Effect of Fly Ash Replacement on Alkali and Sulphate Resistance of Mortars

Tarek Salloum

A Thesis
in
The Department
of
Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Building Engineering) at
Concordia University
Montreal, Quebec, Canada

July 2007

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-34773-7
Our file Notre référence
ISBN: 978-0-494-34773-7

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

Effect of Fly Ash Replacement on Alkali and Sulphate Resistance of Mortars

Tarek Salloum

The use of fly ash as a supplementary cementing material in concrete and mortar has dramatically increased in recent years due to its improvement of concrete and mortar properties and its environmentally friendly impact. In this thesis, the sulfate resistance and alkali-silica reaction in mortars containing 0, 20, 40, 60, and 80% fly ash replacement levels were investigated to determine the effect of fly ash content on durability. Four types of cement and two types of fly ash were used in the tests, the cements used were of different alkali contents and with and without blended silica fume. The fly ashes consisted of medium and high calcium contents.

The results showed that the expansion resulting from sulfate attack as well as the alkali-silica reaction considerably decreased with the increase of fly ash content, but the strength of the mortar samples greatly decreased as well. The effectiveness of fly ash in both tests was highly dependent on their CaO content and on the chemistry of cements utilized. 20% Sundance fly ash replacement was sufficient to maintain the sulfate expansion after six months of exposure below CSA allowable expansion limit of 0.05% for high sulfate resistance cement and also below the Canadian limit of 0.1% in the ASR test. For Rockport fly ash, replacement levels at 40% were needed to maintain the expansion below the limit of 0.1% in ASR and sulfate test. The presence of silica fume blends significantly reduced the expansion due to alkali- silica reaction and sulfate attack; addition of fly ash to silica fume blended cements did not significantly improve performance.

Acknowledgments

I would like to thank my supervisor Dr. Michelle Nokken for her guidance and assistance throughout this project. I would like to express my gratitude to her for her valuable and kind support. I would also like to thank Hind and Nima for their encouragement assistance. Thanks also go to my family and friends for all their support over the years.

Table of Contents

List of Figures

List of Tables

Table of Appendices

Abbreviations

The following abbreviations were used in this thesis:

ACI	American Concrete Institute
A-S-H	Alkali-Silica Hydrate
ASR	Alkali-Silica Reaction
ASTM	ASTM International
C_3A	Tricalcium Aluminate
C-S-H	Calcium Silicate Hydrate
C_2S	Dicalcium Silicate
C_3S	Tricalcium Silicate
CH	Calcium Hydroxide (Portlandite)
$C\overline{S}$	Anhydrous Calcium Sulfate $CaO.SO_3$
CSA	Canadian Standards Association
DEF	Delayed Ettringite Formation
H	H_2O
SCMs	Supplementary Cementing Materials
SF	Silica Fume
SRPC	Sulfate Resistance Portland Cement
$\overline{S}$	SO_3
w/c	Water to cement ratio
w/cm	Water to cementitious materials ratio

1. Introduction

The dramatic increase for worldwide demand on cement is due to the unprecedented ratio of growth of world population in the last 100 years and the accompanied needs of infrastructure and buildings. The world wide cement production is estimated at 1.6 billion tons per year and it is expected to be 2 billion in the year 2010 [1]. This continuous growth in cement industry has created an increasing concern on its impact on the environment. However, knowing that the production of each ton of Portland cement clinker releases one ton of carbon dioxide, and that the world wide release of carbon dioxide from all sources is estimated at 23 billion tons a year, it can be concluded that the cement industry contributes almost 7% of world carbon dioxide emission [2]. Carbon dioxide is a major component of the greenhouse gas responsible for global warming which became recently on the top of the list of environmental problems. Moreover, the cement industry is the most energy consuming process after aluminum and steel manufacturing. The production of every ton of cement consumes 4GJ of energy [1,2,3]. Accordingly, the idea of using supplementary cementing materials gained a wide acceptance as an attempt to embrace sustainability in cement and concrete industry, and as a step toward making cement industry more environmentally friendly.

The most common supplementary cementing materials used in concrete are fly ash, blast-furnace slag, and silica fume. Fly ash results from the combustion of the pulverized coal in electric power generating plants, whereas blast-furnace slag and silica fume are byproducts of the steel and silicon industries respectively. These supplementary cementing materials chemically react in the presence of moisture and with the calcium hydroxide released by the hydration of Portland cement to form cementing compounds [4]. The use of fly ash, slag, and silica fume as a partial replacement for cement has proved to be effective in improving concrete and mortar properties. However, The use of fly ash replacements reduce the early strength of concrete and mortars; nevertheless, fly ash is considered the most common supplementary cementing material due to its low price and wide availability. The yearly worldwide production of fly ash is currently about 500 million tons most of which is in Europe, China, India, and North America where the consumption of cement is high [1]. Consequently, the concrete industry can be the ideal place for disposal of the large amounts of fly ash; thus, we can meet the cement demand in the future without increasing the production [1].

The effect of fly ash on durability of concrete and mortar has been the subject of much of research. Many deterioration mechanisms of concrete and mortar incorporating fly ash were investigated under different variables. However, the most common causes of concrete deterioration can be presented as physical processes, mainly freezing and thawing cycles, and chemical processes which are corrosion of steel reinforcement, alkali-aggregate reaction, delayed hydration of free CaO and MgO, and paste deterioration by exposure to aggressive sulfates or acids [5,6]. Previous studies have shown that the effect of fly ash on concrete durability varied widely and it was mainly dependant on calcium content of fly ash [7]. In general, the use of fly ash in concrete and mortar can be effective in increasing the resistance to chemical attack due to permeability reduction and also to control the thermal cracking [1]. It was found that high calcium fly ash can effectively control the expansion of mortars due to sulfate attack or alkali reactivity of aggregates [7].

The aim of this study is to perform a systematic comprehensive investigation of the effect of wide range of fly ash replacement on sulfate and alkali resistance of mortars in order to determine the optimum replacement level. Moreover, since not many researchers have studied high volume fly ash concretes and mortars which can be defined as those of cement replacement levels beyond 50%, this study investigated high fly ash replacement levels of up to 80% to determine the upper acceptable limits of replacement. ASTM C 1012 and ASTM C 1260 standard test methods were used to evaluate the sulfate and alkali resistance of specimens respectively. The effect of water to cement ratio w/c on sulfate resistance of the mortars were investigated by casting two mixtures of 80% fly ash replacement and lower w/c that result in the same flow as the plain mixture made of the same cement; the amount of w/c utilized was determined by trial and error. The time at which specimens were immersed in sulfate solution is an important variable that may affect sulfate resistance; accordingly, two sets of specimens were immersed after demolding for comparison. Strength development was not one of the main objectives of this project, but it was monitored by testing compressive strength of mortar cubes to determine the immersion time of the bars in sulfate in accordance with ASTM C1012.

2. Literature review

2.1. Sulfate Attack

Sulfate attack is one of the major causes of concrete deterioration and it presents a considerable risk to the durability of structures. It occurs in concrete structures that are placed in soils containing sulfate as well as structures exposed to groundwater, wastewater, or seawater. A lot of research has been conducted to investigate concrete damage due to sulfate attack, study the deterioration mechanisms, and to determine the specification of high quality concrete in terms of resisting sulfate attack. However, the deterioration of concrete under sulfate attack occurs as a result of the reaction between sulfates and hydrated cement paste forming ettringite and gypsum [5]. The sources of sulfate, deterioration mechanism, classification of the attack, and methods of assessment are discussed in the following sections.

2.1.1. Sources of Sulfate and Forms of Sulfate Attack

There are various sources of sulfates that can cause sulfate attack on concrete. Based on the source of sulfate, sulfate attack can be divided into two groups; internal sulfate attack and external sulfate attack [8].

2.1.1.1. Internal Sulfate Attack

Internal sulfate attack occurs due to the presence of sulfate in the cement itself since calcium sulfate is an important component of Portland cement. Calcium sulfate is added to clinker during cement grinding in order to regulate the setting time, control drying shrinkage properties, and increase early strength of cement by accelerating the hydration of calcium silicates present in Portland clinker. Sulfate is added to the clinker in the form of gypsum (calcium sulfate dihydrate) and it can be natural or industrial; it also may be added in the form of calcium sulfate anhydrate [9,10]. Moreover, the clinker itself contains additional amount of sulfates present mainly in the form of alkali sulfates. They are formed during manufacturing process from raw materials and fuel combustion products. In addition, the sulfates or sulfides present in aggregate can be a minor source of sulfate in concrete. The sulfate contents of ASTM and CSA cement types as well as the fineness of those cements are shown in table 2.1 [6].

Table 2.1: Sulfate content and fineness cements as determined by ASTM and CSA 3000 [6]

ASTM Type	Fineness m^2/kg	Maximum allowable SO_3 content %	CSA Type	Maximum allowable SO_3 content %
I	369	3.0	GU (10)	3.5
II	377	2.7	MS (20)	3.0
III	548	3.5	MH (30)	3.5
IV	340	2.2	HE (40)	2.5
V	373	2.3	HS (50)	2.5

Delayed ettringite formation (DEF) may be observed after heat curing of concretes and mortars or with steam-cured concrete products, and it can be considered as the major form of internal sulfate attack [8]. It happens when C-S-H absorbs the sulfate ions released by the decomposition of ettringite which are not stable above 65°C, then after curing ettringite is re-formed by the desorbed sulfate ions causing expansion and cracking [5]. Many studies investigating DEF at temperatures up to 100°C using different cements and aggregates found that the expansion related to DEF starts after 14 days of exposure and it could reach up to 3% expansion. It was also observed that DEF is related to MgO and alkali content of cement; higher content of those two components could accelerate expansion. [11,12]. Internal sulfate attack was not investigated in this thesis.

2.1.1.2. External Sulfate Attack

External sulfate attack takes place in the case of concrete or mortar exposure to external sources of sulfates such as soils, ground water, or seawater. Even though sulfates present in the form of gypsum are reported in most soils all around the world, the amount is not considerably harmful to concrete in most cases. Ground water may contain magnesium, sodium, and potassium sulfates at higher concentrations [5]. However, sodium sulfate is the most common sulfate that can be found in ground water. In addition, industrial and agricultural wastes may contain high sulfate concentration and can be considered as possible external sources of sulfates.

2.1.2. Deterioration Mechanism

The deterioration mechanism of concrete exposed to external sulfate attack and the chemistry of the attack itself is significantly dependent of the source of sulfate and the cement composition; however, the manifestations or damages of sulfate attack on concrete may vary according to the exposure conditions [6]. The deterioration of concrete exposed to sulfate attack takes place due to the chemical reaction between sulfate with calcium hydroxide and calcium aluminate hydrate forming gypsum, ettringite, thaumasite, or brucite depending on the type of the sulfate. It was confirmed by most of the researchers investigating sulfate attack that the sulfate-related expansion in concrete is a result of ettringite formation, but the mechanism by which ettringite leads to expansion is not adequately understood. However, swelling due to poorly crystalline ettringite absorption of water, and pressure due to increasing ettringite volume are the most acceptable scenarios suggested by researchers [5,6,13]. The following equation explains the deterioration due to sodium sulfate attack. The reaction occurs as the sulfate reacts chemically with calcium hydroxide present in the concrete mass; both alumina-containing hydrates are converted to ettringite as shown in Equation (1).

$$C_3A.CH.H18 + 2CH + 3\bar{S} + 12H \rightarrow C_3A.3C\bar{S}.H32 \qquad (1)$$

It was found that ettringite crystals in concrete can be categorized based on differences in size and behavior to two types, one of these types which is typically 1-2 μm long and 0.1-0.2 μm wide is known to be expansive [14].

Sulfate-related expansion is also caused by gypsum formation which results from the reaction of both calcium hydroxide and C-S-H present in the hydrated cement paste with sulfate. The formation of gypsum in concrete exposed to sodium sulfate attack occurs as shown in Equation (2); the presence of sodium hydroxide as a by-product of the reaction maintains the stability of the calcium silicate hydrate by maintaining high alkalinity of the system.

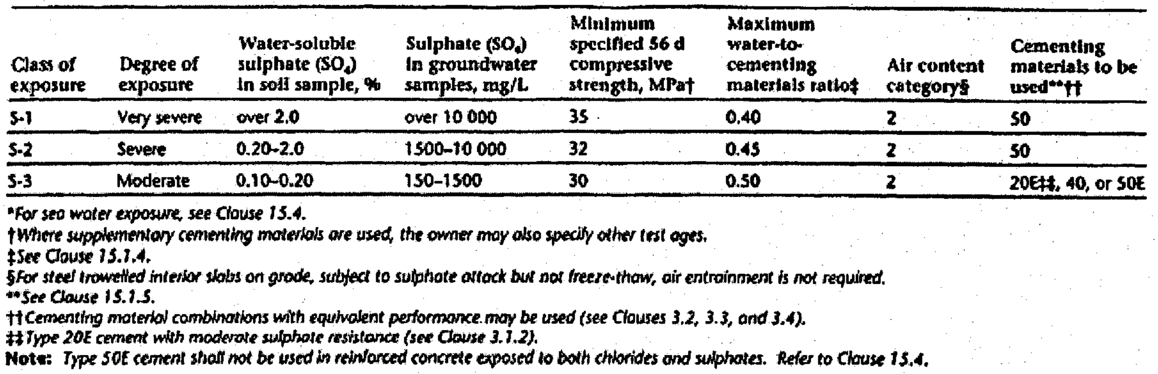
$$Na_2SO_4 + Ca(OH)_2 + 2H_2O \rightarrow CaSO_4.2H_2O + 2NaOH \quad (2)$$

The ettringite and gypsum formed by the mentioned reaction result in concrete expansion due to the increase in overall solid volume and they result in loss of cohesion and strength as well [5]. Moreover, the deterioration process is time dependent; therefore, its long term effect on concrete durability is a major concern.

2.1.3. Classification of Sulfate Attack

According to the Canadian Standards Association [15], external sulfate exposure is classified into three levels moderate, severe, and very severe. This classification is based on the concentration of sulfate in soil and underground water as shown in Table 2.2. Recommended compressive strength and water to cement ratio (w/c) to be used for each class of exposure are also included. For sulfate concentrations less than mentioned in CSA standard, under 0.1% in soil and under 150 mg/liter in water, sulfate attack is negligible.

Table 2.2: Requirements for Concrete Subjected to Sulfate Attack [15]



Class of exposure	Degree of exposure	Water-soluble sulphate (SO_4) in soil sample, %	Sulphate (SO_4) in groundwater samples, mg/L	Minimum specified 56 d compressive strength, MPa†	Maximum water-to-cementing materials ratio‡	Air content category§	Cementing materials to be used**††
S-1	Very severe	over 2.0	over 10 000	35	0.40	2	50
S-2	Severe	0.20–2.0	1500–10 000	32	0.45	2	50
S-3	Moderate	0.10–0.20	150–1500	30	0.50	2	20E‡‡, 40, or 50E

**For sea water exposure, see Clause 15.4.*
†Where supplementary cementing materials are used, the owner may also specify other test ages.
‡See Clause 15.1.4.
§For steel trowelled interior slabs on grade, subject to sulphate attack but not freeze-thaw, air entrainment is not required.
***See Clause 15.1.5.*
††Cementing material combinations with equivalent performance may be used (see Clauses 3.2, 3.3, and 3.4).
‡‡Type 20E cement with moderate sulphate resistance (see Clause 3.1.2).
Note: *Type 50E cement shall not be used in reinforced concrete exposed to both chlorides and sulphates. Refer to Clause 15.4.*

The American Concrete Institute has also developed a classification of sulfate attack on concrete; the limits defined by ACI classification are similar to the Canadian standards defined by CSA. It also includes similar recommendations for cements and water to cement ratio to be used based on the severity of the potential exposure [16].

2.1.4. Methods of Assessment

Sulfate attack in concrete is usually associated with expansion, cracking, reduction in cohesion, and softening. Accordingly, the effects of sulfate attack on concrete can be evaluated either by measurement of strength reduction or the usual accompanying change of length due to expansion. The reduction in concrete and mortar compressive strength due to sulfate attack has been proved to be the most sensitive indicator in terms of damage assessment [17]. Nevertheless, change of length measurement is the most commonly used as the same specimens can be measured over time. Moreover, the visual inspection of superficial damage of specimens can be a valuable early indicator of performance [18].

2.1.5. Severity of Sulfate Attack

The variables that may affect the severity of sulfate attack and their influence on the extent of damage on concretes and mortars are discussed in this section.

2.1.5.1. Effect of Sulfate Concentration

The major factor that determines the severity of sulfate attack is the concentration of sulfates in the solution or in the soil. The increase in the concentration of sulfate enhances the chemical reaction with cement and the formation of ettringite and gypsum as a consequence. Many studies have investigated the effect of sulfate concentration on the severity of the attack; it was found that the increase in sulfate concentration increases the expansion of mortars exposed to sodium sulfate attack [19,20]. The expansion of Portland cement mortars exposed to different concentrations of sodium sulfate is shown in Figure 2.1 [21].

It was also noted that the deterioration of mortars exposed sulfate sodium sulfate attack develops slowly until certain time when it start to accelerate; this critical time is a function of sulfate concentration [22,23]. Mortars exposed to low concentrations of sodium sulfate up to 18000 mg/L showed no significant change in properties even at 300 days of exposure, whereas those exposed to concentration of 72000 mg/L showed dramatic decrease in compressive and flexural strength after 90 to 180 days of exposure [23].

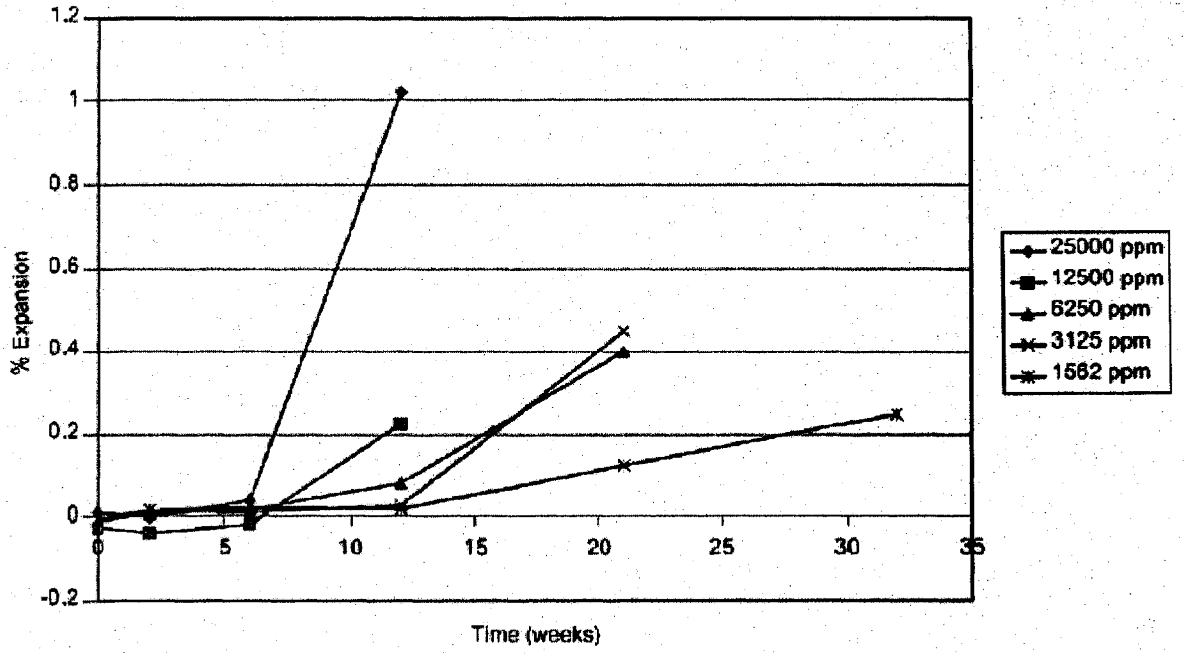


Figure 2.1: Expansion of Mortars Exposed to Different Sodium Sulfate Concentration [21]

2.1.5.2. Effect of Type of Sulfate

The severity of the sulfate attack is also a function of the chemical form of sulfate. However, it was noted that magnesium sulfate solution is more aggressive than sodium sulfate solution and both are potentially more destructive than calcium sulfate [24]. Figure 2.2 shows expansion versus time of Portland cement mortars exposed to sodium and magnesium sulfate solutions [25].

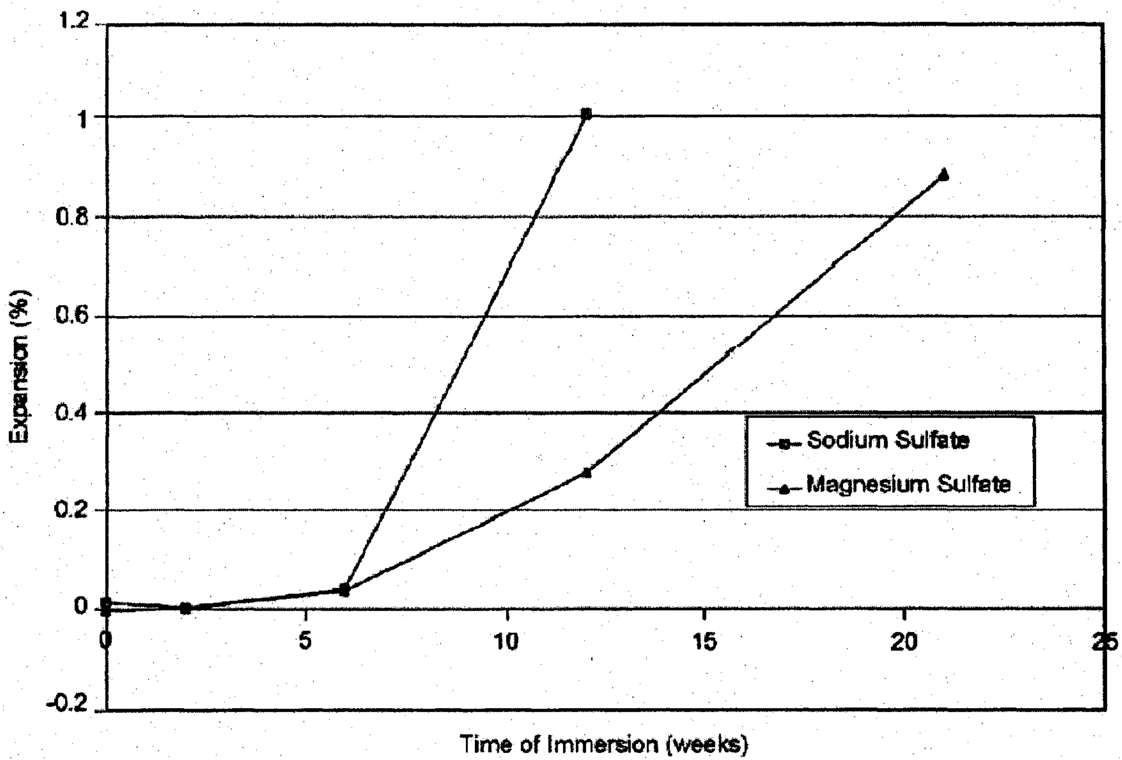


Figure 2.2: Expansion of Mortars Exposed to Sodium and Magnesium Sulfate Solutions [25]

2.1.5.3. Effect of Temperature

Temperature can be one of the factors affecting sulfate attack by enhancing delayed ettringite formation in internal sulfate attack. The effect of temperature of sulfate solution on the resistance of mortars was investigated by Akoz et al. [26], by exposing mortars to sodium and magnesium sulfate solutions of temperatures 20 and 40°C. The results showed that raising temperature of sulfate solution did not accelerate the deterioration of mortars [26]. On the other hand, "Author of 27" found that the effect of various temperatures of sulfate solutions on the type and extent of damage in mortars was investigated; the temperatures of exposure were 23 and 65°C [27]. It was found that the variable extent of damage which was observed depended on the availability of Al^{3+} and SO_4^{2-}, crystal arrangement, ion adsorption capacity of the CSH gel and on the thermal instability of ettringite [27].

