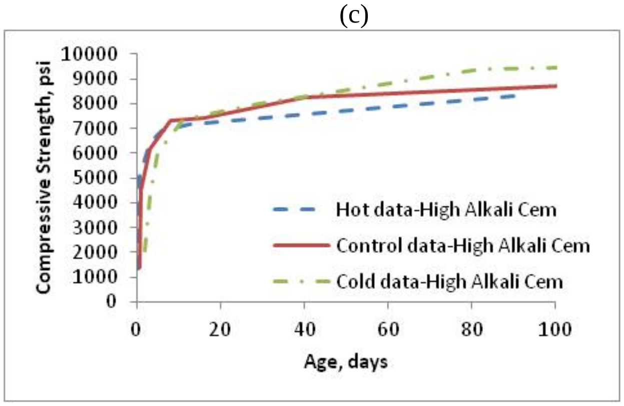
(b)



(c)

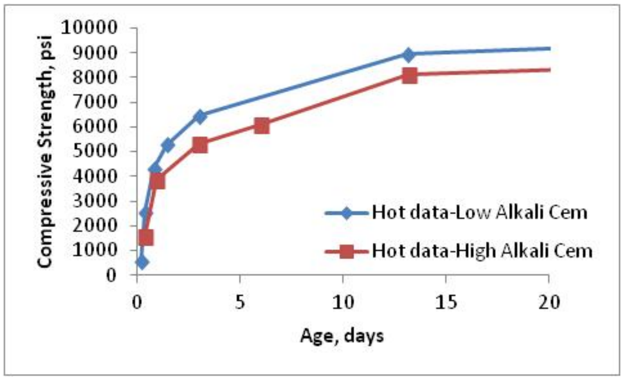


(d)

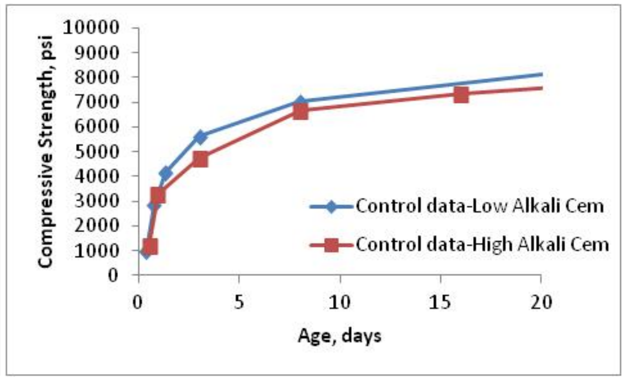


(e)

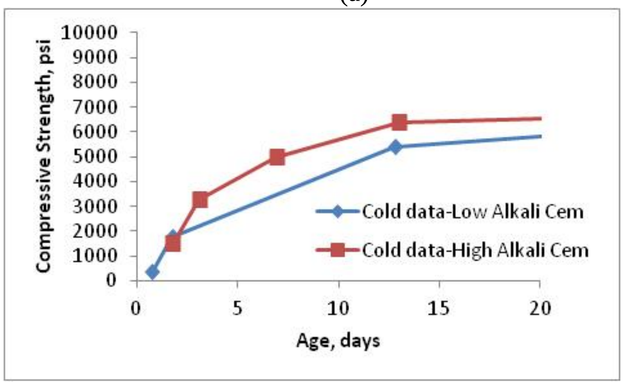
Figure C.1 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.43PC Mixture



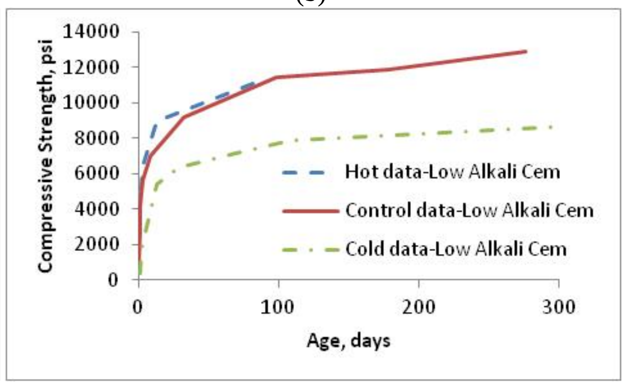
(a)