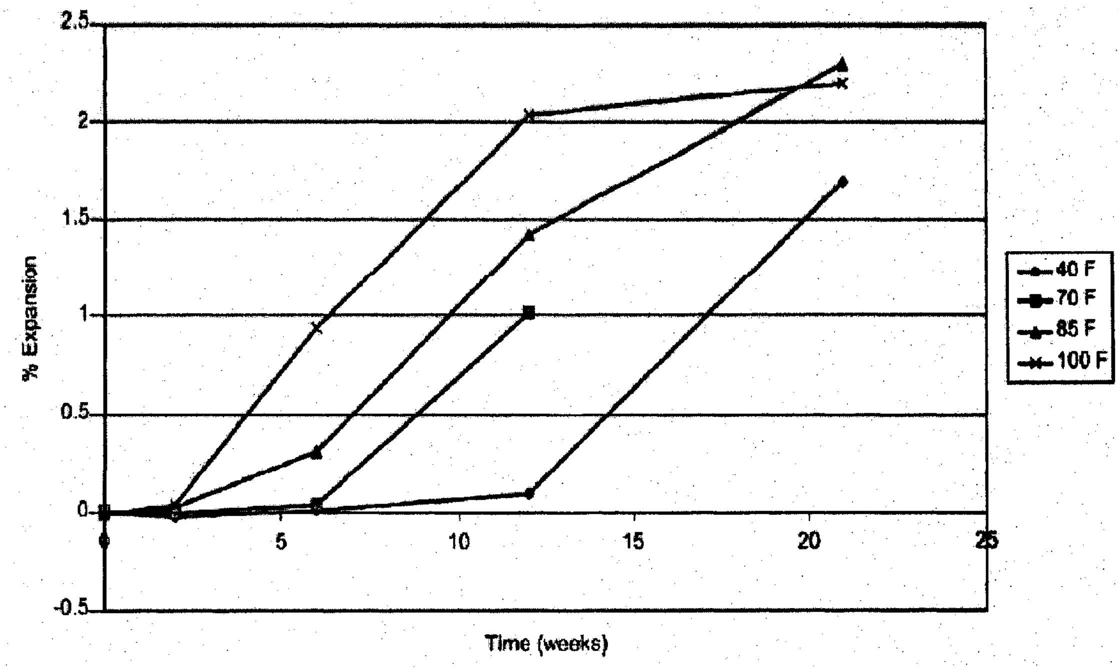


Figure 2.3 Expansion vs. Time of Mortars Exposed to Sodium Sulfate Solutions at Different Temperatures [21]

Santhanam et al. [21] investigated the effect of higher range of temperature on mortars exposed to external sulfate attack found that temperatures over 70°F (21°C) accelerated the expansion and deterioration of mortars; the results are shown in Figure 2.3 [21]. However, concretes and mortars exposed to sulfate attack in field conditions may be subjected to variation of temperature and humidity with time; that may enhance the destructive effect of sulfate attack on concretes and mortars [6].

2.1.5.4. Effect of pH of Sulfate Solution

The pH of sulfate solutions is another major parameter that influences the severity of sulfate attack. It was found that the expansion of specimens exposed to sulfate solution is particularly sensitive to the pH of the solution; the aggressiveness of sulfate attack decreases with the increase of the pH [6,28]. It was also confirmed that the sodium sulfate solutions in sulfate resistance tests performed in compliance with ASTM C 1012 changes from pH 6-7 directly after mixing to around 12.2 after few hours of immersing the mortar bars; thus, the pH of the solution which is renewed periodically in accordance with the mentioned standard is not adequately controlled. The change in the pH could be ignored or it could be could kept constant by adding hydrochloric acid to the solution to reflect conditions in the field. It was observed that maintaining a constant level around 7 of the pH of the solution significantly reduces the time to initiate expansion and accelerate strength loss of specimens [17,28]. It was reported that changing solution at every measurement of specimens instead of controlling the pH of the solution resulted in longer time to reach expansion of 1% as is shown in Figure 2.4 [29].

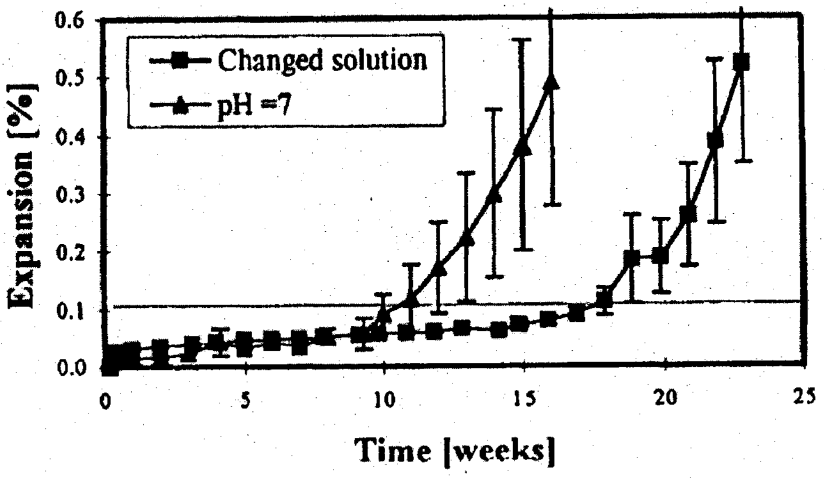


Figure 2.4: Expansion versus time of specimens immersed in 5% sulfate solution with and without controlling the pH of the solution [29]

Effect of pH of sulfate solution on concretes and mortars was investigated by immersing samples in both controlled and uncontrolled sulfate solutions. The controlled sulfate solution had its pH maintained at constant level in an attempt to simulate neutral sulfate environment as present in field. Based on the result of that test and on previous studies it was established that at a pH of 12-12.5 ettringite formation is the only cause of expansion, whereas at pH of 8-11.5 gypsum formation in addition to C-S-H decomposition are responsible for the strength loss and expansion.

On the other hand, at a pH lower than 8 the main deterioration mechanism is calcium leaching and decalcification of C-S-H [30].

2.1.6. Factors Affecting Sulfate Resistance of Concretes and Mortars

As mentioned previously in this report, the deleterious effect of concrete exposure to sulfate occurs as a result of chemical reaction between cement component and sulfate. Thus, the cement composition is essential in determining the extent of deterioration in concretes exposed to sulfates. In addition, the properties of hardened concrete and mortars, mainly porosity and permeability may govern the rate of reaction between sulfate and cement since it affects the depth of penetration of sulfates. Factors affecting the resistance of concrete and mortar to sulfate attack have been studied widely. It was found that the use of low water to cement ratio with proper proportioning, mixing, placing and curing of concrete will result in good resistance to sulfate and other chemical attack [31]. Major factors affecting sulfate attack on concrete are discussed in the following sections.

2.1.6.1. Effect of Cement Composition on Sulfate Resistance

It has been confirmed that cement composition has a major effect on the resistance of concretes and mortars to sulfate attack. Previous studies have proven that C_3A content of cement is the most significant factor that influence cements resistance to sulfate attack [6,20]. As described in section 2.1.2 the mechanism involved in the deterioration of hardened concrete exposed to sulfate attack occurs due to the reaction between calcium sulfate C_3A phase of hydrated cement which produces tricalcium sulfoaluminate and calcium hydroxide. Tricalcium sulfoaluminate also called ettringite has a larger volume than original component, thus results in expansion and destructive effects. Accordingly, it can be concluded that the C_3A content of cement dictates the ettringite formation and control the destructive effect of sulfate attack [19,32,33]. It is a commonly held understanding that the higher C_3A content of cement the greater expansion results in concrete and mortars exposed to sulfate attack [19,32,33].

It was found that concretes made of cements with C_3A content less than 8% and w/c lower than 0.45 did not fail after 40 years of exposure to severe sulfate attack, whereas for those of C_3A content more than 10% failure occurred in less than five years under same exposure conditions [34]. That correlates with previous studies which have suggested that Portland cements of C_3A content less than 8% contain most of their alumina present in the hydration products in the form of monosulfate, but with C_3A contents more than 8% another alumina containing hydrate will be formed; thus enhance ettringite formation [5,35].

A relationship between C_3A content of cement and extent of deterioration of concrete under sulfate attack was established as shown in Figure 2.5. It is shown that with C_3A contents of more than 6%, a sharp increase in the rate of deterioration was observed [33]. However, based on CSA standard A5, sulfate resistant Portland cement (SRPC) should have C_3A content no more than 3.5%. It was also observed that C_3A is not the only factor influencing the resistance of cements to sulfate attack since some sulfate resistant Portland cements of high C_3S content performed poorly in terms of sulfate resistance. A deviation from the C_3A – deterioration relationship was reported both in laboratory and field. Accordingly, it was suggested that cements of lower C_3A and lower C_3S/C_2S ratio performed better under sulfate attack in terms of strength loss and expansion [19,36,37].

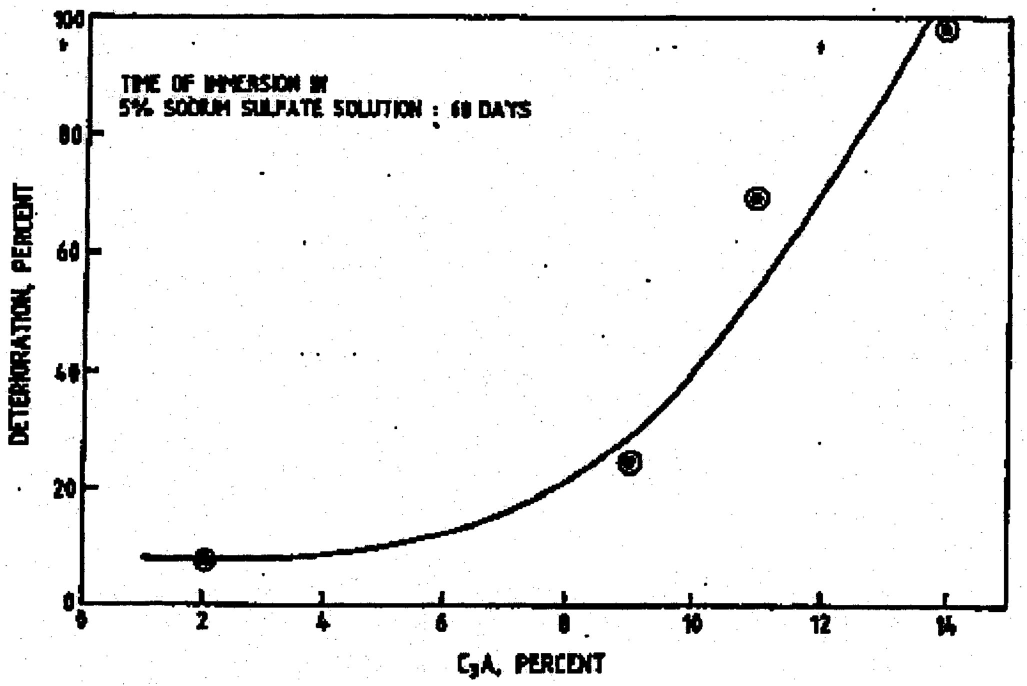


Figure 2.5: Effect of C3A on sulfate attack related deterioration [33]

The role of the increasing ratio of silicate (C_3S/C_2S) in reducing the cements resistance to sulfate attack is due to the fact that hydration of C_3S produces 2.2 times more calcium hydroxide than does the same amount of C_2S [35]. Consequently, it releases larger quantity of calcium hydroxide and increases gypsum formation. Moreover, it causes strength and stiffness reduction of concrete by reducing the solubility of hydrate calcium aluminates and enhancing its expansive nature [35]. The presence of sodium hydroxide in high concentrations is also responsible of forming the expansive microcrystalline ettringite, where in the absence of calcium hydroxide the ettringite is in the form of non expansive large lath-like crystals [38].

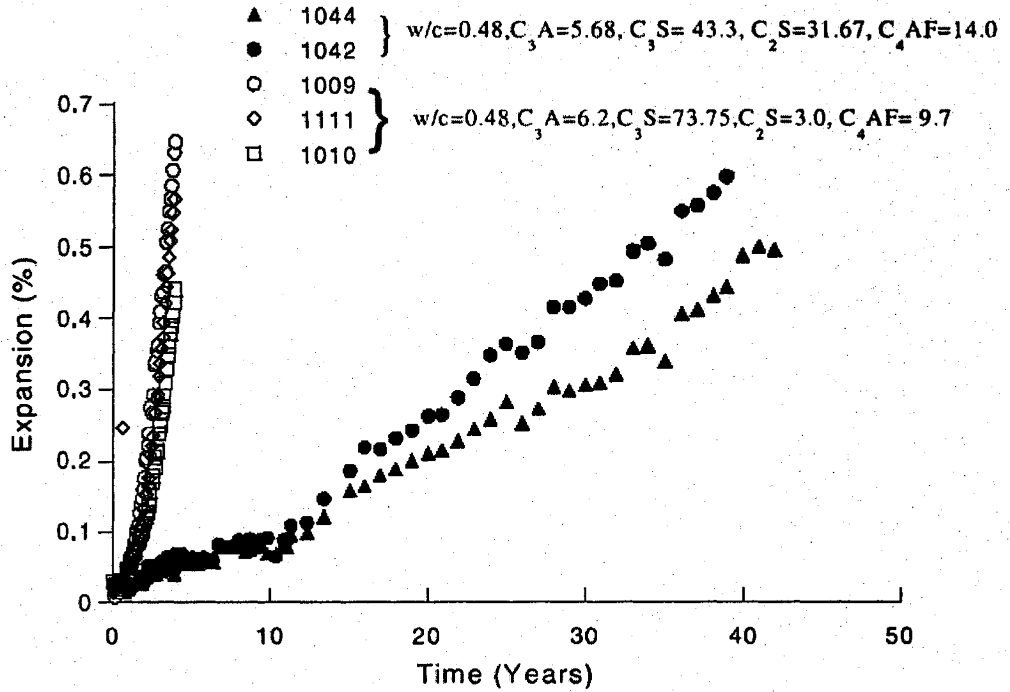


Figure 2.6: The Effect of C3S Content on the Expansion of Concrete [34]

Time of failure of concrete exposed to severe sulfate attack was investigated under similar exposure conditions, cements of different C_3S/C_2S ratios and same proportions were utilized. It was found that concrete made of cements of high C_3S/C_2S ratio failed in 3.6 years, while those of low C_3S/C_2S ratio didn't fail in 40 years [34]. The results are shown in Figure 2.6.

The C_4AF content in cement can be also considered essential in determining the sulfate resistance of cements. Many studies [36,39] found that there is high negative correlation between both Fe_2O_3 and C_4AF and sulfate related expansion, and that cement with high iron contents are highly beneficial in controlling sulfate attack. It was also found that the lower C_3A content, lower C_3S/C_2S, and higher C_4AF are the key factor influencing sulfate resistance of cement. It was suggested that SRPC should be required to have C_4AF content greater than 7% in order to provide adequate sulfate resistance [36,39]. The relationship between C_4AF and expansion are shown in Figure 2.7.

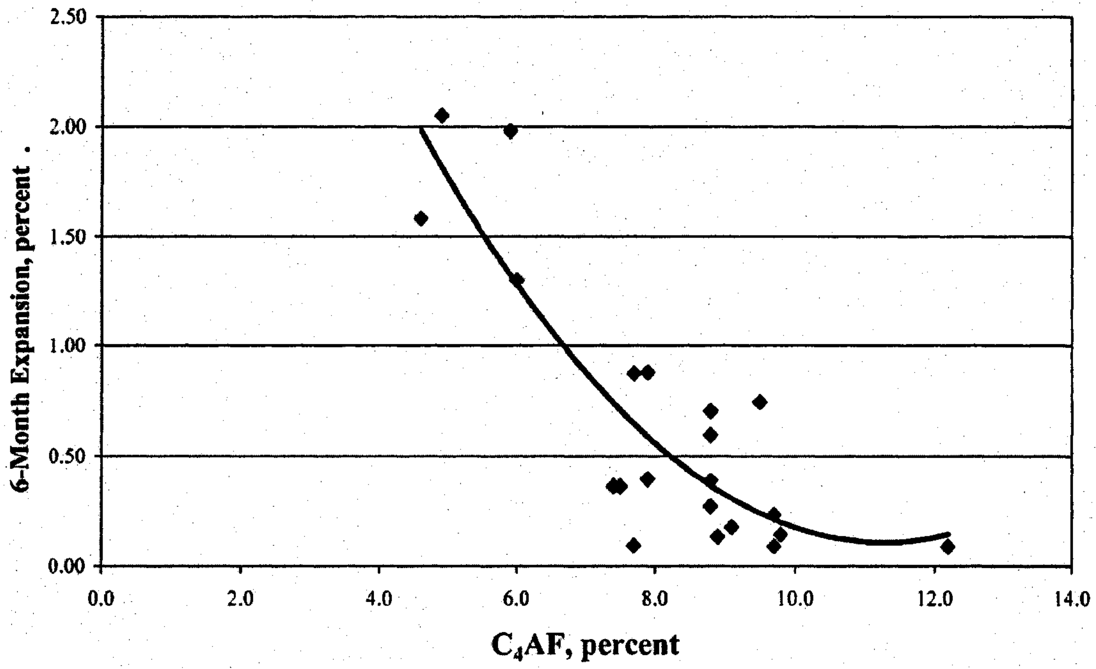


Figure 2.7: Relationship between C_4AF and Sulfate Expansion [39]

2.1.6.2. Effect of Water to Cement Ratio

There is a wide agreement in the studies investigating sulfate resistance that the use of low water to cement ratio improves sulfate resistance of concrete and mortars by controlling expansion and strength reduction. It was suggested that the improvement in sulfate resistance is due to the reduction in permeability associated with the use of lower w/c. Thus, reducing the penetration of sulfates into the concrete matrix and suppressing its destructive effect [6,30,32,36,40]. The relationship between permeability and w/c was investigated by Khatri et al. [30]; mixtures of sulfate resistance cement SRC, high slag cement HSC, and ordinary Portland cement OPC were tested. As shown in Figure 2.8, utilizing lower water to binder ratio considerably reduced the permeability. It can be also noted that incorporating silica fume in mixtures dramatically reduced their permeability.

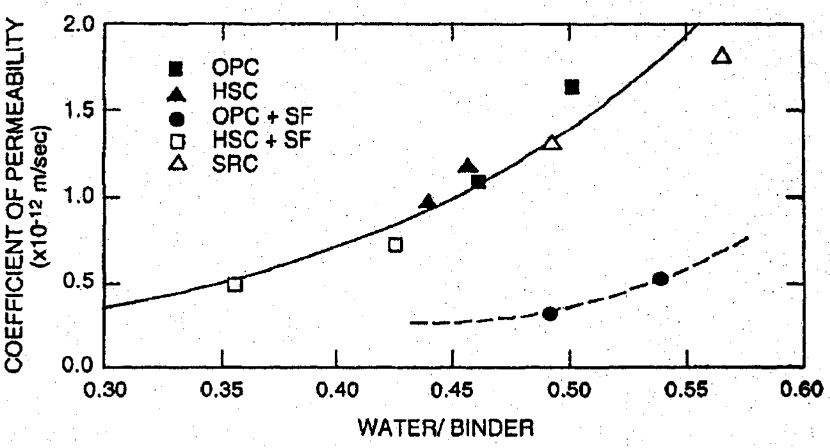


Figure 2.8: Variation of Coefficient of Permeability with Water/Binder Ratio [30]

The effect of low w/c on sulfate resistance was also studied by Sahmaran et al. [41]. It was found that w/c is an important factor affecting the performance of mortars exposed to sulfate attack. Reducing w/c of mortars resulted in improved performance under sulfate attack due to the reduction in permeability. It was also found that the effect of w/c on sulfate resistance was more pronounced when low sulfate-resistant cements were used, whereas the increase of w/c did not greatly affect the sulfate resistance of mortars when blended cements were utilized [41]. Another study investigated the effect of w/c on the performance of concrete exposed to sulfate attack by evaluating compressive and tensile strength. It was found that water to cement ratio influenced the sulfate resistance more than did the cement composition [42].

2.1.6.3. Other Factors Influencing Sulfate Resistance

In addition to factors discussed in the preceding sections, the quality of concrete can be considered an important factor influencing its sulfate resistance. Good quality concrete can be obtained by proper proportioning, adequate consolidation, and effective curing in order to enhance the degree of hydration of the cement to the maximum limit. Moreover, placing and compaction techniques should ensure the lowest possible porosity or permeability [6,30,40]. It was noticed that sulfate-related expansion of mortars was different from expansion of concrete made of the same materials and proportions, and exposed to the same conditions due to the difference in permeability values. Mortar has higher porosity due to its high cement paste content and is therefore more prone to sulfate attack. Thus, the w/c ratio is not the only variable that governs the permeability of concrete but also the aggregate type and gradation [30,36,43]. Finally, the dimension of the specimens subjected to sulfate attack also influences the time of initiation and crack development; a dependency was observed between thickness of the samples and their time of cracking and failure [44].

2.2. Alkali-Silica Reaction

One of major deterioration mechanisms of concrete is the excessive expansion due to alkali-silica reaction (ASR) of aggregates. It was reported in North America since the 1930s and then in many European countries and in other parts of the world [45,46]. Many researchers have investigated alkali-silica reaction in concrete in terms of reaction products, mechanism of deterioration, methods of assessment, and methods of mitigation and control. Although the degree of reactivity of aggregates is the major factor that governs the degree of alkali-silica reaction, it was observed that many other factors may influence the resulting expansion due to ASR [5,45]. The following sections contain a summary of the scientific literature and research on the alkali silica reaction in concrete and mortar.

2.2.1. The Reaction and Mechanism

The alkali-silica reaction is a reaction between the sodium and potassium alkali ions present in the pore solution of concrete and certain phases of silica encountered in significant quantities in the aggregate. Calcium, sodium, and potassium hydroxides are products of cement hydration; calcium hydroxide is mainly present as crystalline hydroxide, whereas most of the metal hydroxides are present in the pore solution [45]. The alkali reaction starts at the accessible surface of silica forming silica hydrous promoted by the high pH in cement paste. Alkali ions then penetrate through the silica particles attacking some of the silicon-oxygen linkages forming Si-O- which absorbs sodium, potassium and calcium ions [5,45]. Consequently, the sodium and potassium cations disperse maintaining an electrical neutrality and attract water to form a gelatinous alkali-metal-ion hydrous silicate [5,45,47]. Containing silica, calcium, sodium, potassium, and water, the resulting gel occupies much larger volume than the silica consumed. Thus, internal forces are induced resulting in expansion and cracking of concrete [45,48,49].

Table 2.3: The oxide contents of the ASR gel [45]

Description	Calcium oxide CaO: %	Sodium oxide Na_2O: %	Potassium oxide K_2O: %	Silica SiO_2: %	Water H_2O: %
Mortar	27·3	1·5	13·9	39·9	16·8
Deteriorated concrete	1	4	2	82	10
Deteriorated concrete	5	13	5	53	21

The composition of gelatinous product taken from two deteriorated concrete samples and mortar sample are given in Table 2.3. The composition of the gel has a major impact on expansion and deterioration of concrete since the mobility and fluidity of the gel is highly dependant on its composition [45]. It was suggested that gels of high calcium content tend to have high mobility [45].

2.2.2. Alkalis in Portland Cement

Reactive silica, sodium and potassium alkalis, and water should be available in order for alkali-silica reaction to occur. The sodium and potassium alkalis in concrete that react with the silica in aggregate are released as a product of Portland cement hydration. The source of alkali in cement is the raw materials used in its manufacture which contain potassium and sodium alkalis which are present in the form of alkali sulfates, alkali silicates, and alkali aluminates. "The alkali sulfates transform into alkali hydroxide in the liquid phase when cement comes into contact with the mixing water increasing the hydroxide concentration in the liquid phase" [45]. This process continues and the alkali concentration keep rising until 28 days, when most of the alkali have transformed into the solution [9,45]. The alkali content of Portland cement ranges from 0.2 to 1.5% Na_2O equivalent and in some cement, alkali contents may exceeds that level, especially when it contains high levels of sulfates. The equivalent sodium oxide (Na_2Oe) in cement represents the alkali of cement and is equal to $Na_2O + 0.658\ K_2O$.

It was observed that Portland cement with Na_2Oe more than 0.6% results in extensive expansion when used with alkali-reactive aggregates. Consequently, based on their alkali content either more or less than 0.6% equivalent Na_2O, cements were classified by ASTM C 150 to high-alkali cements or low-alkali cements respectively. The ASTM C 150 classification of alkali content in cement was adopted by the Canadian Standards Association [5,45].

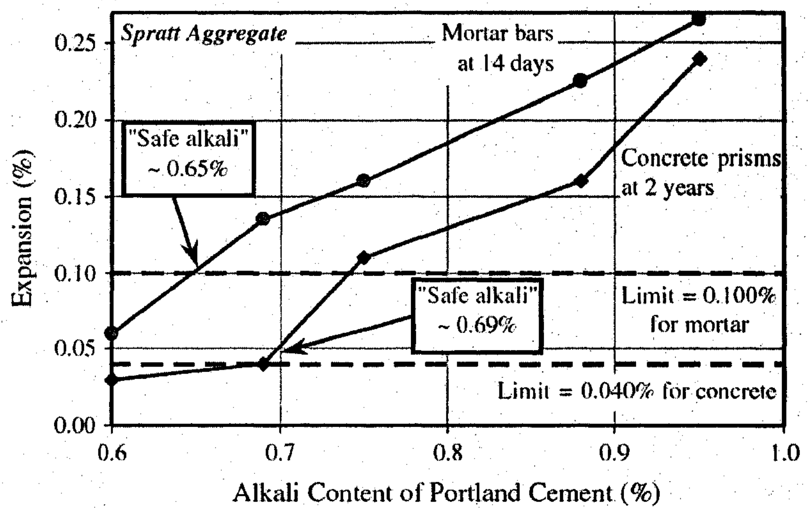


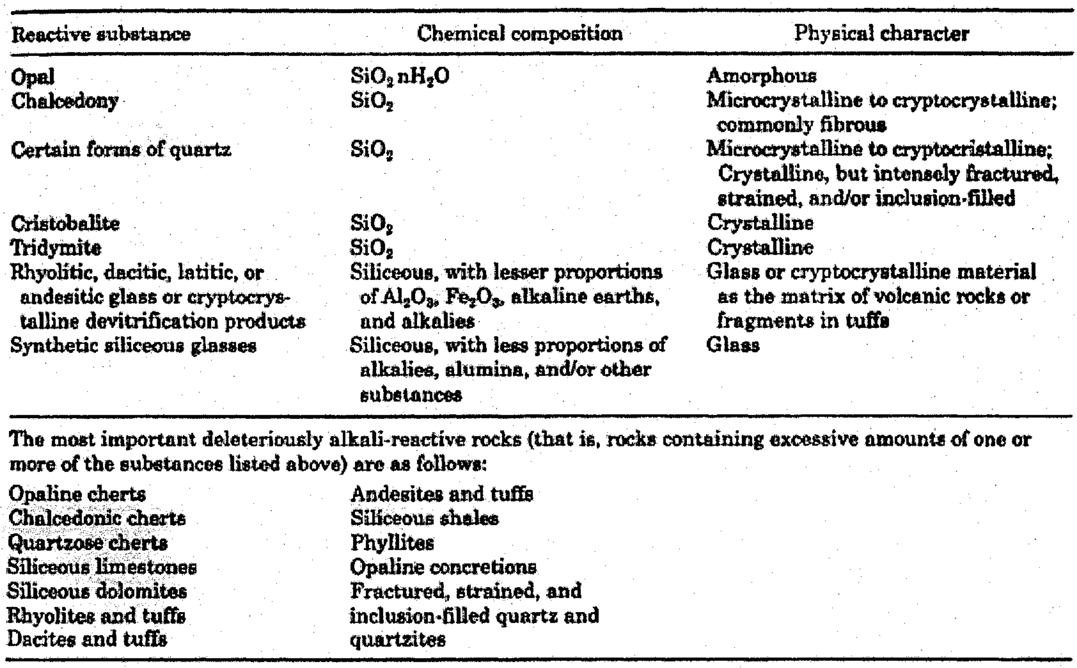
Figure 2.9: Effect of Cement Alkali on Expansion of concrete and Mortar [50]

Effect of cement alkalis on expansion of concrete prisms using Spratt aggregates (siliceous limestone) is shown in Figure 2.9. In addition, it was found that low alkali cement results in pH of the pore solution in concrete in the range 12.7-13.1 whereas for high alkali cement it ranges from 13.5 to 13.9. Moreover, other sources of sodium and potassium compounds such as sodium chlorides present in aggregate can increase the alkalinity of concrete. [45,48,50].

2.2.3. Reactive Sources of Silica

The occurrence of severe expansion and cracking in concrete due to ASR requires a significant amount of reactive silica in addition to the availability of alkalis in sufficient level and an external source of water. Various forms of reactive silica may be encountered in aggregates used in concrete; however, reactive silica involved in ASR can be categorized in two types. First, poorly crystalline or metastable silica minerals such as opal, tridymite, cristobalite, and volcanic or artificial glasses [45]. Aggregates with content as low as 1% of reactive materials may cause expansion in concrete, but cracking in concrete containing such aggregates is usually observed after 10 years of construction even with the presence of a highly alkaline pore solution. Second, various types of quartz may also result in the occurrence of the alkali-silica reaction. These types of aggregates may cause deterioration when the reactive component is present in content of 5%. Nevertheless, cracking of concretes containing these types of aggregates and having a high alkali content may also be observed after 10 years after construction, but in some cases cracking may not be observed in concrete containing such types of aggregates for up to 20 years after construction. The types of reactive rocks, minerals, and synthetic substances are shown in Table 2.4 [5,15,45]. The form of silica can be determined by petrographic examination or X-ray diffraction analysis. However, it was observed that highly disordered forms of silica may have more deleterious effect than less disordered forms. Moreover, the content of a mineral in an aggregate that causes the maximum expansion in concrete is called the pessimum proportion and it can be influenced by the alkalinity of concrete, particle size, and the water-cement ratio [15,45,48].

Table 2.4: Types of Reactive Rocks, Minerals, and Synthetic Substances [45]



Reactive substance	Chemical composition	Physical character
Opal	$SiO_2 nH_2O$	Amorphous
Chalcedony	SiO_2	Microcrystalline to cryptocrystalline; commonly fibrous
Certain forms of quartz	SiO_2	Microcrystalline to cryptocristalline; Crystalline, but intensely fractured, strained, and/or inclusion-filled
Cristobalite	SiO_2	Crystalline
Tridymite	SiO_2	Crystalline
Rhyolitic, dacitic, latitic, or andesitic glass or cryptocrystalline devitrification products	Siliceous, with lesser proportions of Al_2O_3, Fe_2O_3, alkaline earths, and alkalies	Glass or cryptocrystalline material as the matrix of volcanic rocks or fragments in tuffs
Synthetic siliceous glasses	Siliceous, with less proportions of alkalies, alumina, and/or other substances	Glass

The most important deleteriously alkali-reactive rocks (that is, rocks containing excessive amounts of one or more of the substances listed above) are as follows:

Opaline cherts
Chalcedonic cherts
Quartzose cherts
Siliceous limestones
Siliceous dolomites
Rhyolites and tuffs
Dacites and tuffs
Andesites and tuffs
Siliceous shales
Phyllites
Opaline concretions
Fractured, strained, and inclusion-filled quartz and quartzites

2.2.4. Manifestation of The Damage Caused by ASR

The expansion resulting due to ASR has been attributed to the stresses induced by volume increase of the gel caused by absorption of pore solution. If the concentration of the gel is high enough and its rate of expansion occurs rapidly, internal stresses may be induced sufficiently to cause deleterious expansion and cracking. The growth of the gel results in microcracks in the internal layers of the concrete matrix and macro cracks on the surface. However, in most cases cracks occur within a period of 3.5 years [45]. The severity of the expansion and cracking mainly depend on the amount of reactive aggregates which is expressed by aggregate to cement ratio and on the degree of alkalinity which governs the pH of the pore solution. The severity may be also promoted by exposure to external sources of water, extensive humidity, or prolonged period of wet weather [45,51]. The macro cracks are usually perpendicular to the surface of concrete of depth 25-50 mm and a width 0.1mm up to 10mm [5,45]. The level of expansion and cracking is not only related to the properties of the gel but also to the geometry of concrete member, curing conditions, presence of reinforcement, and applied loads. In most unreinforced concrete, a map cracking pattern is observed whereas in reinforced concrete cracking is mitigated by the reinforcement and applied loads. Pop-outs in concrete may also occur due to ASR and it mainly depends on the aggregate particle size [48,52].

2.2.5. Method of Assessment

In order to investigate potential reactivity of aggregates that are going to be used in concrete, laboratory tests should be undertaken. Two types of test methods may be performed, petrographic and chemical tests, or length change measurements. First, in petrographic evaluation, the mineralogical texture of an aggregate is compared with known reactive and non deleterious aggregates; moreover, a chemical analysis may be performed to determine the chemical composition. Petrographic evaluation is an easy and rapid way to determine the degree of reactivity of aggregates; nonetheless, it lacks effectiveness and accuracy due to the poor correlation between composition and texture of minerals and their potential alkali reactivity [15]. However, in some cases it shows acceptable correlation with different test methods such as X-ray diffraction [53]. ASTM developed two test methods for petrographic and chemical examination ASTM C 295 and ASTM C 289 respectively [5,15]. Secondly, length change measurements are applied to mortar and concrete prisms, and performed under high temperatures to accelerate the reaction. This method provides a reliable and rapid evaluation of reactivity of aggregates. The accelerated test method has been well researched and the correlation with the field performance has been considered acceptable [5,54]. Accordingly, many standard test methods were developed based on length change examination such as CSA test mortar bar method A23.2-25A, CSA test concrete prism method A23.2-14A, ASTM standard C 227 mortar bar method, ASTM standard C 1293 concrete prisms method and ASTM standard C 1260 accelerated mortar bar methods. The draft test procedure of accelerated test bar method was adopted by CSA and ASTM in 1988 and 1989 respectively, as a result of developing the NBRI rapid mortar bar test by Oberholster and Davies in the early 1980s [56]. CSA A23.2-25A and ASTM C 1260 were formally adopted by CSA and ASTM in 1994. Although the CSA mortar bar method is similar to ASTM C 1260 in most technical respects, there are some differences in water content and cement requirement between the two tests. The former specify the w/c of mixtures by 0.5 and total alkali content of cement by 0.9 ± 0.10 %, whereas the latter require w/c of 0.47 and call for cement with autoclave expansion of less than 0.20% [45,55,56,103].

2.2.6. Factors Affecting the Accelerated Length Change Test Method

The length change method is the most common, rapid, and effective test method used to predict the potential reactivity of aggregates. However, several variables govern the alkali-silica reactivity and may impact the resulting deterioration. The variables influencing the alkali-silica reaction in concrete and mortar have been adequately researched and understood and are discussed in the following sections.

2.2.6.1. Effect of Water to Cement Ratio

Even though the alkali-silica reaction may be enhanced and a severe expansion in concrete may occur in the presence of an external source of water, research shows conflicting results concerning the influence of the amount of mixing water has in mitigating or enhancing the alkali-silica reaction. It was found that utilizing lower water to cement ratio in concrete and mortar may reduce or increase the expansion resulting from alkali-silica reaction depending on the proportion of reactive silica [45,57]. However, it was also observed that in concretes containing a high w/c, more extensive damage occurred in the surface than the inner part [58]. Other research suggested that since w/c impacts concrete porosity of mortar and concrete, high w/c results in voids in which may allow the alkali-silica gel to move through and leak from the surface. Thus, the leakage prevents the ASR gel from inducing enough pressure to cause severe expansion and cracking. Accordingly, the low ASR related expansion of mortar samples of high w/c was interpreted. Figure 2.10 shows alkali-silica gel pressure versus water to cement ratio of mortar specimens, where the highest pressure was measured on a specimen of 0.45-water-to-cement ratio [59].

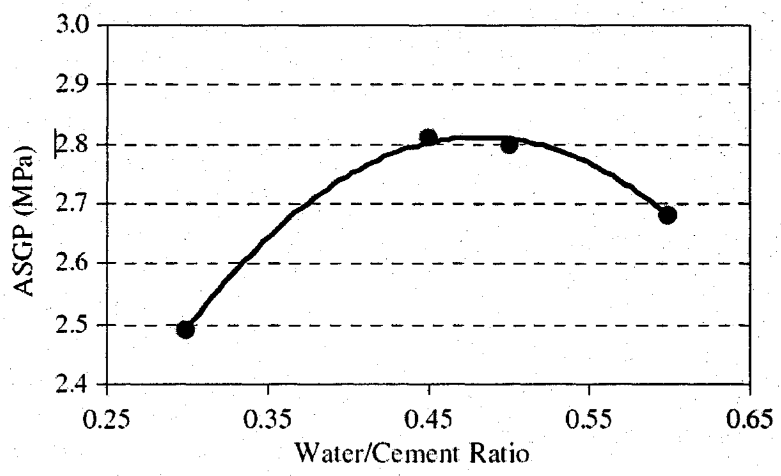


Figure 2.10: The Effect of w/c on ASR gel pressure and expansion [59]

2.2.6.2. Effect of Type of Solution

There is a wide agreement in the scientific literature that the sodium-rich alkali silica gels would manifest greater expansion than those that are potassium-rich [5]. The alkali-silica gel pressures induced in mortar specimens immersed in different base solutions at 80°C is shown in Figure 2.11, where specimens exposed to 1M NaOH solution resulted in the highest gel pressure. The effect of mixing water containing different forms of alkali on ASR related expansion is shown in Figure 2.12 where the expansion of mortar bars prepared with a 1-M NaOH, KOH, and LiOH content in the mixing water was investigated. It was noted that sodium content of mixing water may significantly enhance the expansion [5,45].

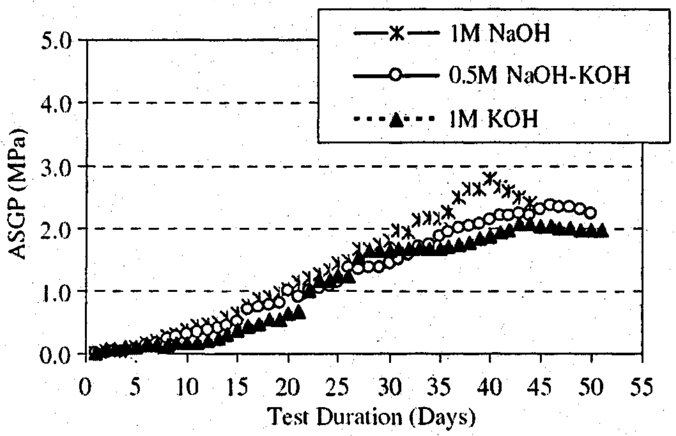


Figure 2.11: Effect of alkali solution on gel pressure [59]

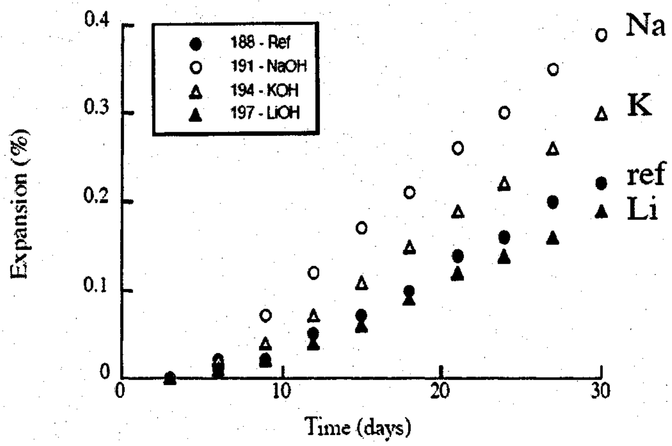


Figure 2.12: Expansion of mortar bars prepared with mixing water of different alkali contents [5]

2.2.6.3. Effect of Solution Concentration and Temperature

Temperature and concentration of alkali solution were considered by many researchers to be the most dominating factors that affect the expansion in the accelerated length change method since they enhance the alkali-silica reaction and accelerate the production of expansive gel. However, it was observed that there are upper limits of alkali concentration and temperature beyond which less expansion was reported. The highest expansion of mortars was reported of those tested at 80°C and immersed in solution of 1M NaOH concentration [ref]. The same results were confirmed by alkali-silica gel pressure measurement [59,60] which is shown in Figure 2.13.

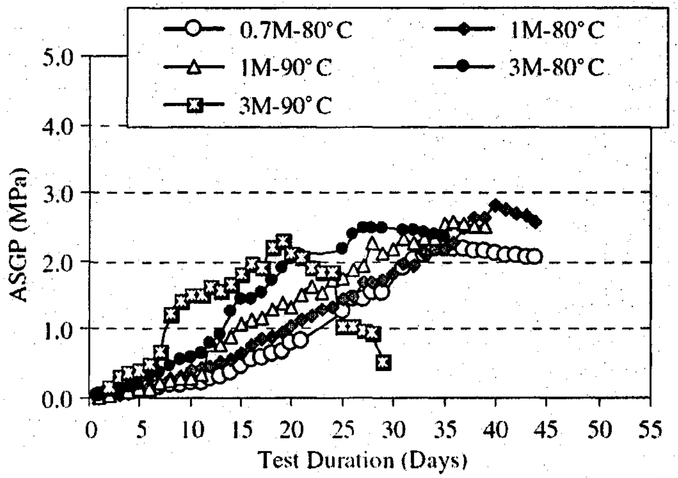


Figure 2.13: Alkali-silica gel pressure versus time under different alkali concentrations and temperatures [59]

These extreme conditions of temperature and concentration are the basis of the ASTM C 1260 test. However, it should be noted that the presence of sodium chloride in aggregates or mix water increases the hydroxyl ion concentration since it reacts with the tricalcium aluminate in Portland cement which consumes some of the chlorides and forms sodium hydroxide [61].

2.2.6.4. Influence of Aggregate Type and Particle Size

The expansion caused by the alkali-silica reaction is greatly influenced by the type and particle size of the reactive aggregates. It was found that forms of silica of higher disordered arrangement of the silicon oxygen tetrahedra, like Opal, produce higher reactivity that those of less disordered as Quartz. The effect of grain size was widely examined by researchers, it was found that no significant expansion occurred with particle size less than 20 μm [45,62]. It was also reported that the highest expansion occurred in mortar bars of particle size of 150 μm – 300 μm. The influence of grain size of reactive aggregates on expansion over time is shown in Figure 2.14. [45,63,64].

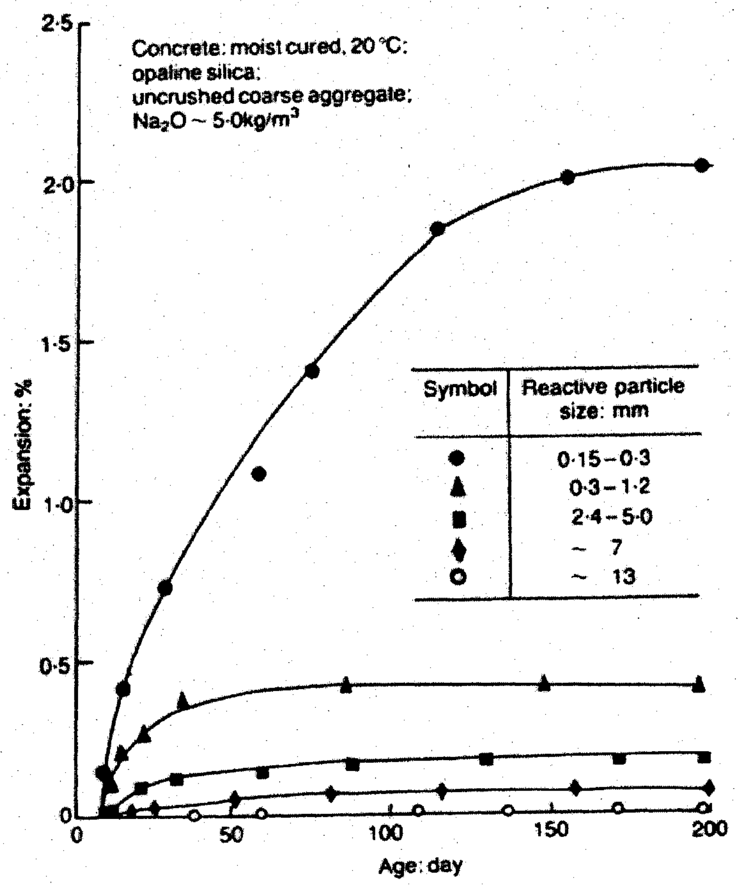


Figure 2.14: The relationship between aggregate size and ASR related expansion [45]

Moreover, it was observed that crushed aggregates showed higher expansion when used in mortars than natural aggregates in all the sizes utilized [65]. In addition, a very minor effect of the angularity of aggregates on ASR related expansion was noticed when very small and very large particles where utilized [45,65].

2.3. Fly Ash

2.3.1. Fly Ash Definition and Properties

Fly ash is a fine grained material collected from the exhaust gases released as a result of combustion of pulverized coal in thermal power plants. Fly ash particles are typically spherical of a glassy nature and particle sizes ranging from 1μm to 150μm with typical particle size of around 20μm [66,67]. In some cases fly ash has an irregular shape with angular edges and a size larger than 150μm [66,67]. The typical surface area of fly ash ranges from 300 to 500 m^2/kg and its relative density ranges from 1.9 to 2.8 [66,67,68].

Fly ash has been considered a pozzolanic material and has been widely utilized in concrete since the 1930s; it has been widely researched and understood and it gained a worldwide acceptance [7,70]. ASTM defines a pozzolan as "a siliceous or aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties" [69]. Fly ash exhibits a pozzolanic behavior since its content of aluminate silicates is unstable and is transformed to calcium silicate hydrate through reacting with calcium ions in the presence of moisture [7,70].

2.3.2. Fly Ash Composition and Classification

Chemical analyses performed for utilized types of fly ashes showed that the major components are SiO_2, Al_2O_3, Fe_2O_3, and CaO. Other minor constituents present in fly ashes are MgO, NaO_2, K_2O, SO_3, MnO, TiO_2, and C. Due to wide range of coal used in power plants, a wide variation of fly ash composition may be encountered. Based on their calcium content, fly ashes were classified by Canadian Standard Association to be: Type F fly ash which contains a low calcium content of less than 8%; Type CI fly ash of moderate calcium in the range 8%-20%; and Type CH fly ash having a high calcium content greater than 20%. Class F fly ash is typically produced from burning anthracite or bituminous coal whereas class C fly ash is a by-product of lignite or sub-bituminous combustion. It was noted that high calcium fly ashes have finer particles than low calcium fly ashes [7,10,71]. The mineralogical composition of fly ash is dependant on its type and source; however, it mainly consists of noncrystalline particles or glass, and a small amount of crystalline material. Unburned coal may be collected with the fly ash [7]. The chemical requirement of fly ash as defined by CSA A232.5 is shown in Table 2.5. In contrast, ASTM C618 has defined the specification limits of fly ash based on the some of the major oxides present as follows:

Class F fly ash: $SiO_2 + Al_2O_3 + Fe_2O_3 = 70\%$; $SO_3 = 5\%$ max; LOI = 5% max

Class C fly ash: $SiO_2 + Al_2O_3 + Fe_2O_3 = 50\%$; $SO_3 = 5\%$ max; LOI = 5% max

Table 2.5: The chemical requirement of fly ash and silica fume as defined by CSA A232.5 [15]

	Class F Fly Ash	**Class CH Fly Ash**	**Ground Slag**	**Silica Fume**
SiO_2, %	52	35	35	90
Al_2O_3, %	23	18	12	0.4
Fe_2O_3, %	11	6	1	0.4
CaO, %	5	21	40	1.6
SO_3, %	0.8	4.1	9	0.4
Na_2O, %	1.0	5.8	0.3	0.5
K_2O, %	2.0	0.7	0.4	2.2
Total Na eq. alk, %	2.2	6.3	0.6	1.9
Loss on ignition, %	2.8	0.5	1.0	3.0
Blaine fineness, m^2/kg	420	420	400	20,000
Relative density	2.38	2.65	2.94	2.40

Where LOI is loss on ignition which represents the weight loss of fly ash after burning at temperature of 1000°C and it is mainly related to carbon content of fly ash. However, it was found that the unburned carbon content of high calcium fly ash is <1%, whereas for low calcium fly ash unburned carbon may present in higher levels up to 10%. The carbon content of fly ash also impacts the amount of water needed to obtain adequate workability of mortars and concrete; the higher the carbon content the more water needed [7,66,72,73].