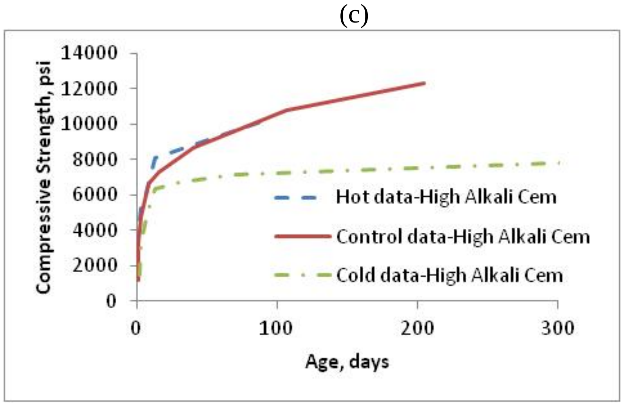
(b)



(c)

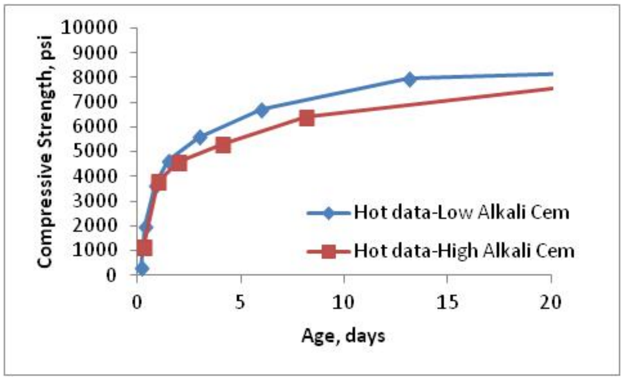


(d)

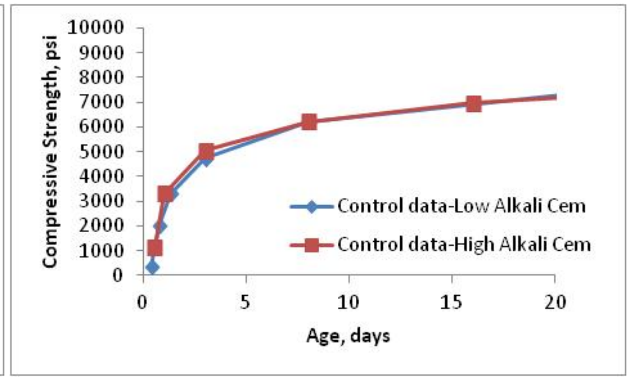


(e)

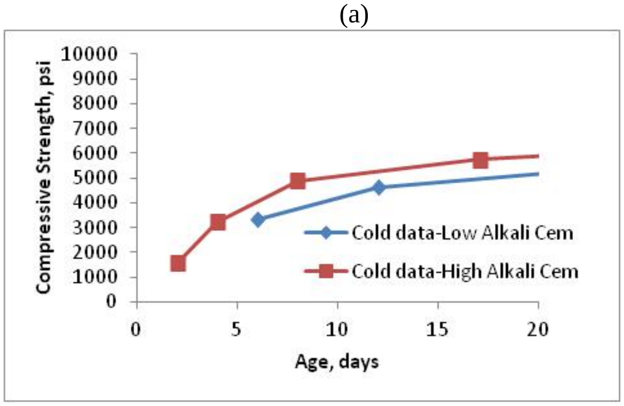
Figure C.2 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.39FAA35 Mixture



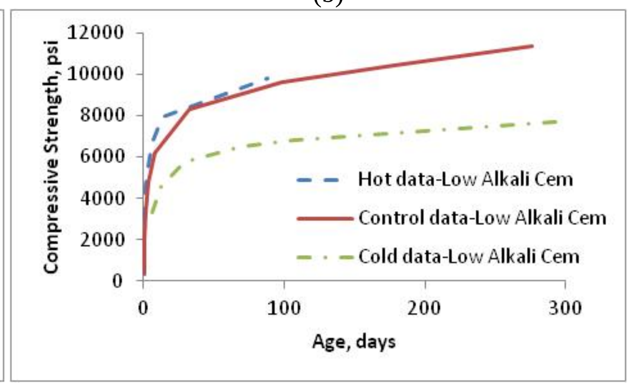
(a)