2.3.3. Fly Ash in Concrete

Incorporation of fly ash in concrete by either adding as an admixture or intergrinding has been considered to be as an effective way to promote concrete durability. It is typically utilized at dosages of 15% to 25% and has proved to improve the quality of concrete. Nevertheless, higher dosages were considered recently, which will be discussed in a later section. The effect of fly ash on concrete properties has been a subject of much research. It was found that based on its properties, chemical composition, particle size, and reactivity of fly ash has various effects on concrete. Fly ash significantly increases fluidity of fresh concrete which improves its workability and reduces its water requirement [7,71,74]. The relationship between fly ash replacement for cement and water requirement is shown in Figure 2.15 [75].

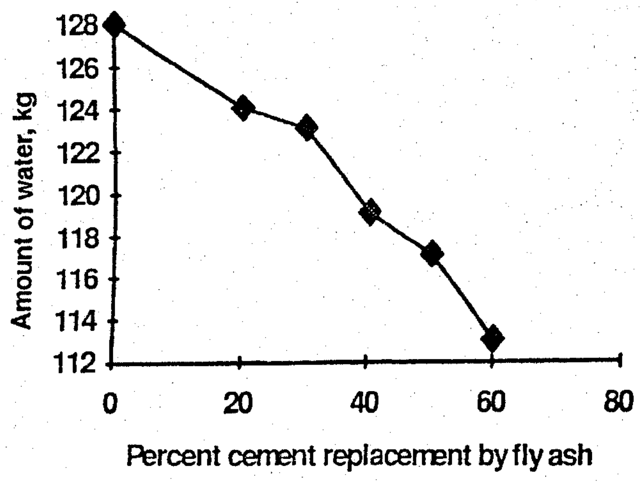


Figure 2.15: Relationship between water requirement and fly ash replacement level [75]

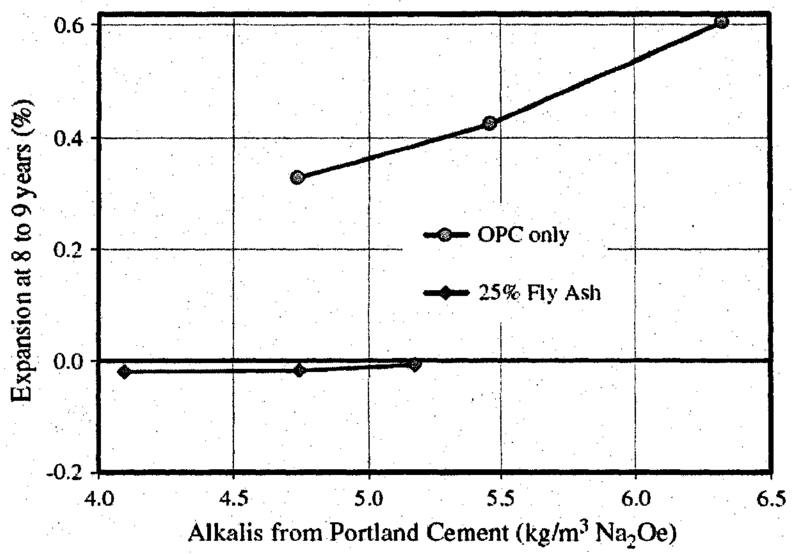


Figure 2.16: Effect of fly ash on concrete alkalinity [50]

Moreover, fly ash reduces the alkalinity of concrete through the pozzolanic reaction, increases its setting time, reduces segregation and bleeding, and mitigates the temperature rise during hydration [76]. The effect of fly ash on alkalinity reduction and expansion control in concrete incorporating 25% replacement of low calcium fly ash is shown in Figure 2.16. Furthermore, it was also found that fly ash markedly improved water tightness of hardened concrete and mortar by reducing permeability and porosity which contributes in increasing concrete durability [50,76,77,78].

The effect of fly ash on concrete strength varies widely depending on fly ash type and composition. It was found that the effect of fly ash on concrete strength development is mainly dependant of its calcium content and fineness [7,68,79]. It was widely reported that high calcium fly ash does not markedly influence strength development in concrete when replacement levels of up 30% are utilized [1,80]. On the other hand, low calcium fly ash exhibits very low self cementing properties; consequently, it reduces the early strength of concrete and may significantly reduce the long-term compressive strength of mature concrete if not cured at high temperatures (>30°C) [68,81]. Furthermore, the use of fly ash in concrete increases its modulus of elasticity, reduces creep, and reduces drying shrinkage [76,82]. Finally, the use of fly ash reduces the cost of concrete and the energy consumed in its manufacture [1,7].

2.3.4. Factors Affecting Pozzolanic Reactivity of Fly Ash

The pozzolanic reaction of fly ash in concrete and mortar is the reaction between the reactive silica and alumina of fly ash and calcium hydroxide produced by cement hydration. Thus, fly ash produces mainly calcium silicate and calcium aluminate hydrates. It was observed that even though fly ash hydration occurs in a like manner as cement, the formation of calcium silica hydrate takes place at slower rate since it is formed from the glass phase [7,83]. Factors influencing the pozzolanic reactivity have been widely investigated. It was confirmed that the chemical composition, fineness, and the amount of glass phase are the most important variables affecting the reactivity of fly ash. It was also confirmed that increased temperatures significantly affect the pozzolanic reactivity of fly ash. It was also found that higher silica and alumina content of fly ash markedly enhance the long-term pozzolanic reactivity, whereas the iron oxide and carbon content has poor influence on fly ash reactivity [76,84,85]. The effect of the content of the glass phase of fly ash was investigated and found to have good correlation with its reactivity [86]. However, other studies have suggested that the fineness of fly ash is the factor which has the greatest impact on its reactivity [87], where other factors showed poor correlation [88]. The effect of temperature on fly ash reactivity has been well researched and investigated. It was confirmed that higher temperatures increase the reactivity of fly ash. It was observed that time needed to reach certain strength at 20°C can be reduced 96% at a temperature of 80°C [88].

2.3.5. Fly Ash Effect on Sulfate Resistance

Various studies have investigated the effect of the use of fly ash in concrete on sulfate resistance using different types of cement and fly ash with various exposure conditions and periods of time up to 40 years. It was found that partial low-calcium fly ash replacement for cement in concretes and mortars proved to be very effective in increasing sulfate resistance even when exposed to severe sulfate attack [89,90] whereas the high-calcium fly ash have shown widely varying performance based on their calcium content, and in many cases fly ash of CaO content more than 20% enhanced the expansion resulting from sulfate attack [20,34,91,92]. Another study [41] investigated the sulfate resistance of different mortars containing normal Portland cement, sulfate resistant cement, and fly ash blended cement of a replacement level of 32%. The resulting expansion after 78 weeks of exposure in mortars containing blended fly ash cement was almost 50% of mortars made of sulfate resistant cement and 23% of those made of normal Portland cement. Both w/c ratio of 0.485 and 0.560 were used to determine the importance of w/c ratio as one of the variables that may dictate the sulfate resistance of mortar [41]. It was reported that the use of the lower w/c ratio (0.485) in mortars containing fly ash did not improve the sulfate resistance whereas in the plain mortars it remarkably reduced the expansion. However, the effectiveness of fly ash in improving sulfate resistance is also related to the chemical composition of fly ash, its particle size, the type and pH of sulfate solution [7,87,93]. The improving impact of fly ash on sulfate resistance of concrete and mortar is mainly due to the low permeability and high water tightness of the fly ash concrete and mortar systems, the consumption of the $Ca(OH)_2$ in the pozzolanic reaction which consequently limits the formation of ettringite and gypsum, and the reduction in C_3A and $Ca(OH)_2$ content as a result of using lower amount of cement [94,95]. Furthermore, the reactive phases in concrete are coated by a film produced by secondary formation of C-S-H as result of the pozzolanic reaction; thus, preventing the formation of secondary ettringite. It also should be noted that since ettringite is expansive only at high pH values over 12, the formation of ettringite in fly ash concrete does not necessary have deleterious effects due to the low alkalinity of these systems [20,32,96].

2.3.6. Fly Ash Effect on Alkali-Silica Reaction

Previous studies have shown that the use of fly ash in concrete can be considered an effective method to reduce the undesirable expansion due to alkali-silica reaction. Calcium content of fly ash is the most influential factor in controlling ASR-related expansion [97]. It was found that replacement levels of 25% - 30% of low-calcium fly ash for cement in concrete significantly reduce the expansion of concretes and mortars caused by alkali-silica reaction [7,98]. The effectiveness of fly ash in controlling alkali-silica reaction has been the subject of much research. However, the results reported from different studies vary widely. It was noted that some high calcium fly ashes were ineffective in controlling ASR and in some cases they increased the expansion as a result of their high content of soluble alkali sulfates. However, it was concluded that the effectiveness of fly ash is also a function of its alkali and silica content and fineness. And it was confirmed that ASR-related expansion increases with the increase of calcium and alkali content of fly ash and with the decrease of silica content and fineness [7,99]. In other studies, the minimum alkali content of fly ash at which fly ash acts effectively was investigated; it was estimated that alkali content of 3.4 kg/m^3 is the lowest concentration at which cracks in mortars start to be observed [45,100]. Concrete systems of fly ash at 55% replacement level and known reactive aggregates were also investigated, it was found that the reduction of expansion is mainly dependant upon calcium and alkali content of the fly ash used [95,98]. It was also found after 9 years of measurement, concrete incorporating fly ash at 40% replacement level is more effective in controlling ASR-related expansion than utilizing low-alkali cement. It was also noted that after two years of exposure alkali ions start to leach from the concrete mitigating the expansion and flattening the expansion curves of tested specimens [101]. In another study [102], the alkali, sulfate and MgO content of cement proved not to be related to alkali-silica reaction [102]. The reduction in expansion in concrete with the use of fly ash is mainly due to its effect in reducing permeability, reducing the PH of the pore fluid through the pozzolanic reaction, and changing the C-S-H composition. In addition, the fly ash replacement reduces the cement content in concrete and consequently dilutes concrete alkalinity; thus, reduces the expansion resulting from alkali-silica reactivity [1,103].

2.4. High Volume Fly Ash Concrete

2.4.1. Definition

The term High Volume Fly Ash (HVFA) Concrete was adopted by Malhotra [1] at the Canadian Center for Mineral and Energy Technology (CANMET) of Natural Resources Canada in the 1980s. "This concrete has very low water content and at least 50% of the portland cement by mass is replaced with ASTM class F or class C fly ash" [1]. Incorporating such high contents of fly ash in concrete improves most of the properties of fresh and hardened concrete and significantly reduces the world wide consumption of cement. Accordingly, HVFA concrete is suggested to be an effective method to dramatically enhance the durability of concrete construction and to embrace sustainability in construction industry.

2.4.2. HVFA Concrete Proportioning and Characteristics

The effect of proportioning on concrete properties is more pronounced in HVFA concrete than normal Portland cement concrete since fly ash has significant effect on the strength development of concrete [7]. Mixture proportions of HVFA concrete depend mainly on the strength requirement; however, other durability requirements should be also taken into account. The main characteristic of HVFA concrete is the low water to cementing materials ratio (w/cm) of maximum of 0.4; thus, increasing the early strength [95]. Since high slump is required to achieve high durability, superplasticizers are used with low w/cm especially when a 28-day compressive strength of more than 30 MPa is needed [1]. Since the effect of fly ash on strength development is a major concern in HVFA concrete, the effect of mixture proportions on strength gain of HVFA concrete has been well researched and understood. It was found that a 28-day compressive strength of 40 MPa can be reached with concrete of fly ash replacement levels of 55% [1]. However, the suggested proportions for HVFA concretes based on their strength requirement are shown in Table 2.6

Table 2.6: Typical Proportions for HVFA concrete [1]

Mixture Proportions Kg/m3			
Specified f'c at 28 days Specified f'c at 56 days	20 MPa 30 MPa	30 MPa 40 MPa	40 MPa 50 MPa
Water	120-130	115-125	100-110
ASTM Type I / Type II Cement	100-130	150-165	180-200
ASTM Class F, Fly Ash	125-150	180-200	200-230
W/CM	0.40-0.45	0.33-0.35	0.30-0.32
Coarse Aggregate (19 mm max.)	1100-1200	1100-1200	1100-1200
Fine Aggregate	810-900	810-900	810-900

Note: For cold environments, use an air-entraining admixture.
For slump >100 mm or W/CM<0.40; use a superplasticizer.

2.4.3. HVFA Concrete Properties

The effect incorporating fly ash on concrete properties was discussed in section 2.3.3. Due to its high content of fly ash, HVFA concrete has excellent workability and very low heat of hydration. A very low bleeding is also observed in HVFA concrete systems due to its low unit water content. Moreover, the HVFA concrete system has very low porosity and discontinuous pore structure which results in very low water permeability; thus, mitigates the penetration of chemicals and increase concrete resistance to carbonation and sulfate attack. The sulfate resistance of HVFA concrete was investigated at CANMET [1]. It was found that after seven years of exposure, specimens made of HVFA concrete showed expansion less than 30% of the expansion of the plain specimen made of the same cement [95]. The ASR-related expansion of HVFA concrete systems of 58% replacement level and known reactive aggregates was also investigated; a very minor expansion after 275 days of exposure was observed under various test conditions [104]. The high content of fly ash in concrete reduces the early strength of concrete; the fly ash

2.5. Silica Fume

2.5.1. Composition and Properties

Silica fume is a by-product of silicon industry and it is used in small amounts in concrete as a pozzolanic or cementitious material. Silica fume results from condensing of oxidized vapor in the 2000°C furnace used to reduce high-purity quartz with coal in an electric arc furnace in the manufacture of silicon metal or ferrosilicon alloys. Silicon dioxide is the main constituent of silica fume and it represents the reactive material; its content in silica fume ranges from 85% to 97% of the total mass. Other elements present in silica fume depend upon type of metal being produced and they have no significant influence on the performance of silica fume [10,105]. However, the alkali content of silica fume may influence its effectiveness in concrete; high alkali content may be encountered in silica fume of low silica content [106]. Although it is chemically similar to sand present in concrete, silica fume reacts in concrete due to its non crystalline nature [10]. It has extremely fine particles of average diameter of 0.1 μm which is 100 times smaller that average cement particle [105]. The chemical requirement of silica fume as defined by CSA A232.5 is shown in Table 2.5.

2.5.2. Silica Fume in Concrete

Typically, silica fume is blended in cement in contents not exceeding 10% of total weight [105]. Silica fume, when used in concrete, affects both its fresh and hardened properties. It increases the cohesion of fresh concrete and markedly reduces bleeding. Moreover, it significantly reduces permeability of hardened concrete and enhances its compressive strength and modulus of elasticity [10,105]. It acts as micro filler with its fine particles filling the voids between aggregates and cement grains; thus, significantly reduce permeability of concrete [30]. Due to its pozzolanic properties, silica fume reacts with calcium hydroxide produced by cement hydration forming calcium silicate hydrate similarly to cement. The additional C-S-H binder produced by silica fume contributes to the strength development of concrete [105,106].

2.5.3. Silica Fume Effect on Sulfate Resistance of concrete

It has been confirmed by many researchers that partial replacement of silica fume for cement or the use of silica fume blended cement in concrete and mortar significantly improve its sulfate resistance. The sulfate-related expansion was markedly reduced in mortars containing silica fume in contents as low as 7% under various exposure conditions and different types and concentrations of sulfates [20,25,30]. Other studies investigated the effect of various replacement levels (5-10%) of silica fume on concrete and mortar resistance to sulfate attack in terms of strength loss. It was found that utilizing silica fume is very beneficial in mitigating strength loss of mortars exposed to sodium sulfate attack. However, the use of silica fume did not result in considerable improvement of sulfate resistance exposed to magnesium sulfate attack since serious loss of strength was reported [107,108]. The improving effect of silica fume on sulfate resistance of concrete and mortars is mainly due to the significant reduction in permeability, the lower capillary water absorption, and alkali reduction through pozzolanic reaction [23,30].

2.5.4. Silica Fume Effect on Controlling ASR in Concrete

The influence of silica fume in on alkali silica reaction has been widely researched; it was found that silica fume can adequately mitigate the reaction and control related expansion by reducing the alkali concentration of cement paste pore solution. It was observed that the reduction in expansion of concrete and mortar was dependant on the amount of silica fume utilized [109]. It was reported that silica fume content of 11% could reduce the ASR expansion of specimens at one year age between 43%-80% depending on the alkali content of the cement used [110]. Other studies showed that the use of silica fume (SF) in mortar in low content up to 5% does not necessarily reduce the expansion, whereas mortars of higher SF contents (more than 8%) remarkably reduced the ASR related expansion regardless of the type of silica fume utilized. However, it was noted that the performance of silica fume in suppressing the alkali silica reaction is a mainly dependant on its silica content; silica fume of low silica content at 68% was not effective in controlling the alkali silica reaction. Furthermore, the performance of silica fume is also a function of its crystallinity [111,112,113].

In addition, it was found that incorporating low contents of silica fume in concrete also containing partial replacement of fly ash could effectively mitigate the deleterious effect of fly ash on concrete strength [114].The investigation of alkali-silica reaction in concrete containing approximately 5% silica fume with different replacement levels of fly ash have shown that the presence of silica fume significantly enhances the reduction of expansion [115].

3. Materials and Procedures

In this section, all the materials used in this test and the reasons for choosing those materials are described. The procedures and standards based on which the materials were proportioned and the specimens were prepared and tested are also described.

3.1. Materials

3.1.1. Cementitous materials

3.1.1.1. Cement

Four kinds of cements were used to perform the tests. The cements are listed below, and their chemical analyses are given in Table 3.1.

- St. Constant, CSA Type GU cement, St. Constant, Quebec
- St. Constant, CSA Type GUb-7SF cement,
- Herndon, ASTM Type I cement, Herndon, Virginia , and
- Brookfield, CSA Type GUb-7SF cement, Brookfield, Nova Scotia

Table 3.1
The chemical analyses of the cements used in the experiments (wt %)

	ST CONSTANT GU	ST CONSTANT SF	HERNDON	BROOKFIELD SF
SiO_2	19.22	24.38	19.71	26.57
Al_2O_3	4.75	4.82	4.35	4.33
TiO_2	0.21	0.22	0.20	0.34
P_2O_5	0.29	0.24	0.08	0.04
Fe_2O_3	2.24	2.24	2.64	2.62
CaO	62.2	59.15	62.76	59.1
MgO	2.61	2.33	3.74	1.19
Na_2O	0.24	0.26	0.17	0.1
K_2O	0.95	0.91	0.60	0.59
Mn_2O_3	0.06	0.06	0,06	0.09
SrO	0.26	0.23	0.05	0.07
LSO_3	4.11	3.46	2.39	2.9
LOI @ 1000°C	2.22	1.20	2.80	1.59
Total	99.35	99.45	99.55	99.51
Na_2Oe	0.86	0.85	0.56	0.48
C3A	8.8	9.0	7.1	7.0

The two St. Constant cements were selected because of their high alkali content in order to determine the effect of cement alkalinity on its sulfate resistance and the alkali silica reaction. Herndon and Brookfield have low alkali contents. Moreover, two of the cements utilized were silica fume blends in order to investigate the effect of silica fume inclusion on the mortar resistance to sulfate attack and alkali-silica reactivity.

3.1.1.2. Fly Ash

Two kinds of fly ash were utilized in this test; the fly ashes are listed below, and their chemical analyses are given in Table 3.2.

- Sundance Fly Ash. Type CI, Sundance, Alberta, and
- Rockport Fly Ash Type CI, Rockport, Indiana

Table 3.2
The chemical analyses of the fly ashes used in the experiments (wt %)

	Sundance	**Rockport**
SiO_2	54.67	44.28
Al_2O_3	22.93	20.96
TiO_2	0.65	1.43
P_2O_5	0.09	0.83
Fe_2O_3	3.82	6.93
CaO	10.94	16.35
MgO	1.16	3.69
Na_2O	2.97	1.21
K_2O	0.71	1.29
Mn_2O_3	0.06	0.03
SrO	0.11	0.26
LSO_3	0.17	0.8
BaO	0.5	0.58
ZnO	0.01	0.02
Cr_2O_3	0.00	0.02
LOI @ 750°C	0.40	1.13
Na_2Oe	3.43	2.04

The two fly ashes are classified based on their calcium content as type CI; nevertheless, the calcium content of Sundance fly ash is lower than that of Rockport fly ash. Fly ashes were selected of class CI since it was a subject of a less research than class F fly ash and its behavior in concrete and mortar is not yet fully understood. The difference in calcium content between the two fly ashes was intended to investigate the effect of calcium content in fly ash on sulfate resistance and ASR of mortars. The alkali content of the Sundance ash was higher than the Rockport ash so the effect of alkaline content of fly ash can be also investigated

3.1.2. Sand

The sand used for the sulphate testing in this test program was purely crystalline silica ASTM C 109 sand from Ottawa, IL USA as per specified in ASTM C778.

3.1.3. Aggregates

The aggregate used in the mixtures for the ASTM C 1260 tests were crushed Spratt, which is known to be reactive. The source of the Spratt aggregate was a mine near Ottawa Ontario, Canada. The aggregates were further crushed, pulverized, and sieved to get the proper gradation to comply with the requirements of ASTM C 1260. The aggregates were graded using square hole woven wire cloth sieves of numbers 4, 8, 16, 30, and 50.

3.1.4. Supply Water

All the mixing water used in the experiments was city of Montreal tap water. Distilled water was used to prepare the sodium sulfate and sodium hydroxide solutions.

3.2. Mixtures

In this test program, each of the four cements was combined with both of the fly ashes at replacement levels of 0%, 20%, 40%, 60%, and 80% by mass of the binder. Accordingly, 36 different mixtures were cast for the sulfate test covering all the probable combinations of the four cements and two fly ashes. All of the mixtures prepared for the sulfate attack test have a w/c of 0.485 except for two mixtures which were recast with lower water cement ratio for comparison. The standard states to cast the mortars to a constant consistency, but in this program it was decided to compare the combinations using constant water to cementing materials ratio. In order to determine the effect of water to cement ratio, two mixtures were cast with a water to cementing materials ratio to yield the same consistency as the 100% cement mixture of the same materials. Since increasing fly ash increases consistency, 80% fly ash mixtures of the least and most expansive mixtures were selected. Another 36 mixture were prepared for ASR test using the same combinations and the same fly ash contents but using Spratt aggregate instead of sand and w/c of 0.47.

3.3. Casting of Specimens

The casting of the specimens for the sulfate resistance test was performed according to ASTM C 1012. For each mixture, four 25 x 25 x 285 mm mortar bars and six 50 x 50 x 50 mm cubes were prepared. One set of samples (4 bars and 6 cubes) were mixed in one batch for every mixture. The molds were prepared in accordance with ASTM C 490 and the interior surfaces of the molds were covered with a release agent to facilitate the demolding process. Each mold had gauge studs at either end set to 250 mm spacing. The mixtures contained 1 part cement to 2.75 parts sand and had a water to cement ratio of 0.485. Accordingly, the mix proportions needed to make the above mentioned samples of each mixture were 2475 g of sand, 436.6 ml of water, and 900 g of binder. The amount of binder represents the total amount of cement and fly ash in the mixture. An electrically driven mechanical mixer of the epicyclical type was used and the total time of mixing procedure was 4 minutes as described in ASTM C 305. The laboratory temperature where the mixing of all mortars took place was maintained between 22° C and 24° C. All the mixtures were tested for workability using a flow table according to ASTM C 230. As mentioned previously, all the mixtures have a w/c of 0.485 except for two batches where a lower water to cement ratio (0.40 and 0.39 respectively) was used to comply with the ASTM C 1012 requirement of developing a flow within 5% of that of the Portland cement mortar at a water-cement ratio of 0.485. Those two batches were cast to be compared with the similar mixtures of w/c of 0.485 to determine the effect of the flow requirement on the test results.

For the Alkali Silica Reaction test the proportioning and molding were in accordance with ASTM C 1260. For each mixture, three 25 x 25 x 285 mm mortar bars were cast using 1 part of binder to 2.25 parts of graded aggregates by mass and water to cement ratio of 0.47 by mass; accordingly, the quantities of dry material used for making three specimens were 440 g of binder and 990 g of aggregates. The mixing of specimens was performed in accordance with ASTM C 305. The aggregates were graded as mentioned in section 3.1.3 using square hole woven wire cloth sieves. The grading of the aggregates used is shown in Table 3.3. The mass of each portion of aggregate required for every batch is shown as well. Preparing the specimen molds was done in accordance with requirements of practice ASTM C 490, but the internal surfaces were covered with a release agent. All test specimens were molded within total time of 2 min and 15 s after completion of mixing the mortar batch.

Table 3.3: Grading of Aggregates

Sieve Size		Mass Used
Passing	Retained on	
4.75 mm (No. 4)	2.36 mm (No. 8)	99 g
2.36 mm (No. 8)	1.18 mm (No. 16)	247.5 g
1.18 mm (No. 16)	600 μm (No. 30	247.5 g
600 μm (No. 30	300 μm (No. 50)	247.5 g
300 μm (No. 50)	150 μm (No. 100)	148.5 g

3.4. The Sulfate Resistance Test

The sulfate resistance test was done in accordance with the ASTM C 1012 which is an accelerated test method developed for assessing the sulfate resistance of mortars and concretes made of blended cements or blends of Portland cements with pozzolans. In this test method, the sulfate resistance is determined by measuring the length change of mortar bars exposed to a sulfate solution. Mortar bars were made as described in section 3.3., and then cured until the cubes made of the same mortar attained a compressive strength of 20.0 ± 1.0 MPa after which they were immersed in sulfate solution.

3.4.1. Curing of Specimens

Immediately after casting, all the specimens in the molds were put into a sealed plastic container containing a layer of water on its bottom to maintain 95%+ relative humidity and stored in the laboratory at temperature of 24° C. All specimens were demolded after 24 h of casting except for the samples of 80% fly ash; they were demolded after 48 h because of being so fragile that they broke while demolding due to their low early strength. After initial curing and demolding, all bars and cubes were immersed in lime-saturated water at 24°C for curing until they reached the required strength to be immersed in the sulfate solution.

Two cubes were tested at a time for compressive strength in accordance with the ASTM C 109 which describes the test method for compressive strength of hydraulic cement mortars. If the cubes had not reached the strength limit of 20.0 ± 1.0 MPa, a subsequent compressive strength test of two additional cubes was performed at a later date. The time at which the subsequent tests were to be performed was predicted based upon the value of the first test. In some cases, a third test was done after evaluating the results of the first two tests and giving the samples the sufficient time to develop strength. The age at which the cubes of each mixture reached the required strength widely varied and that was normal because the strength of the specimen depends on the type of cement used and the content of fly ash in the mixture. However, all the samples of 80% content of fly ash didn't reach the required strength even after 28 days of curing and most of them were immersed in the sulfate solution at 28 days; two were immersed at 21 days and one at 49 days. The result of the compressive strength test and age at which the bars were immersed in sulfate solution are outlined and discussed in Chapter 4 later on in this report.

3.4.2. Sodium Sulfate Solution

A 5% sodium sulfate solution has been used in this test as per the standard. It contains 352 moles of Na_2SO_4 per m^3 which equals 50.0 gram per liter. The quantity of solution prepared for each set of bars was 1800 ml. It was prepared by mixing 90 grams of sodium sulfate powder in 1800 ml of distilled water. The sulfate solution was prepared on the day before use and stored in 32cm x 21cm x 5cm plastic containers and tightly covered at the laboratory temperature for the initial immersing of mortar bars. For the subsequent changing of solution after each length measurement, the sulfate solution was being prepared one to three days before measurement and stored in a 10 liter plastic container. All the plastic containers in which the specimens were immersed in the sulfate solution were stored in the laboratory at a temperature of 24° C.

3.4.3. Measurement of Length Change

Measurement of length change of the mortar bars was done as described in the ASTM C 1012 using a comparator conforming to the requirements of specification ASTM C 490. When the cubes of each mixture reached a compressive strength of at least 20 MPa the bars were measured and then immersed in the sulfate solution. This measurement is designated as the initial length. The subsequent measurements of length change were taken at 1, 2, 3, 4, 8, 13, and 15 weeks after measurement of initial length. For all the mixtures, the data at 15 weeks were reviewed and the expansion of the mortar bars was found to be slight, gradual, and uniform. It was thought that the interval between readings was adequate and it was providing an optimum monitoring of the behavior of the bars. Accordingly, the subsequent measurements were scheduled at 4, 6, 9, and 12 months as recommended in the ASTM C 1012. At every measurement of each mixture, the value of length change of each specimen was recorded and then the relative expansion of each specimen and average expansion of the four specimens was calculated. The gauge stud hole of the comparator at the lower end was cleaned after every reading as described in the standard. Most of the measurements were taken on the exact time and date as scheduled especially at the early weeks when the change rate was relatively high, but some measurements were not performed on the precise date. However, all the measurements were reported at the time that they were taken (elapsed time). In all cases where measurements were not taken exactly on the specified time, the variance of the elapsed time at which they were taken was within the time tolerance of ±2% permitted in the ASTM C 1012.

After every measurement the bars were carefully examined and tested for warping by placing on a plane surface and no considerable bowing was detected. The cracks were reported once noticed and the width and type were mentioned. The expansion of the specimen for specific period was recorded as the difference between the zero reading of the specimen and the reading at that period. The relative expansion at x age, ΔL, was calculated using the following equation.

$$\Delta L = \frac{L_x - L_i}{L_g} \times 100\%$$

where: L_x: Comparator reading at x age.

L_i: zero comparator reading of specimen.

L_g: 250 mm.

The average expansion of the three specimen of each mixture was considered to be the expansion of the combination for a given period.

3.5. The Alkali-Silica Reaction Test

In this thesis, the alkali-silica reaction using Spratt aggregate was studied using the mortar-bar method in accordance with ASTM C 1260 standard test method. ASTM C 1260 is an accelerated test method that permits detection of potential alkali reactivity of aggregates. The test was performed using four kinds of cements and two kinds of fly ash that are described in section 3.1.1 and the mixtures used are outlined in Table 3.2.1. The use of different cements with the same aggregate type was performed in order to give an idea about the degree of resistance that each cement-fly ash combination afforded. Moreover, the use of different content of fly ash was considered to show the effect of the use of fly ash on the expansion of specimens containing alkali-reactive aggregates.

3.5.1. Sodium Hydroxide Solution

The sodium hydroxide (NaOH) solution used in this test was of concentration of 4% (1M). Each liter of solution contained 40.0 g of sodium hydroxide powder (NaOH) dissolved in 900 mL of water and then diluted with additional water to obtained 1.0 liter of solution. The amount of solution used for each set of samples was 2 liters so that the specimens were adequately immersed. The specimens were supported by two plastic tubes to provide separation between the bottom of the specimens and the bottom of the container in order to ensure that the solution reached all sides of the sample.

3.5.2. Storage and Measurement of Specimens

After molding, specimens and molds were placed in an airtight plastic container (maintained > 95% rh and 24°C) and remained for 24 h before demolding. At the time of demolding, sodium hydroxide solution was prepared, put in 32cm x 21cm x 5 cm plastic containers, and placed in the oven at of 80°C. An initial comparator reading was taken immediately after demolding, then each set of specimens was placed in the plastic container of water of 80°C so that the specimens were totally immersed and the containers were placed back into the oven for another 24 h. On the next day at the same time the zero readings were taken and the specimens were placed in the sodium hydroxide solution at 80°C and returned to the oven. Subsequent readings were taken every two days for 14 days after the zero readings and were continued to be taken at wider frequencies beyond the 14 days period. The level of solution was marked on the sides of the plastic container in order to monitor any evaporation. Additional water was added when a considerable loss was noticed to maintain the volume and concentration of solution.

The expansion of the specimen for specific period was recorded as the difference between the zero reading of the specimen and the reading at that period. The relative expansion at each required age was calculated as mentioned in section 3.4.3. The average expansion of the three specimen of each mixture was considered to be the expansion of the combination for a given period.

4. Results and Discussion

4.1. The Sulfate Resistance Test

The results of the expansion, flow and strength for the sulfate test program are given in this section.

4.1.1. Sulfate Expansion with Time

Figures 4.1 to 4.8 show change of length over time of all the mixtures; it can be observed that all specimens showed increasing expansion with prolonged periods of exposure. It also can be observed that the severity of expansion is highly dependant on the type of cement and fly ash utilized. Generally, incorporating fly ash reduced the extent of expansion of most of the mixtures. For mixtures containing Herndon and St. Constant GU cements, higher rates of expansion after 15 weeks of exposure were observed in control mixtures, whereas mixtures of high fly ash replacement levels manifested minor length change as shown in Figures 4.1, 4.2, 4.5, and 4.6. For the control mixture containing St. Constant GU cement, the rate of expansion after 26 weeks of exposure was almost constant whereas increasing rate of expansion was observed in control mixture made of Herndon cement.

For all mixtures containing silica fume blended cements (St. Constant SF and Brookfield) at all fly ash replacement levels utilized, a sharp increase in length of specimens was reported at the early stages until 3-4 weeks exposure as shown in Figures 4.3, 4.4, 4.7, and 4.8. After the fourth week, lower rates of expansion were observed depending on fly ash content.

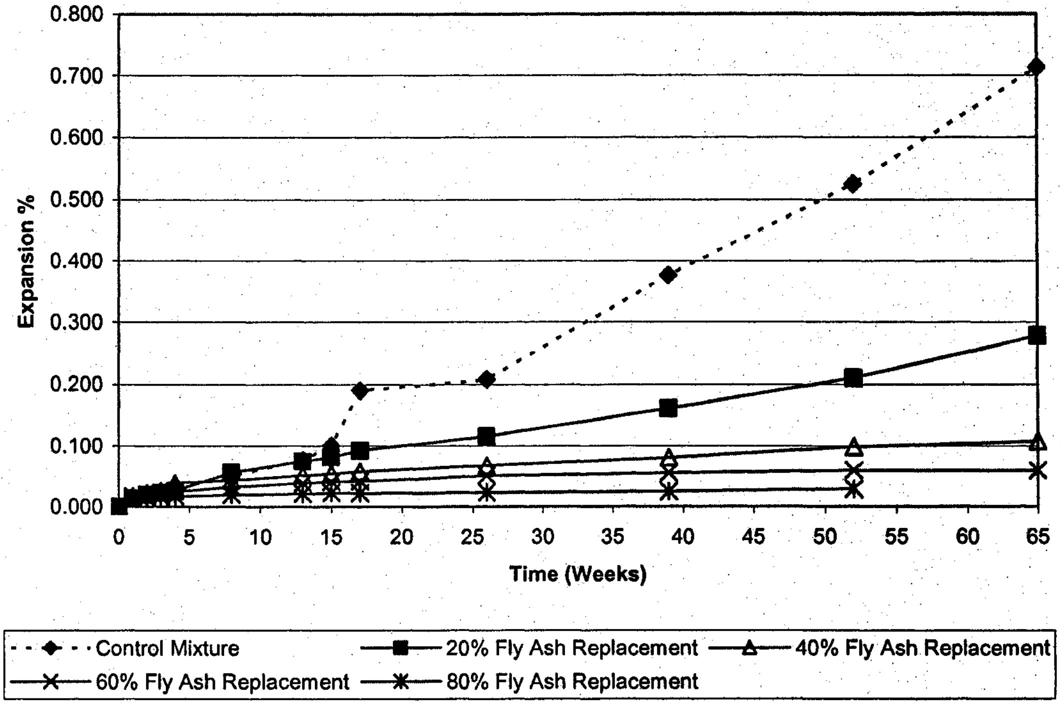


Figure 4.1: Sulfate Expansion vs. Time of Mixtures of St Constant GU with Rockport Fly Ash

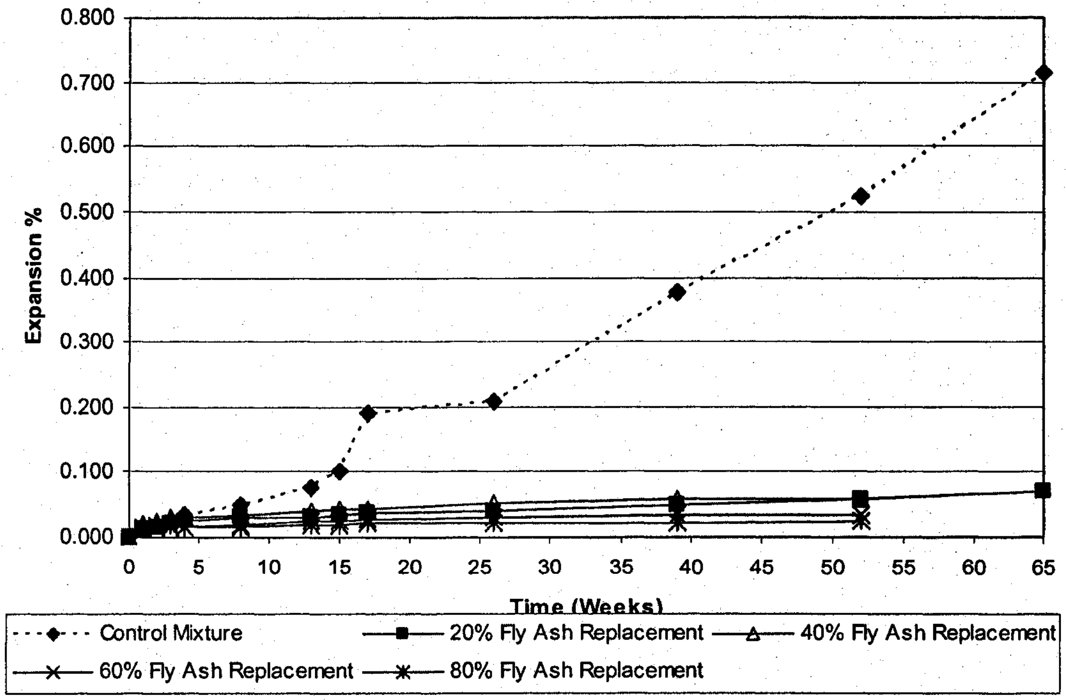


Figure 4.2: Sulfate Expansion vs. Time of Mixtures of St. Constant GU with Sundance Fly Ash

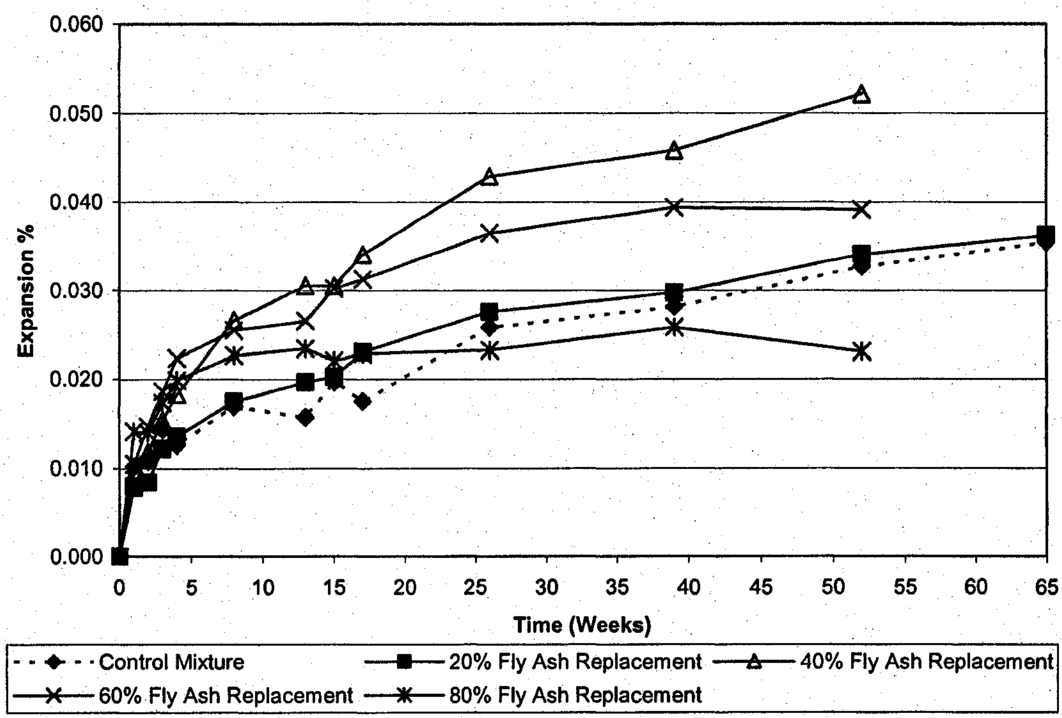


Figure 4.3: Sulfate Expansion vs. Time of Mixtures of Brookfield with Rockport Fly Ash

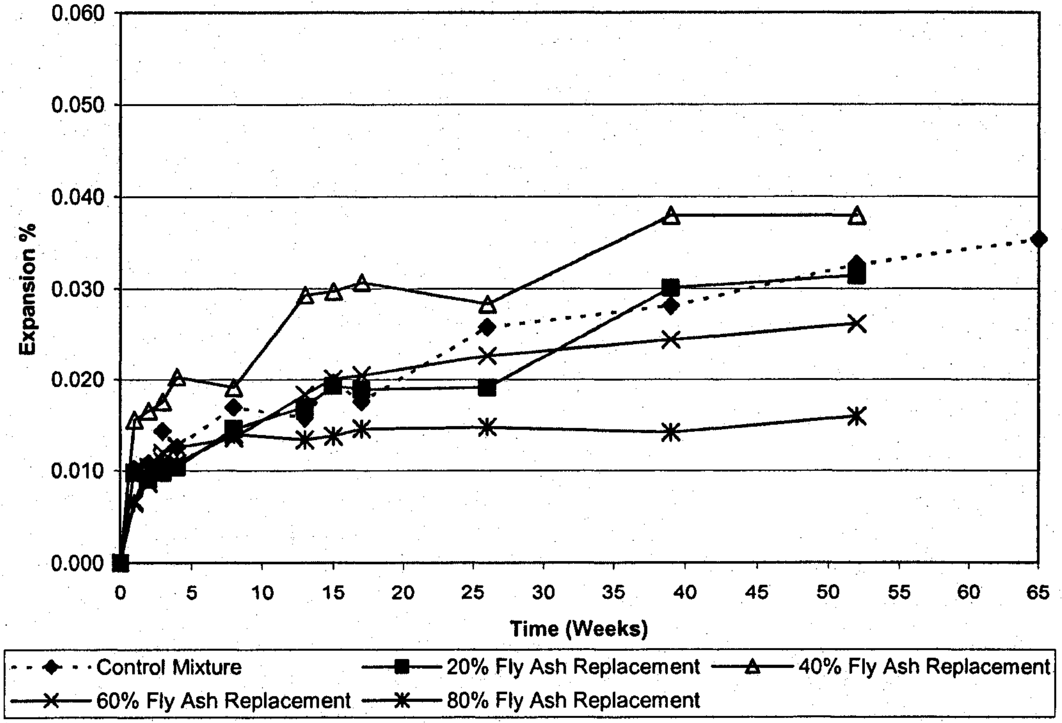


Figure 4.4: Sulfate Expansion vs. Time of Mixtures of Brookfield with Sundance Fly Ash

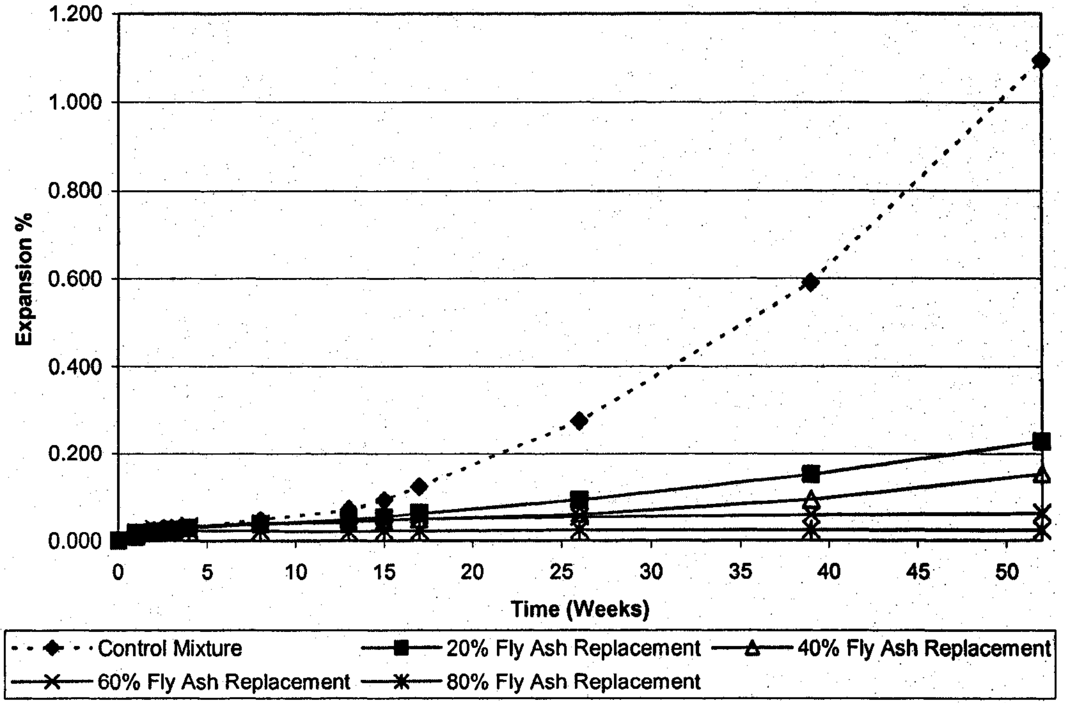


Figure 4.5: Sulfate Expansion vs. Time of Mixtures of Herndon GU with Rockport Fly Ash