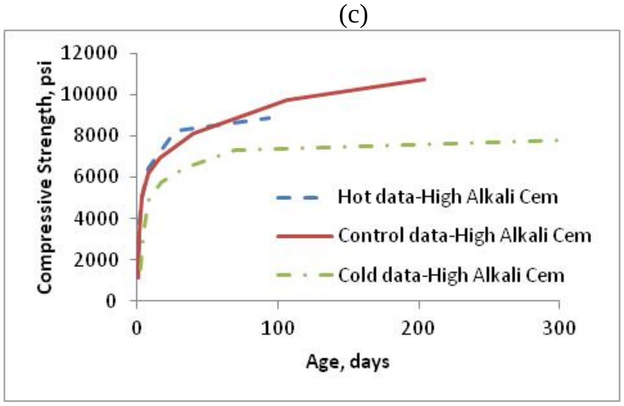
(b)



(c)

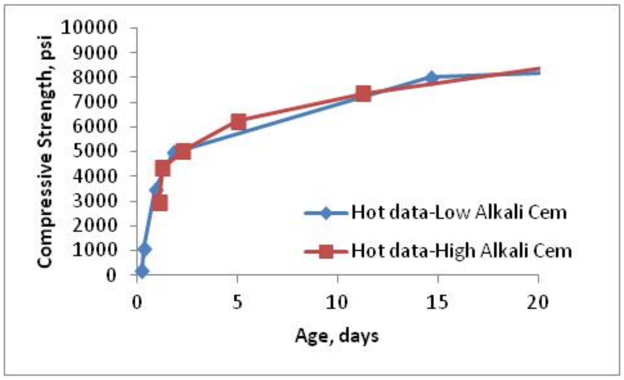


(d)

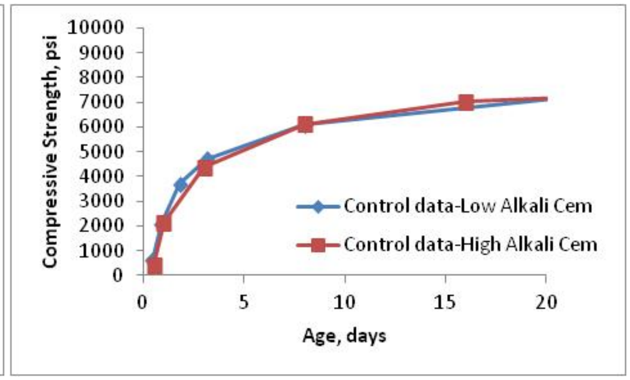


(e)

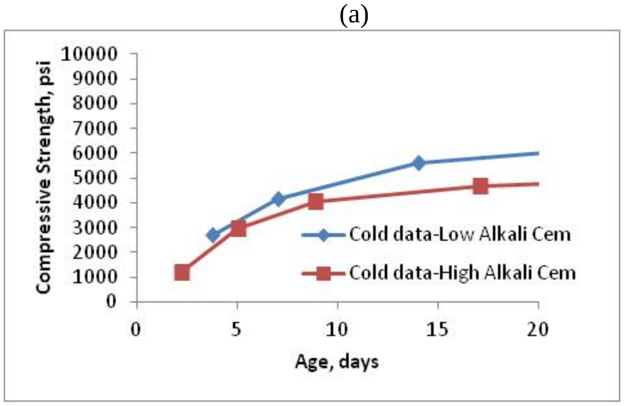
Figure C.3 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.39FAB35 Mixture



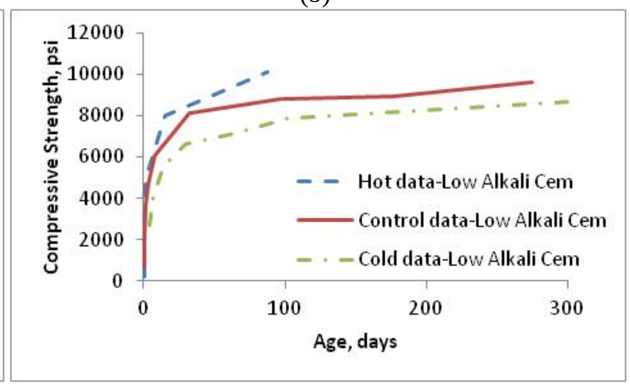
(a)