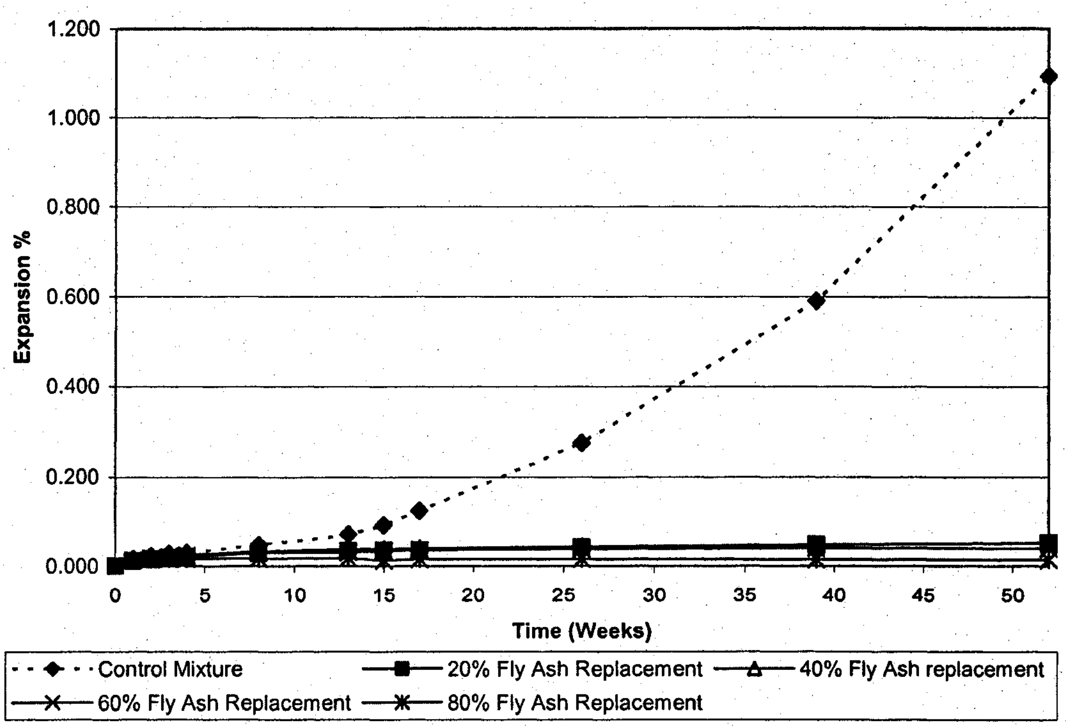


Figure 4.6: Sulfate Expansion vs. Time of Mixtures of Herndon GU with Sundance Fly Ash

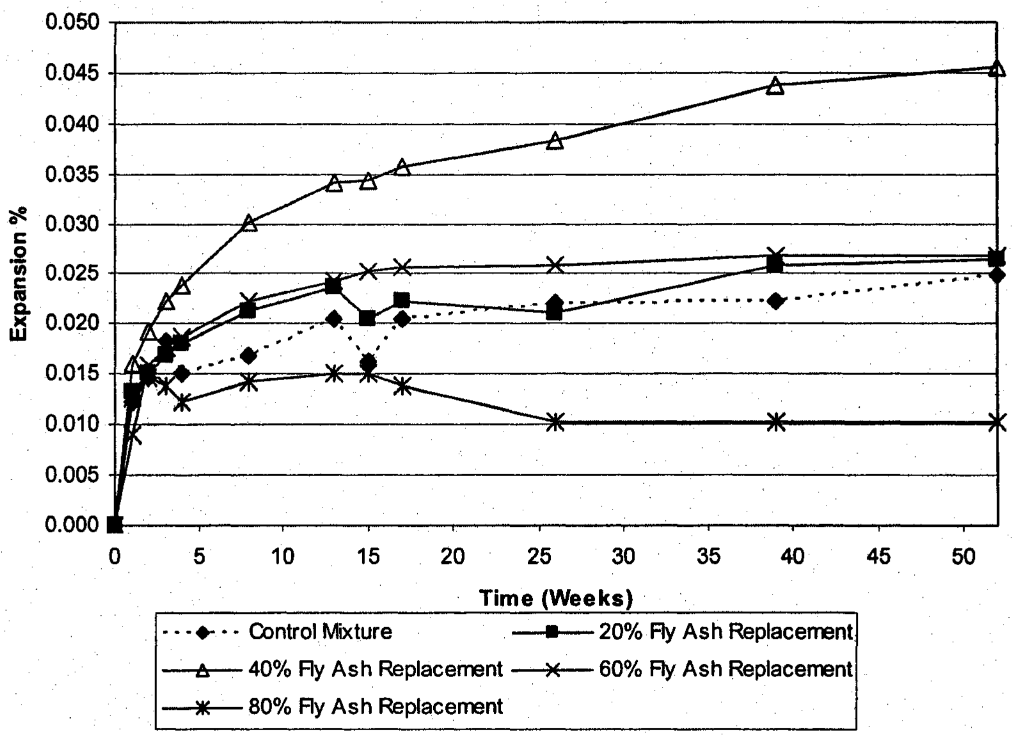


Figure 4.7: Sulfate Expansion vs. Time of Mixtures of St. Constant SF with Rockport Fly Ash

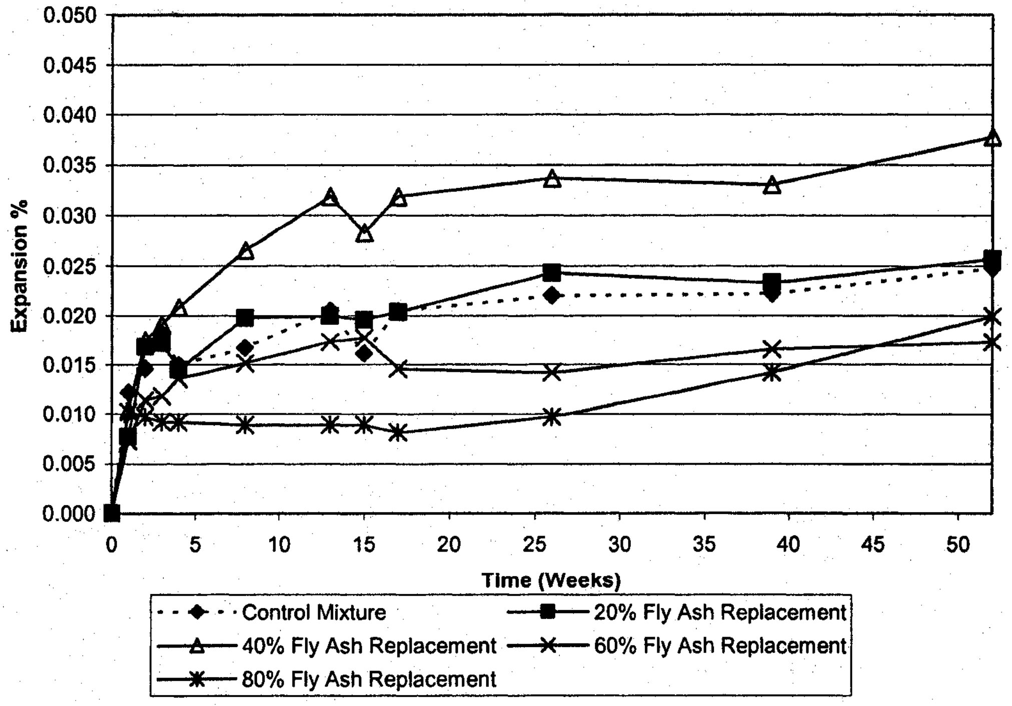


Figure 4.8: Sulfate Expansion vs. Time of Mixtures of St. Constant SF with Sundance Fly Ash

4.1.2. Sulfate Expansion Versus Fly Ash Content

Figures 4.9 - 4.13 illustrate the expansion versus fly ash content for all the mixtures used for the sulfate resistance test at different intervals from 4 weeks to 12 months. For the mixtures containing Portland cement (Herndon and St. Constant GU), the expansion generally decreased with increasing replacements of fly ash after 4 months of exposure (Figures 4.10 and 4.11). The reduction of expansion with the increase of fly ash replacement is more pronounced after 6 months of exposure when the control mixtures reach high levels of expansion (Figure 4.12). The major reduction of expansion occurred at replacement level of 20% mainly due to fly ash's effect of reducing permeability of mortars. Replacement levels higher than 20% did not reduce permeability much further; nevertheless, it controlled expansion by reducing the formation of gypsum. Accordingly, the highest expansion for most of the mixtures at early stages until 4 weeks occurred when 40% replacement level were utilized which explains the peak at 40% replacement level shown in Figure 4.9. The pozzolanic reaction of fly ash, which consumes the $Ca(OH)_2$ and limits Ettringite formation, starts after 4 weeks of exposure when most of the cement is hydrated. Consequently, the improving effect of fly ash at 20% replacement level on sulfate resistance of mortars was observed since the first week of exposure, whereas for 40% and 60% replacement levels it was observed after 4 weeks of exposure.

All mixtures contained SF cement showed excellent sulfate resistance and resulted in expansion below 0.05% after 6 month of exposure which is the expansion limit specified by CSA A 3000 for high sulfate resistance cement. Mixtures containing Herndon and St. Constant GU cement with Sundance fly ash at 20% replacement level also showed an excellent performance and experienced expansion below 0.05%. When Rockport fly ash was used with Herndon and St. Constant GU cement, higher replacement level of 40% was needed to maintain the expansion below 0.1% limit after six month of exposure to sulfate which is the acceptable expansion for moderate sulfate resistance cement as specified by CSA A 3000.

Sundance and Rockport fly ash are of calcium content 10.94% and 16.35% respectively and both are classified as class CI fly ash. Nevertheless, Sundance fly ash performed better than Rockport fly ash. Mixtures containing Portland cement with Sundance fly ash gave lower expansion than those with Rockport fly ash due to the lower CaO content of Sundance fly ash. The resulting expansion of all mixtures with Sundance fly ash at replacement level of 20% was as low expansion as 0.052% after one year of exposure; higher replacement levels didn't significantly reduce the expansion as shown in Figure 4.15. All mixtures with Rockport fly ash at replacement levels of 20% gave expansion of 0.228% after one year of exposure; expansion was further reduced with incorporating higher replacement levels. The specimens made of plain Herndon GU cement expanded 1.094% after one year of exposure which is extremely severe when compared the correspondent value of St. Constant GU cement which was 0.525%. This was mainly due to the thin cracks which started to form on the corners of specimens.

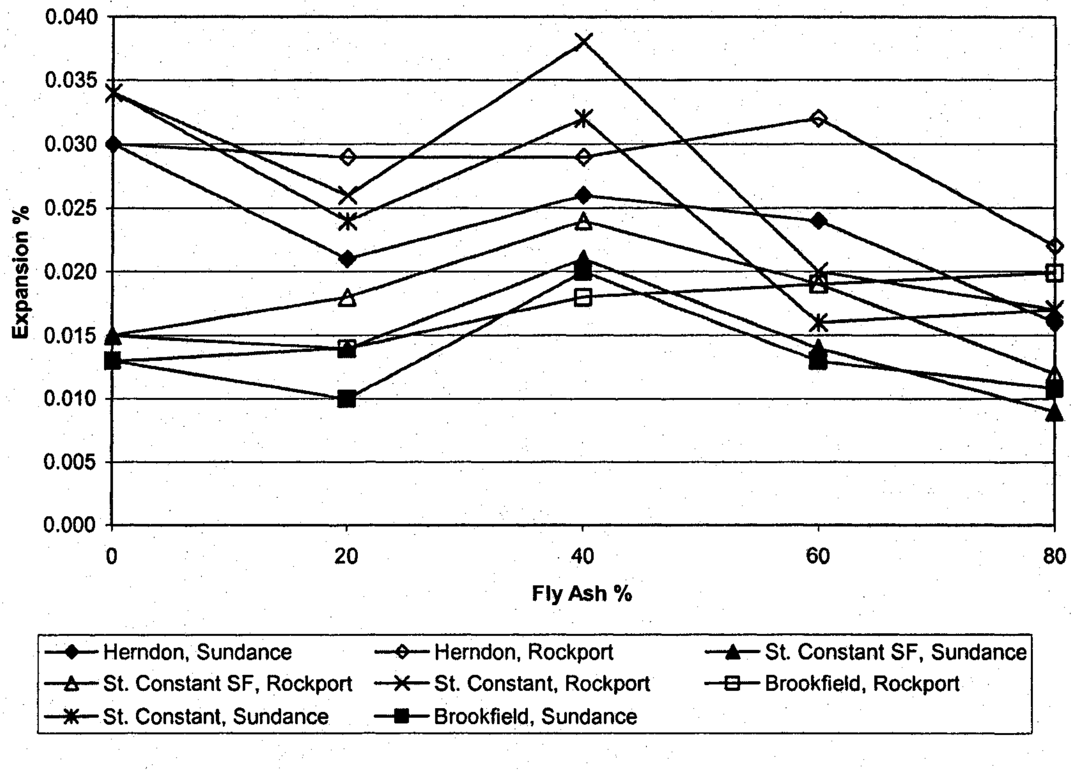


Figure 4.9: Expansion vs. Fly Ash % after 4 weeks

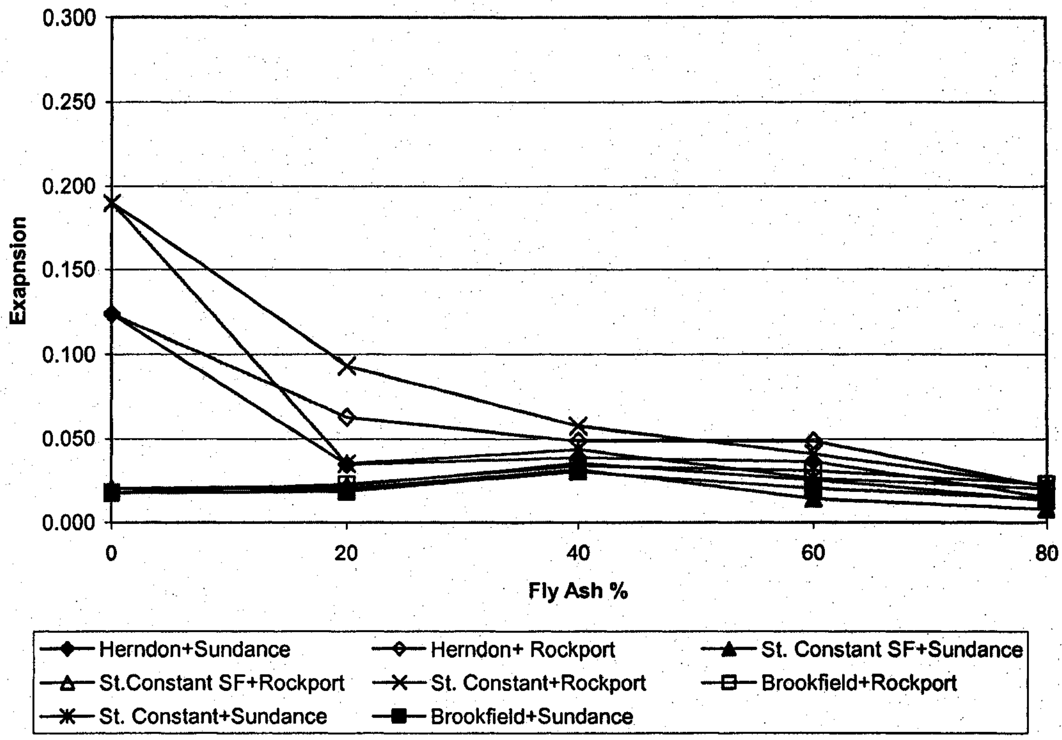


Figure 4.10: Expansion vs. Fly Ash % after 4 months

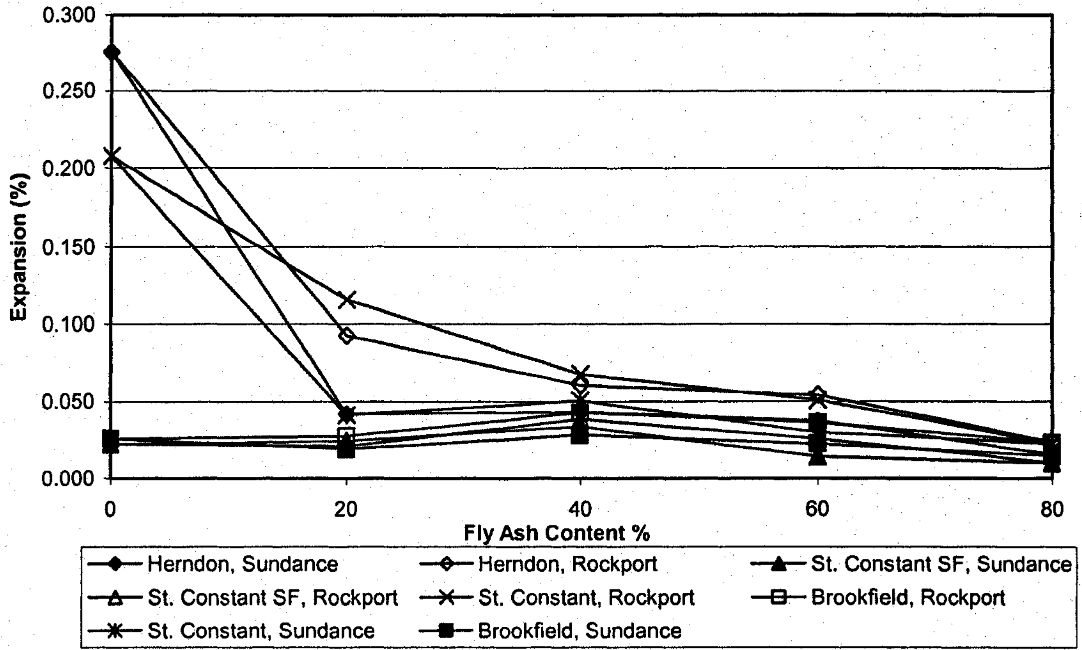


Figure 4.11: Expansion vs. Fly Ash % after 6 months

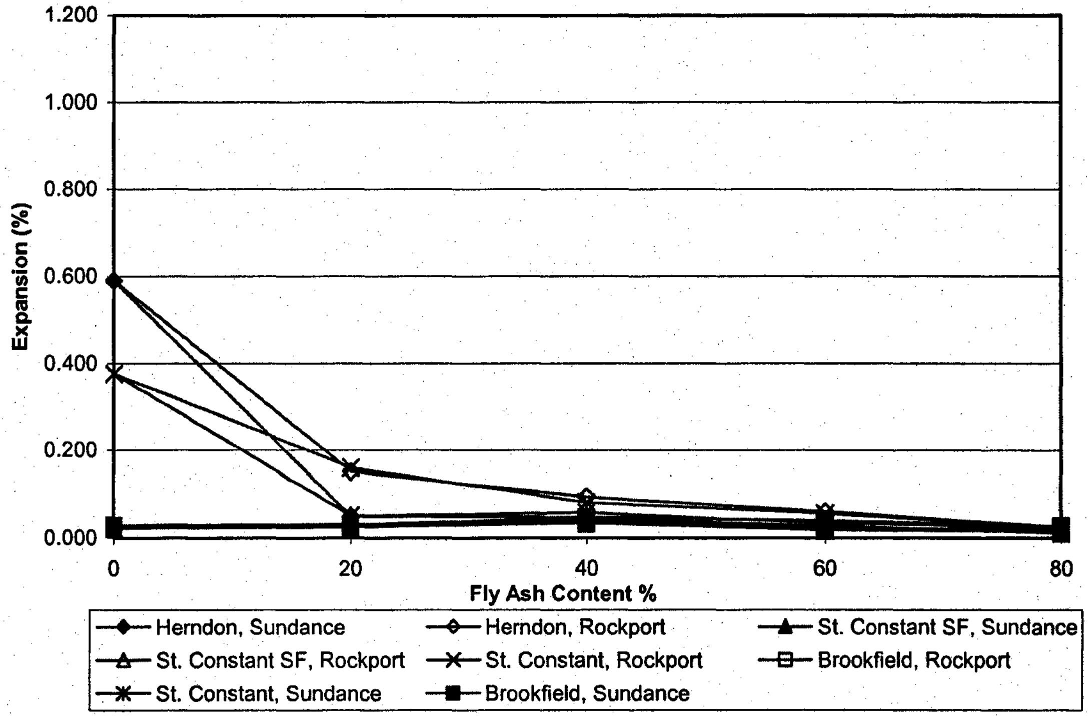


Figure 4.12: Expansion vs. Fly Ash % after 9 months

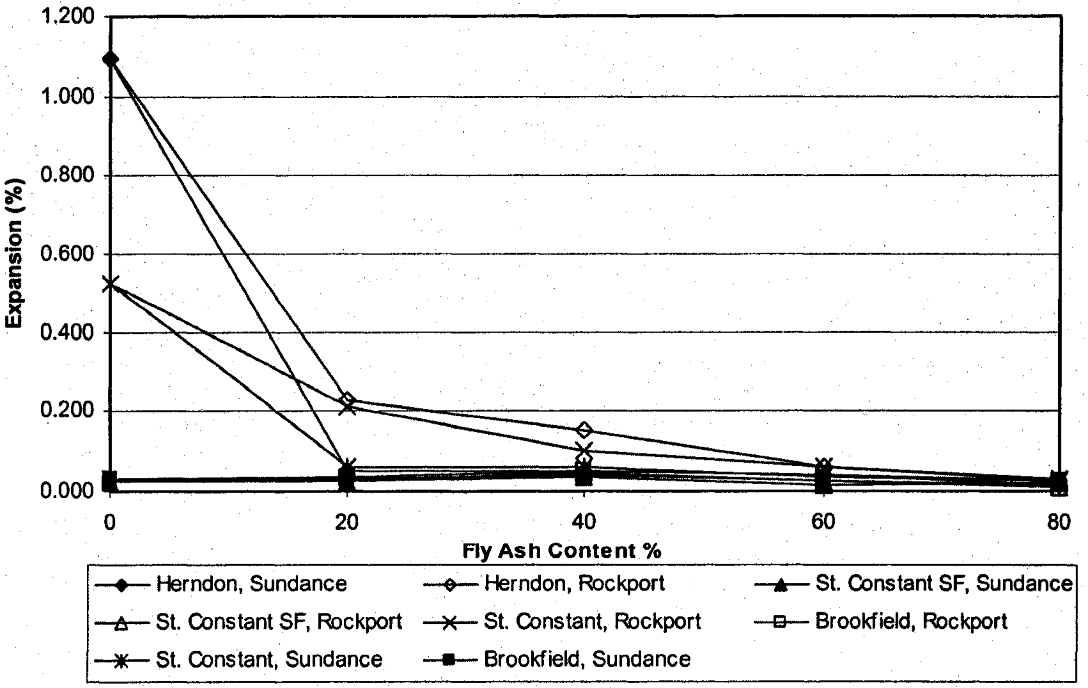


Figure 4.13: Expansion vs. Fly Ash % after 12 months

As mentioned in Table 3.1, the alumina content of St. Constant Portland cement and Herndon Portland cement is 8.8% and 7.1%, respectively. Although St. Constant GU cement has higher alumina content than Herndon cement, it performed better after one year of exposure when no fly ash replacement was utilized. That result does not correlate with the previous research where a correlation between the alumina content of cement and the resulted expansion was observed as mentioned in section 2.1.6.1. However, that is not unusual since there is no significant difference in the alumina content between the two cements. However, mixtures of St. Constant GU cement and Herndon cement showed similar performance under sulfate exposure when fly ash was incorporated at all replacement levels. Moreover, the alkalinity of cement did not affect the sulfate resistance since St. Constant GU cement which is high alkali cement of Na_2Oe at 0.86 performed better than Herndon although the latter has lower alkali content of Na_2Oe at 0.56.

The use of fly ash at 80% replacement levels proved to be very effective in controlling the expansion of mortars exposed to sulfate attack regardless of the type of cement and fly ash utilized. Comparing the expansion values shown in Table 4.1, it can be noticed that specimens of 80% fly ash replacement did not show major length change after the fourth week of exposure. All mixtures of 80% fly ash replacement showed expansion values of 0.01-0.03% after one year of exposure as shown in Figure 4.13. This extent of expansion can be considered as an excellent performance of mortars under such exposure condition. Mixtures of 60% fly ash replacement levels showed wider range of expansions (0.017-0.062 %); the resulting expansion was fairly low compared to the critical expansion which was 1.094%, but the effect of cement and fly ash type was more pronounced.