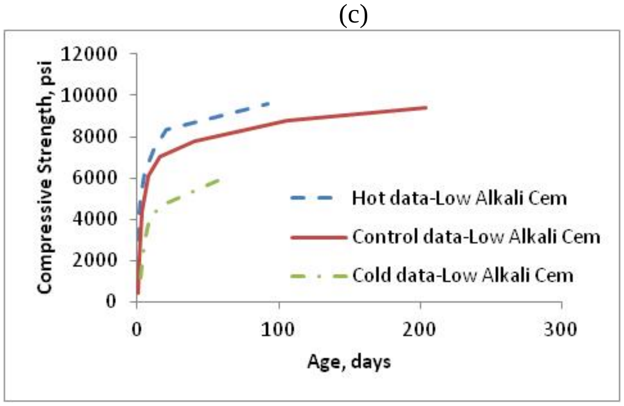
(b)



(c)



(d)



(e)

Figure C.4 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.39FAC35 Mixture

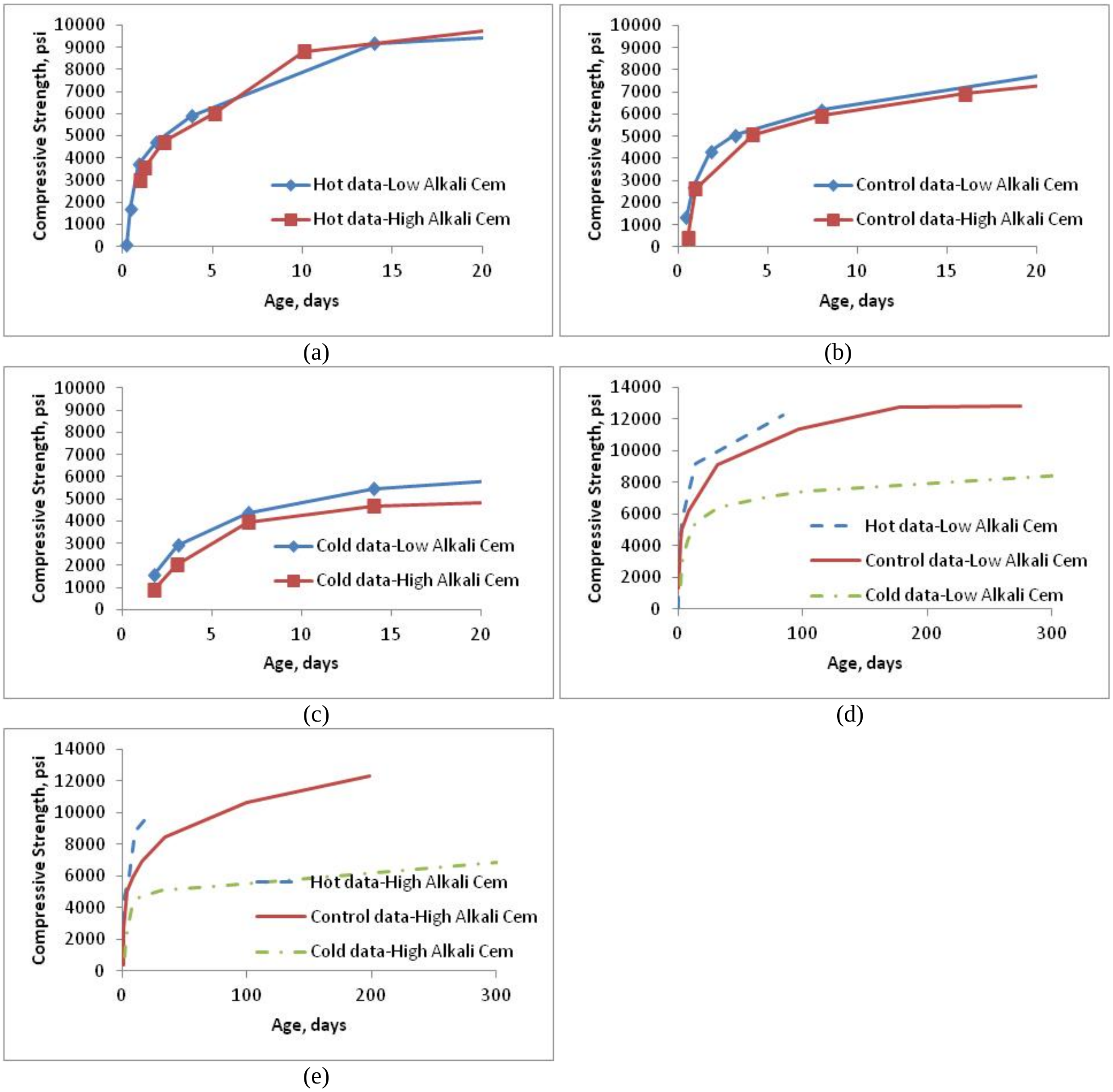