Mixtures without fly ash using Brookfield SF and St. Constant SF cements showed expansions of 0.033% and 0.025% respectively after one year of exposure whereas the corresponding values for plain mixtures containing Herndon and St. Constant were 0.124% and 0.190% respectively. This clearly demonstrates the effect of the silica fume blends on the sulfate resistance of mortar. However, the inclusion of fly ash in mixtures containing the silica fume blended cement marginally affected expansion. The maximum expansion occurred at 40% replacement. That can be interpreted due to the reduction of silica fume content in the cementing material with the increase in fly ash replacement. However, it was mentioned in section 2.4 that the optimum silica fume content in concrete and mortars to resist sulfate attack is 5-10%. Accordingly, incorporating replacement of silica fume blended cements used in this test for fly ash at levels 20% and 40% reduced the content of silica fume of mortars to levels much lower than 5% which dramatically limits the effect of silica fume in controlling expansion. Although the fly ash replacement increased the sulfate resistance of mortars, it did not compensate the effect of silica fume reduction on expansion except when high replacement levels were utilized. When high volume of fly ash at 80% replacement level was utilized, large consumption of alkali through pozzolanic reaction effectively limited formation of gypsum and controlled the expansion. Consequently, a minor reduction in expansion was observed in specimens containing silica fume blended cements with 80% fly ash replacement comparing with those without fly ash.

Table 4.1: Expansion over Time of All mixtures of 80% Fly Ash Replacement

Mixture		Expansion %							
Cement	**Fly Ash**	**4 W**	**8 W**	**13 W**	**15 W**	**4 M**	**6 M**	**9 M**	**12 M**
Herndon	**Sundance**	0.016	0.017	0.018	0.013	0.015	0.016	0.015	0.014
Herndon	**Rockport**	0.022	0.022	0.019	0.023	0.022	0.024	0.024	0.024
St. Constant SF	**Sundance**	0.009	0.009	0.009	0.009	0.008	0.010	0.014	0.020
St. Constant SF	**Rockport**	0.012	0.014	0.015	0.015	0.014	0.010	0.010	0.010
St. Constant GU	**Sundance**	0.017	0.016	0.019	0.020	0.020	0.023	0.023	0.024
St. Constant GU	**Rockport**	0.017	0.019	0.021	0.022	0.022	0.023	0.024	0.029
Brookfield	**Sundance**	0.011	0.014	0.013	0.014	0.015	0.015	0.014	0.016
Brookfield	**Rockport**	0.020	0.023	0.023	0.022	0.023	0.023	0.026	0.023

4.1.3. Visual Examination of Specimens

After every measurement, specimens were examined for any cracks or surface deposits. After one year of exposure, cracks were clearly observed in specimens made of plain Portland cements and in those made of Portland cements with 20% fly ash replacement.

First, the specimens made of plain Herndon GU exhibited very fine cracks starting after 4 months of exposure, which dramatically enhanced the expansion as a consequence of increasing exposure to the sulfate into the specimens. The cracks were longitudinal with the edges of specimens and developed with the expansion over time; they measured 0.2 mm and 0.4 mm after nine months and 12 months of exposure respectively. Second, specimens made of plain St. Constant did not show any visible cracks until 12 month of exposure when fine cracks were noticed. In addition, specimen made of Portland cements with 20% Rockport fly ash replacement showed fine cracks after one year of exposure.

4.1.4. Effect of Water to Cement Ratio

The required water-cement ratio for all mixtures containing only Portland cement for sulfate test is 0.485 in accordance with ASTM C 1012. The water requirement of mixtures containing fly ash is determined by measuring consistency of these mixtures; the proper w/c should develop a flow within ±5% of that of the Portland-cement mortar at a w/c of 0.485. However, all the mixtures in this test were made of w/c of 0.485. The water-cement ratio was kept constant in this test in order to determine the effect of fly ash incorporation in mortars on sulfate resistance with minimum variables involved. Consistency of all mixtures was measured using flow table in compliance with ASTM C 230 and the results are shown in Table 4.2. By comparing flow value, it can be clearly observed that incorporating fly ash in mortar dramatically increased the flow. The improvement in workability with the increase of fly ash replacement was also visually noticed while casting and molding the specimens. The effect of water to cement ratio on sulfate resistance was investigated by comparing two mixtures made of the same proportions of sand and cement but with lower water content. The two mixtures chosen for comparison were those the most and the least expansive. The w/c of those two batches were determined using a flow table; many batches of different w/c were cast and their corresponding flow readings were taken as shown in Table 4.3 , then by trial and error the required w/c could be determined.

Table 4.2: Flow values of all mixtures for sulfate test

Mixture		Flow% for each Replacement Level				
Cement	**Fly Ash**	**0%**	**20%**	**40%**	**60%**	**80%**
Herndon	Sundance	36	56	97	120	125
Herndon	Rockport	36	77	98	107	122
St. Constant SF	Sundance	53	68	89	112	131
St. Constant SF	Rockport	53	68	78	102	129
St. Constant	Sundance	18	53	80	91.3	122
St. Constant	Rockport	18	35	44	75	109.5
Brookfield	Sundance	20	58	63	78	100
Brookfield	Rockport	20	63	59	100	107

Table 4.3: Determining w/c of the comparison Samples

Mixture	St. Constant 10SF 0% fly ash	St. Constant 10SF 20% + Sundance fly ash 80%				Herndon 0% fly ash	Herndon 20% + Rockport fly ash 80%		
W/C	0.485	0.485	0.425	0.405	0.39	485	0.485	0.39	0.4
Flow (mm)	15.3	23.1	17.6	16.3	15.6 *	15.7	22.2	14.6	14.9 **

* - This value is 2% more than the flow value of the mixture made of 100% St. Constant 10SF cement which is acceptable according to ASTM C 1012

** - This value is 5% less of the flow value of the mixture made of 100% Herndon cement.

Figure 4.14.a shows the expansion versus time of two mixtures made of St. Constant SF cement and Sundance fly ash at 80% replacement level with different water to cementing material ratio. The expansion of mortars of 0.485 w/cm was very low; nevertheless, reducing w/cm to 0.390 was very effective since specimens showed no expansion after six month of exposure. Figure 4.14.b shows that reducing w/cm from 0.485 to 0.4 reduces sulfate related expansion from 0.024% to 0.01% after six months of exposure. It can be observed from both Figures that reducing w/c of mortar reduced the expansion by 58-100% and that specimens of lower w/cm didn't expand any further after 4 weeks of

exposure. Since the comparison was made between two mixtures of fly ash replacement level at 80% which experienced very low expansion even with w/cm of 0.485, the effect of reduction of the water content wasn't significant. For each mixture, the average expansion of four specimens is shown in Figure 4.14a. However, the variance in expansion between the four specimens of the low w/c mixture was within the 0.002%, whereas for the mixture of the regular w/c of 0.485 it was within 0.005%. Accordingly, the results confirms that utilizing low water cement ratio is effective in reducing sulfate-related expansion, and that can be interpreted by the effect of reducing water content on permeability and porosity of mortars.

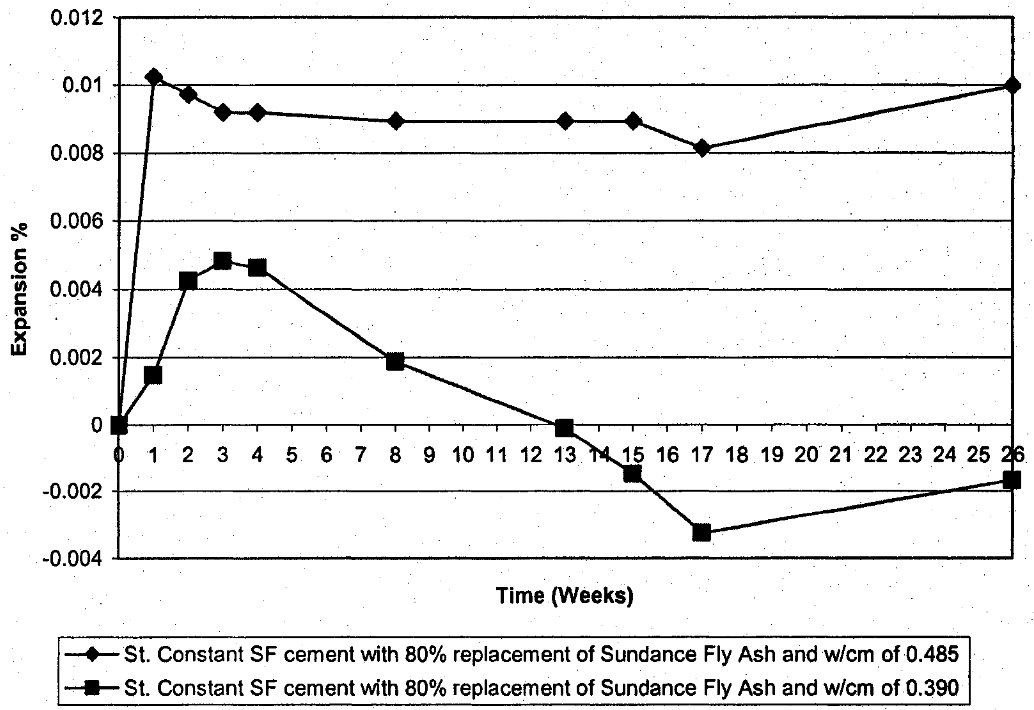


Figure 4.14.a: Effect of w/cm on Expansion

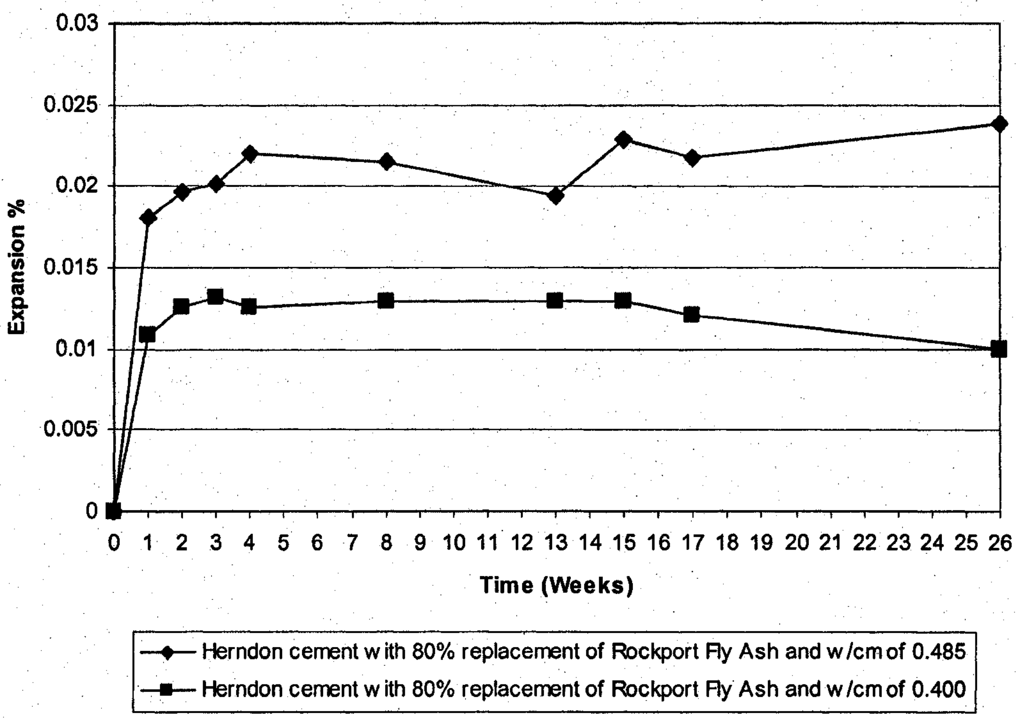


Figure 4.14.b: Effect of w/cm on Expansion

4.1.5. Compressive Strength Results

All of the mixtures had to be immersed in sulfate solution at the time they reached compressive strength of 20.0 ± 1.0 MPa as per ASTM C 1012 requirements. Accordingly, the strength gaining of the mortars were monitored by testing the compressive strength of two cubes at a time as mentioned in section 3.4.1. Strength development of all mixtures are shown in Figures 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4,21, and 4.22. For mixtures with no fly ash replacement, specimens reached 20.0 MPa within 30 hours of curing. All types of cement performed similarly within the first 30 hours; the presence of silica fume did not improve the early strength of mortars. Fly ash replacements at 20% did not significantly affect the strength development of mortars. All mixtures incorporating fly ash replacement at 20% reached the strength limit of 20 MPa within three days of curing. For fly ash replacement levels at 40%, the time at which the specimens reached the required strength varied from 3 to 10 days. Wider variation in the compressive strength results of all mixtures was observed when replacement levels at 60% and 80% were utilized. However, mixtures of 60% fly ash replacement reached the compressive strength of 20 MPa at maximum thirty days of curing, whereas mixtures of 80% replacement levels did not reach that limit even after 49 days of curing. Specimens of high volume fly ash replacement at 80% experienced extremely slow strength development mainly due to the low rate of hydration of fly ash at early ages [1]. The higher calcium content of Rockport fly ash did not result in a better compressive strength since any considerable difference between the performance of Sundance and Rockport fly ash was not observed. The reason of the similar performance of the two fly ashes is due to fact that fly ash contribution to the strength starts after several days and continues until at least one year as mentioned in section 2.4.3. Accordingly, at 28 days were the specimens were tested for compressive strength, the fly ash did not proceed far enough to contribute to the strength of mortars.

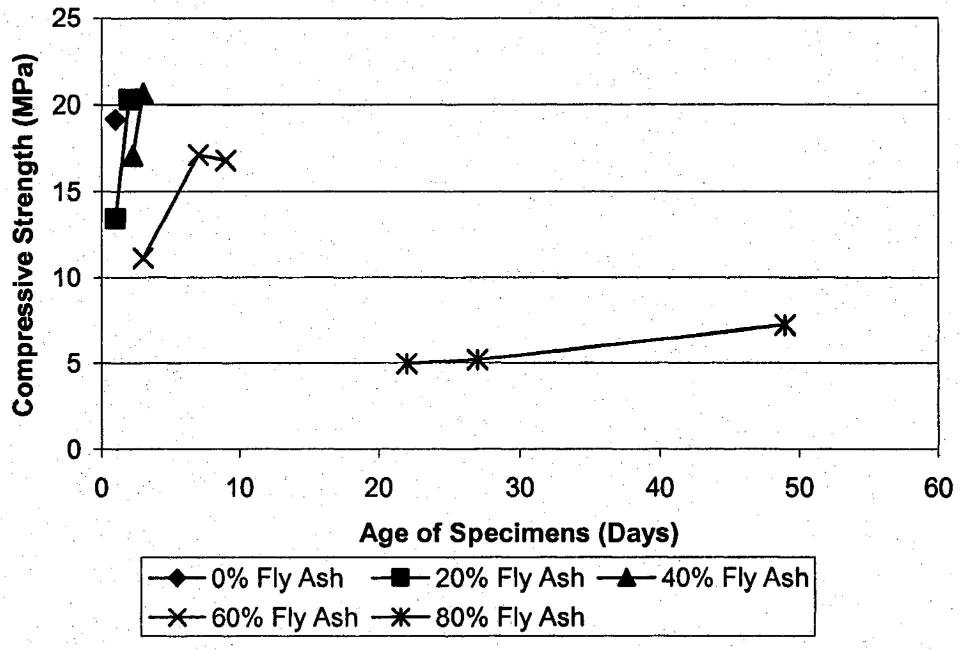


Figure 4.15: Strength Development of Mixtures of St. Constant with Rockport Fly Ash

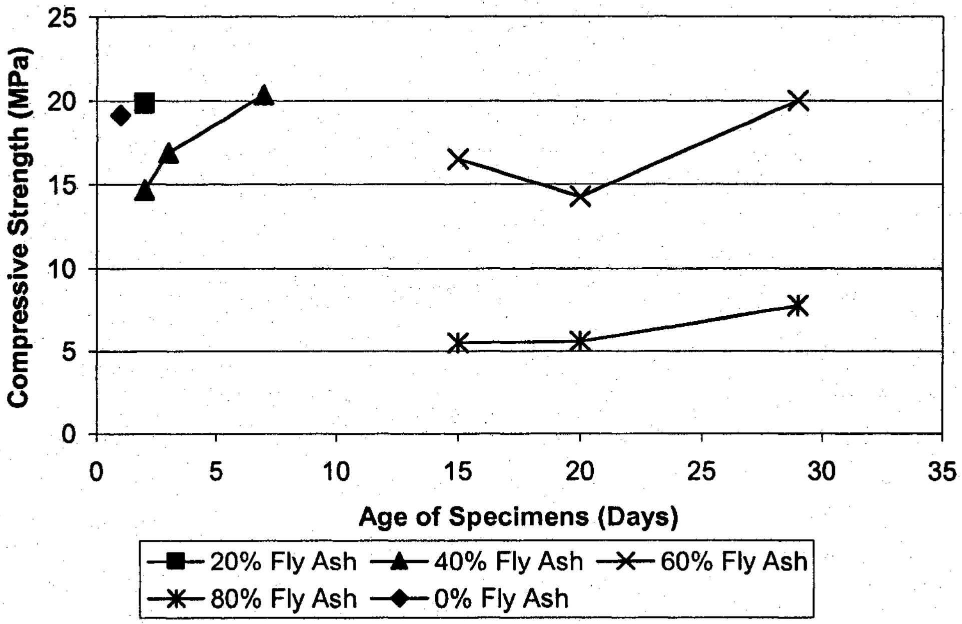


Figure 4.16: Strength Development of Mixtures of St. Constant with Sundance Fly Ash

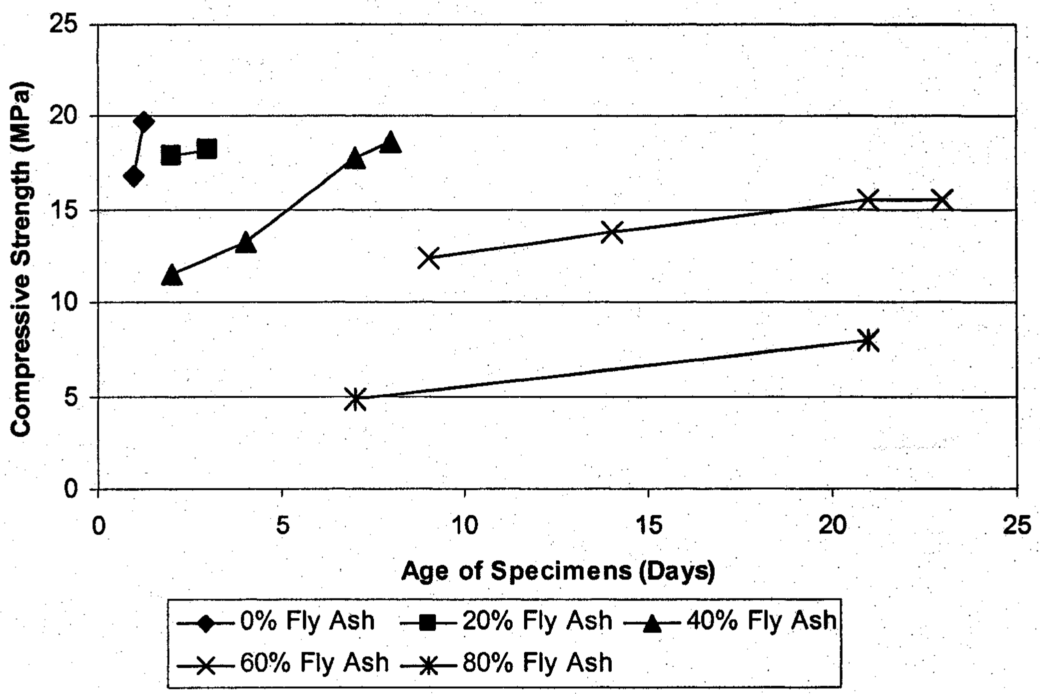


Figure 4.17: Strength Development of Mixtures of Brookfield SF with Rockport Fly Ash

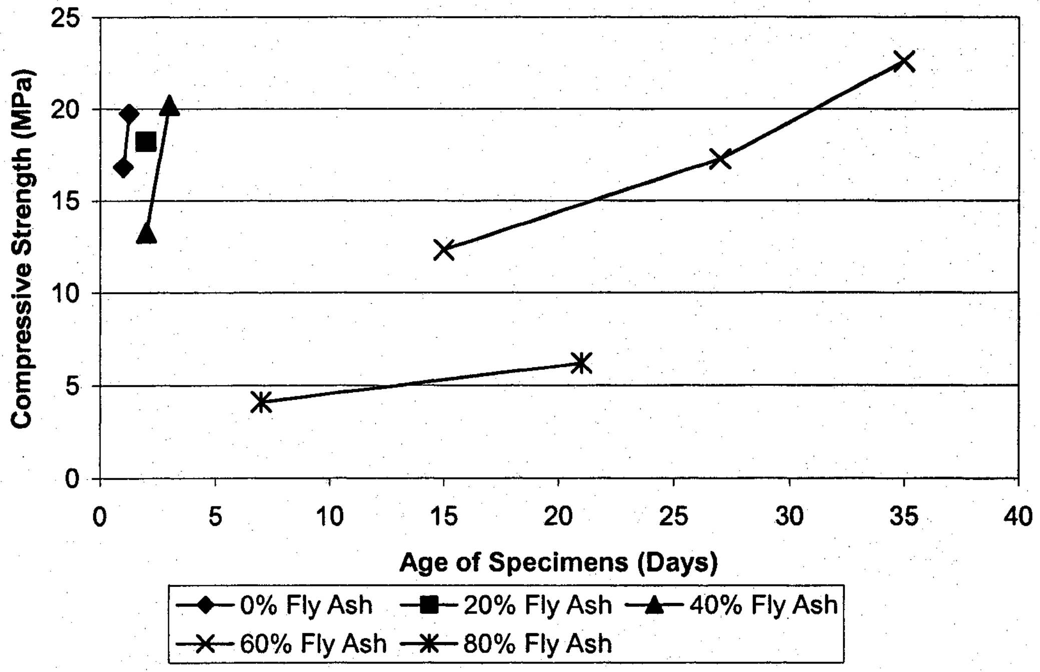


Figure 4.18: Strength Development of Mixtures of Brookfield SF with Sundance Fly Ash