Figure C.5 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.34FAA50 Mixture

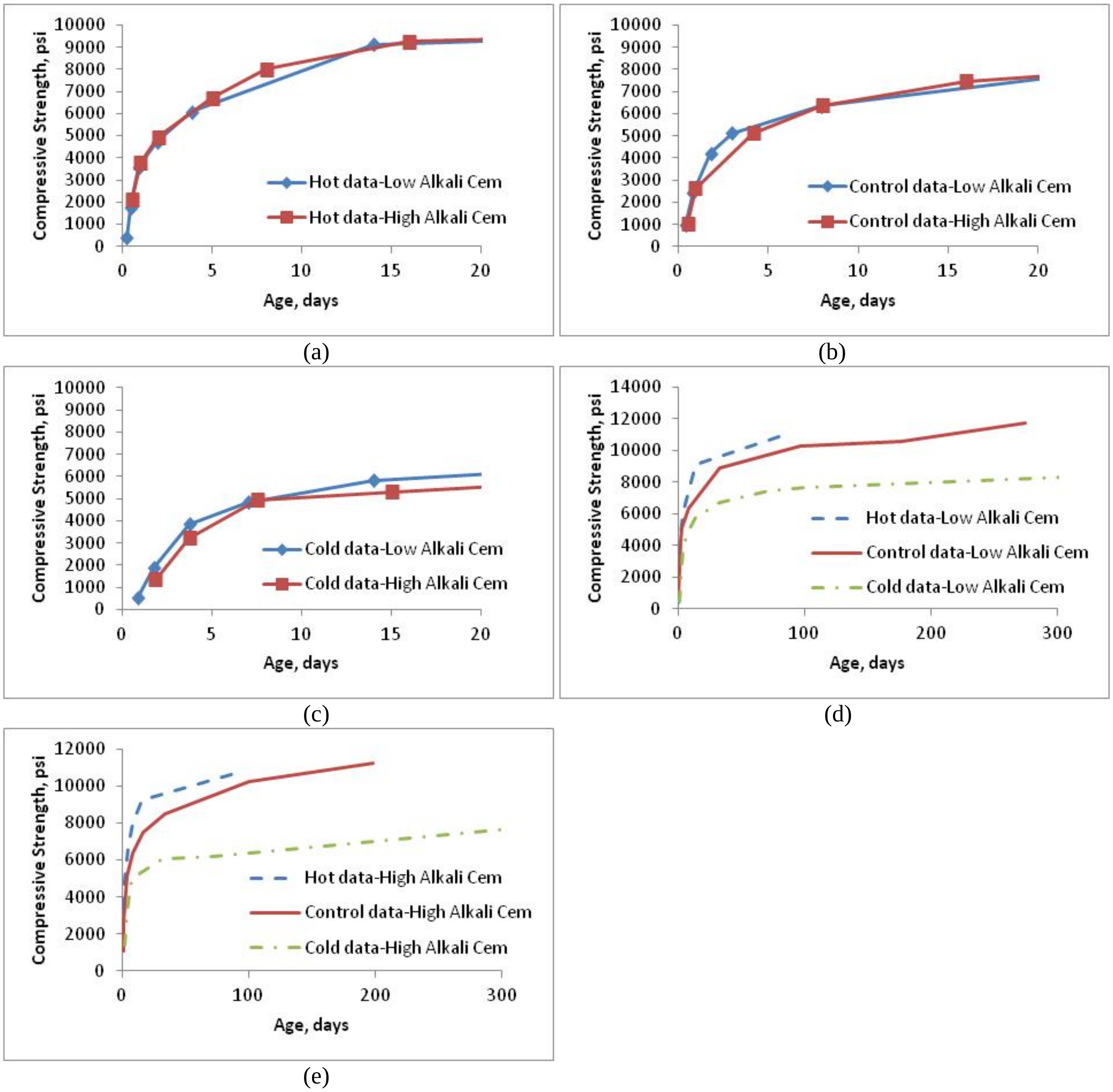
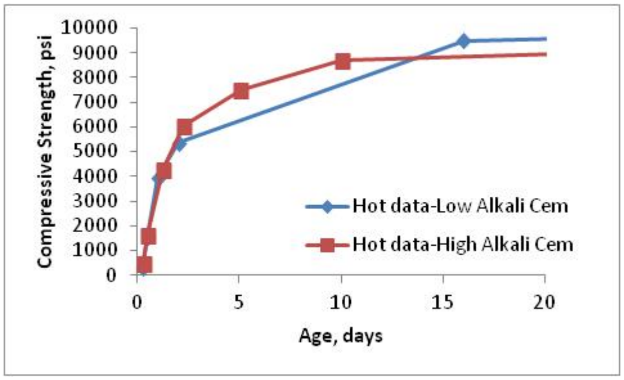
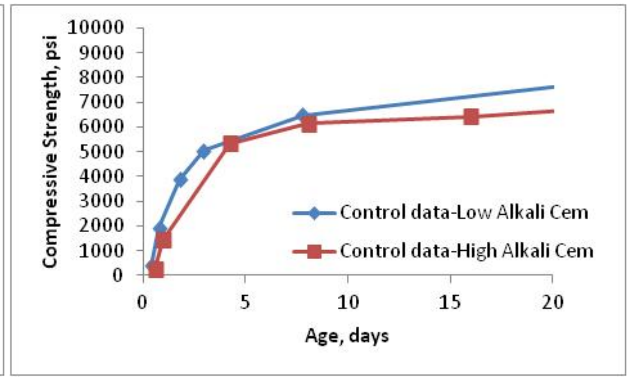


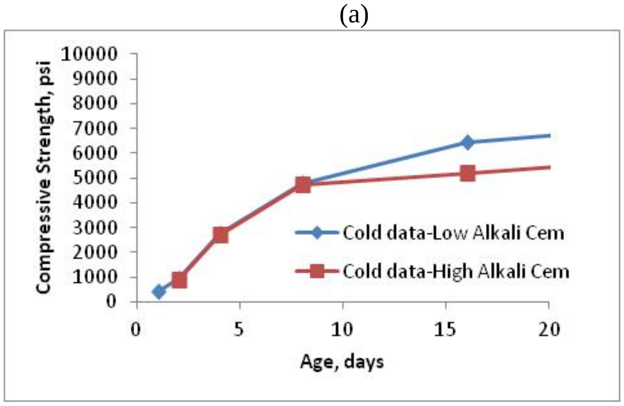
Figure C.6 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.34FAB50 Mixture



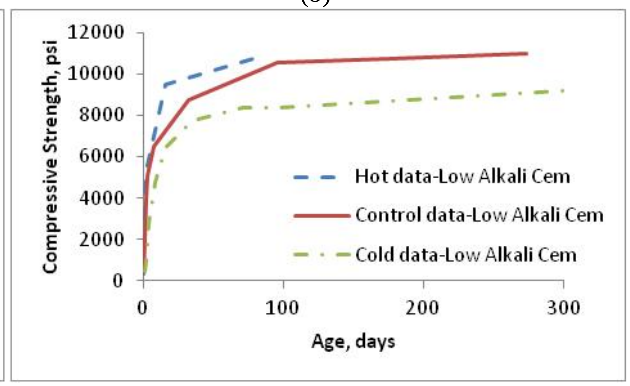
(a)



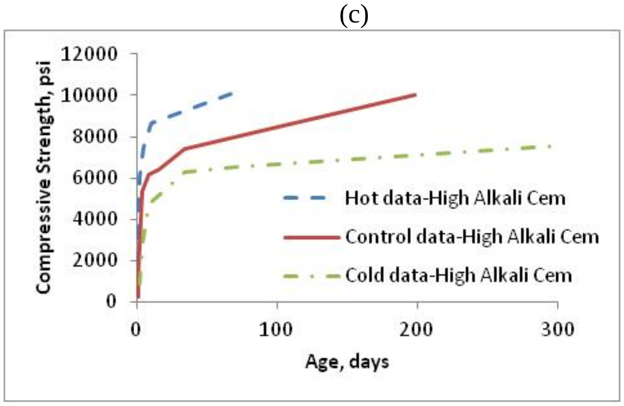
(b)



(c)



(d)



(e)

Figure C.7 Strength-age plot with low and high alkali cement at Hot (a), Control (b), and Cold temperature (c), Strength-age plot with low alkali cement (d), strength-age plot with high alkali cement (e) for 0.34FAC50 Mixture