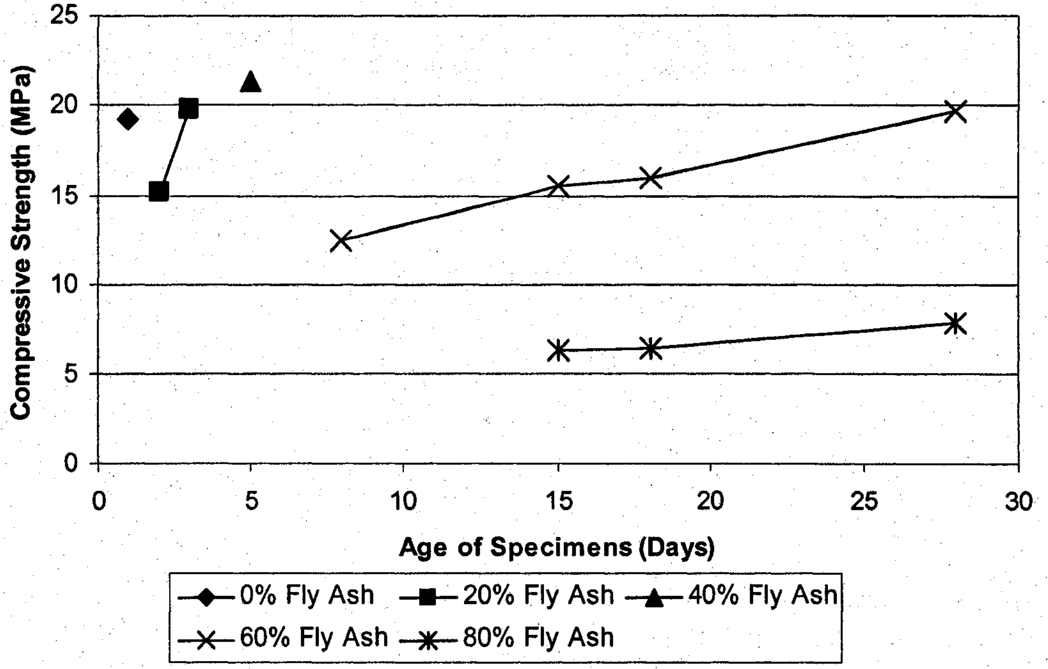


Figure 4.19: Strength Development of Mixtures of Herndon with Rockport Fly Ash

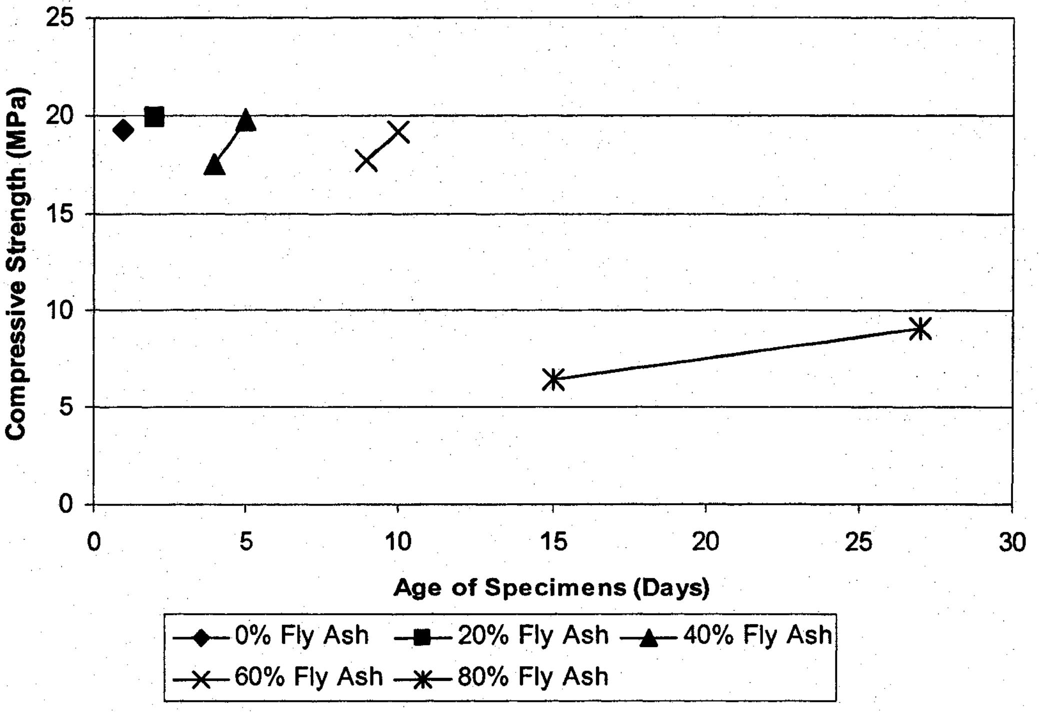


Figure 4.20: Strength Development of Mixtures of Herndon with Sundance Fly Ash

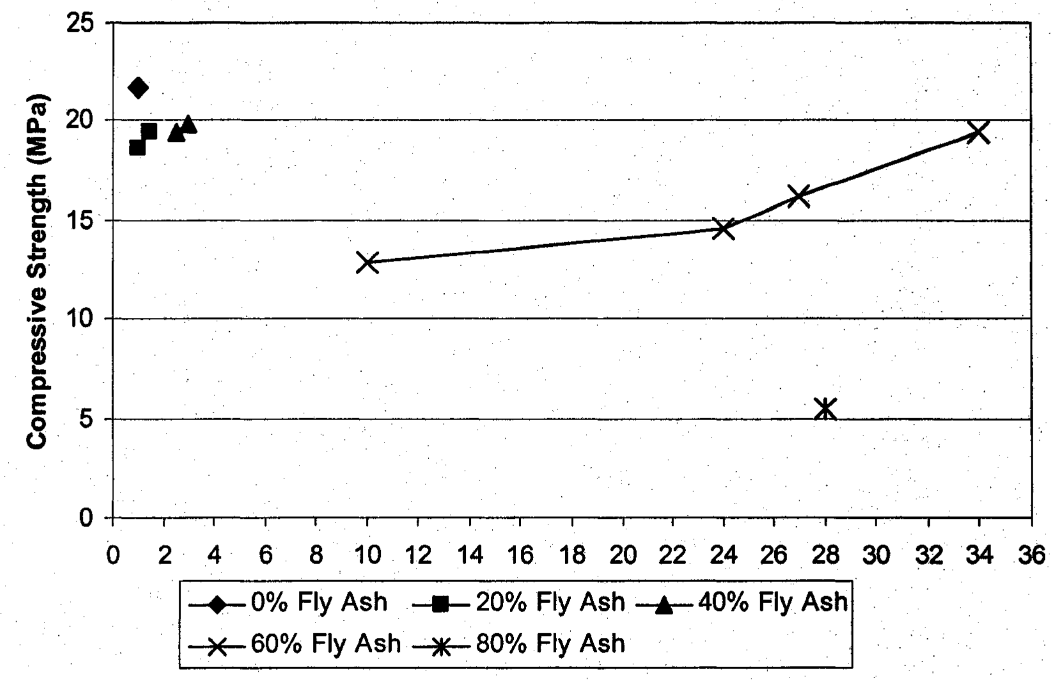


Figure 4.21: Strength Development of Mixtures of St. Constant SF with Rockport Fly Ash

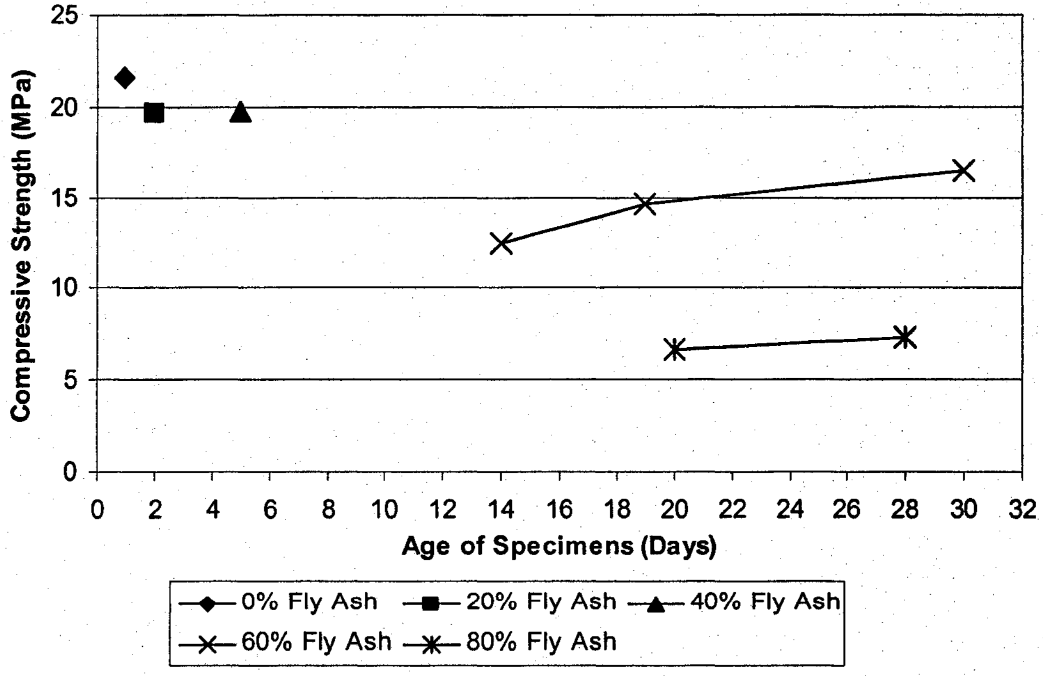


Figure 4.22: Strength Development of Mixtures of St. Constant SF with Sundance Fly Ash

4.1.6. Effect of Time of Immersion

All of the mixtures were immersed in sulfate solution at the time they reached compressive strength of 20.0 ± 1.0 MPa as mentioned in section 4.15. Consequently, mixtures were immersed in sulfate at different ages. Moreover, specimens of high volume fly ash content did not reach the required compressive strength even after 45 days of curing so they were immersed after 28 days in most cases; the time at which specimens were immersed in sulfate and their compressive strength at immersion time are shown in Table 4.4. Two mixtures of 80% fly ash content were cast and immersed in sulfate immediately after demolding in order to determine the effect of time of immersion the specimens in sulfate solution on expansion. Figures 4.23.a shows that after 26 weeks of exposure, Herndon-Rockport specimens immersed into sulfate solution immediately after demolding expanded 0.004% more than did the specimens immersed after reaching the strength limit of 20 MPa. Figure 4.23.b shows that the St. Constant SF-Sundance specimens immersed in sulfate solution immediately after demolding tended to expand a little higher than cured specimens after 15 weeks. After 30 weeks of exposure, specimens of the two mixtures show almost the same extent of expansion. After 9 months of, cured specimens experienced average expansion of 0.014%, whereas expansion of those which were directly immersed exposure was 0.011%. Consequently, time at which specimens were immersed in sulfate solution had a minor effect on the resulting expansion.

Table 4.4: Time of immersing in sulfate and compressive strength of specimens of sulfate test

Mixture		**Time of Immersing-Compressive Strength (Days-MPa)**				
Cement	Fly Ash	0%	20%	40%	60%	80%
Herndon	Sundance	1-19.25	2.75-19.86	5-19.75	10-19.13	27-9.07
Herndon	Rockport	1-19.25	3-19.71	5-21.26	28-19.62	28-7.92
St. Constant SF	Sundance	1-21.62	2-19.66	5-19.75	30-21.40	28-7.29
St. Constant SF	Rockport	1-21.62	1.5-19.39	3-19.84	34-19.48	28-5.48
St. Constant	Sundance	1-19.17	2-19.88	7-20.37	29-20.02	29-7.78
St. Constant	Rockport	1-19.17	2-20.33	3-20.64	9-16.81	49-7.21
Brookfield	Sundance	1.25-19.75	3-18.24	3-20.19	35-22.60	21-6.81
Brookfield	Rockport	1.25-19.75	3-18.90	8-18.68	23-15.48	21-7.91

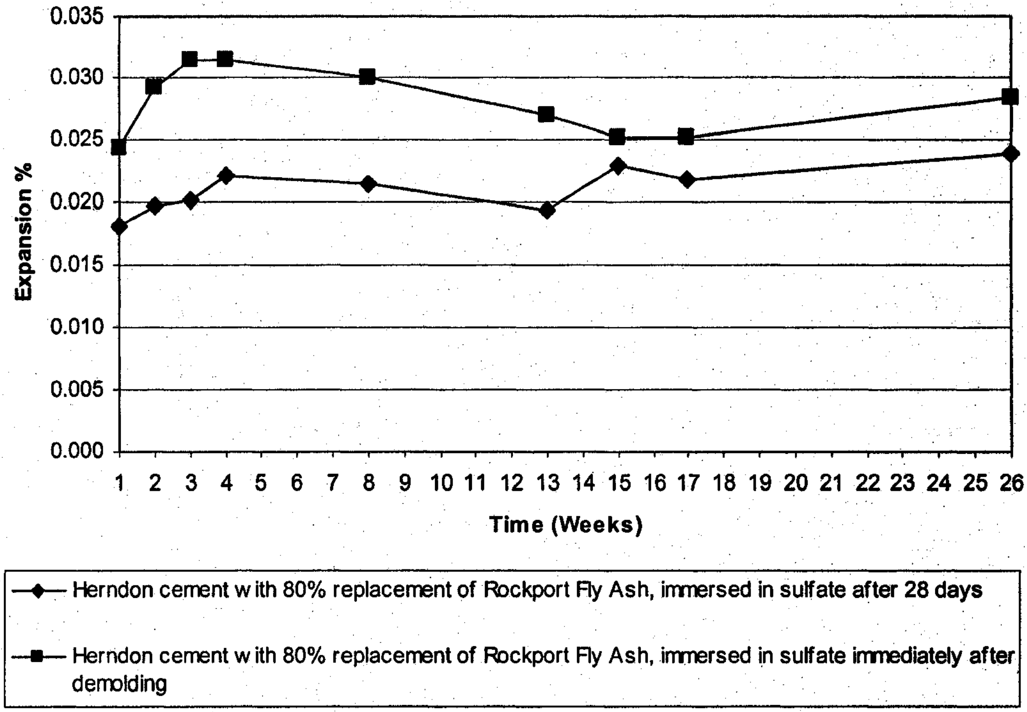


Figure 4.23.a: Effect of the Time of Immersing Specimens in Sulfate

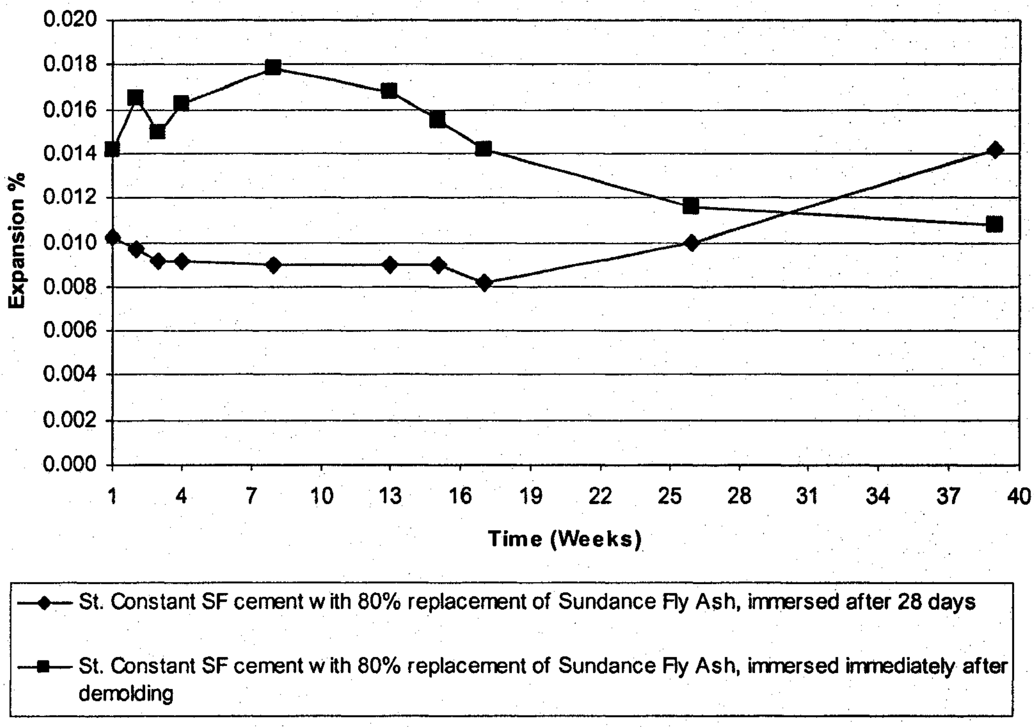


Figure 4.23.b: Effect of the Time of Immersing Specimens in Sulfate

4.2. Alkali Silica Reaction Test

Figures 4.24 to 4.31 show the expansion versus time of all the mixtures tested for potential alkali-silica reactivity in aggregates; each figure represents one combination of cement and fly ash at all tested replacement levels. Each point represents the average of the three bars measured. On each graph the CSA A 3000 expansion limit of 0.10% at 14 days is indicated by a bold line. It can be observed that the amount and rate of expansion are related to both cement and fly ash type as well as percent of fly ash replacement. It can be also noticed that the ASR-related expansion is more sensitive to the cement type used than the fly ash type as shown in Figure 4.32. The effect of fly ash type on expansion was influential at replacement levels 20% and 40%. All mixtures without fly ash experienced rapid expansion; no cracks were observed within the 14 days period of the test. However, incorporation of fly ash in mortar as a partial replacement proved to be very effective in controlling ASR-related expansion. The effect of fly ash in reducing expansion was more pronounced when Sundance fly ash was utilized although it contains higher alkali content than Rockport fly ash. The reason why Sundance fly ash performed better than Rockport fly ash is mainly the higher calcium content of the latter. Moreover, the lower MgO content of Sundance fly ash may also have contributed in improving its performance in controlling the ASR- related expansion. For high replacement levels, no significant difference in performance between the two types of fly ash was observed.

Replacement levels of Sundance fly ash at 20% was effective in maintaining expansion of specimens at 14 days less than the current Canadian limit of 0.10% with all types of cement utilized. All of the 4 cements investigated experienced expansion in excess of the allowable limit. It can be concluded from these results that use of blended silica fume cements (at 7% SF) is not suitable for mixtures with highly reactive aggregate such as Spratt. As the fly ash replacement levels increased, the rate and amount of expansion decreased with all types of cement and fly ash utilized. The use of fly ash at 40% replacement level resulted in expansion ranged from 0.014% to 0.062 %; higher replacement level at 60% reduced the expansion to 0.004-0.023 %. For all types of cement and fly ash utilized in this test, replacement of cement for fly ash at 80% was effective in suppressing the ASR related expansion; specimen of fly ash at 80% replacement levels experienced marginal differences of expansion ranged from -0.004% to 0.006% after 14 days of exposure. The effect of the increasing of fly ash replacement level on controlling the ASR-related expansion is shown in Figure 4.32. The use of Rockport fly ash at replacement level of 80% with Herndon cement reduced the expansion at 14 days from 0.412% in the plain specimens to 0.003%.

The dramatic effect of fly ash in reducing expansion resulting from alkali silica reaction was mainly due the reduction of permeability of mortars resulting from the presence of unhydrated fly ash particles which behaved as fine aggregates filling the voids in the mortar [1]. In addition, replacement of cement by fly ash reduced the cement content in concrete and consequently diluted concrete alkalinity resulting from cement hydration; thus, mitigating alkali-silica reaction and reducing the resulting expansion. Moreover, the pozzolanic reaction of fly ash was enhanced as a consequence of the high temperature of exposure at 80° C in compliance with ASTM C 1260; thus, consumed the alkali and reduced the pH of the pore fluid.

The maximum expansion occurred when Herndon cement was used with no fly ash replacement. The two Type GU cements used in this test performed differently in the plain mixtures, but with the increase of fly ash replacements the variance decreased. The reported expansion after 14 days of specimens made of plain St. Constant and Herndon cements were 0.324% and 0.412% respectively. The difference in expansion is mainly due to the higher content of MgO of the latter. Moreover, Figures 4.26, 4.27, 4.30, and 4.31 show that although the total expansion experienced by the cements containing blended silica fume were less than those without, the expansion at 14 days exceeded the Canadian limit of 0.10% when fly ash was not incorporated. This indicates that silica fume alone is insufficient to reduce expansions to acceptable levels with highly reactive aggregate. However, the combination of silica fume and fly ash in mortars was very effective in controlling the alkali-silica reaction. For mixtures containing silica fume blended cement, 20% of fly ash replacement was sufficient to maintain the ASR-related expansion below the 14 days expansion limit of 0.1%. Thus, agree with the previous research results as mentioned in section 2.5.4. For all mixtures, fly ash replacement level at 20% dramatically decreased the expansion of specimens; higher replacement levels further reduced the resulting expansion. This result supports the commonly held recommendations of the use of fly ash in concrete. The results of this test are in agreement with previous research results that suggested the use of replacement levels at 20% - 35% of low calcium fly ash are recommended to control ASR expansion in concrete As mentioned in section 2.3.6. However, higher range 20% - 60% of medium calcium fly ash used in this test can be recommended to effectively control the alkali-silica reaction in mortars.

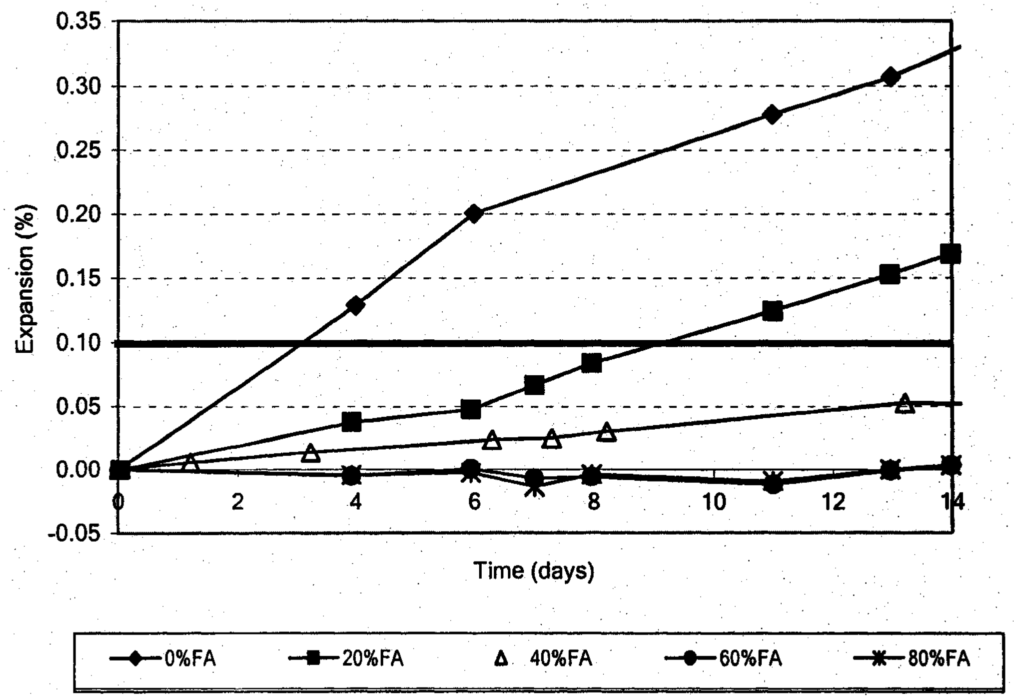


Figure 4.24: Expansion versus Time of Mixtures of St. Constant GU with Rockport Fly Ash

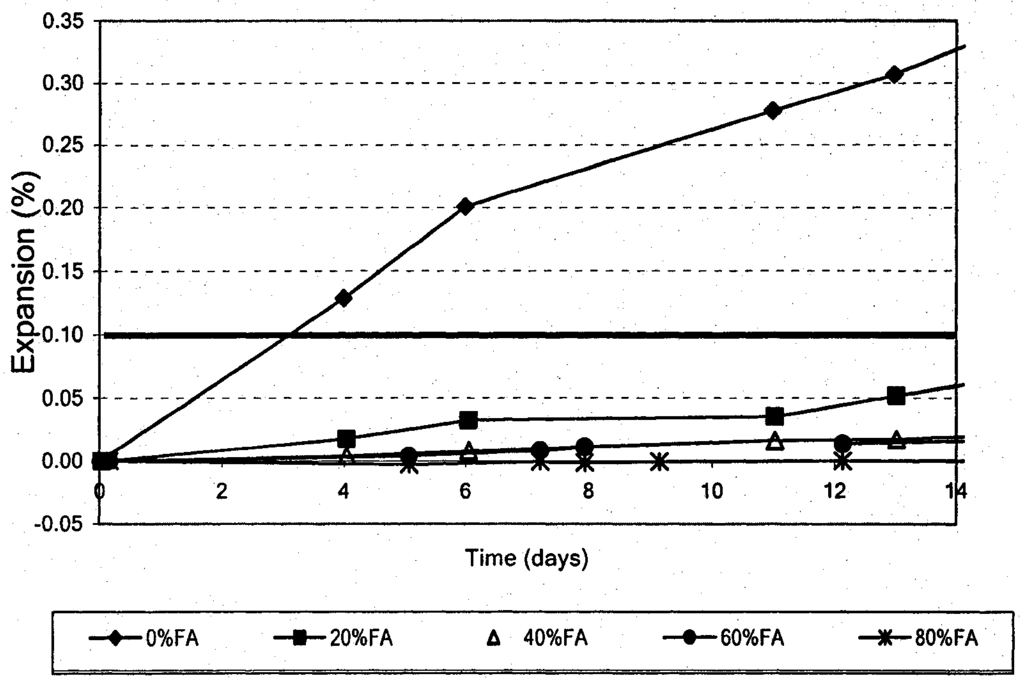


Figure 4.25: Expansion versus Time of Mixtures of St. Constant GU with Sundance Fly Ash

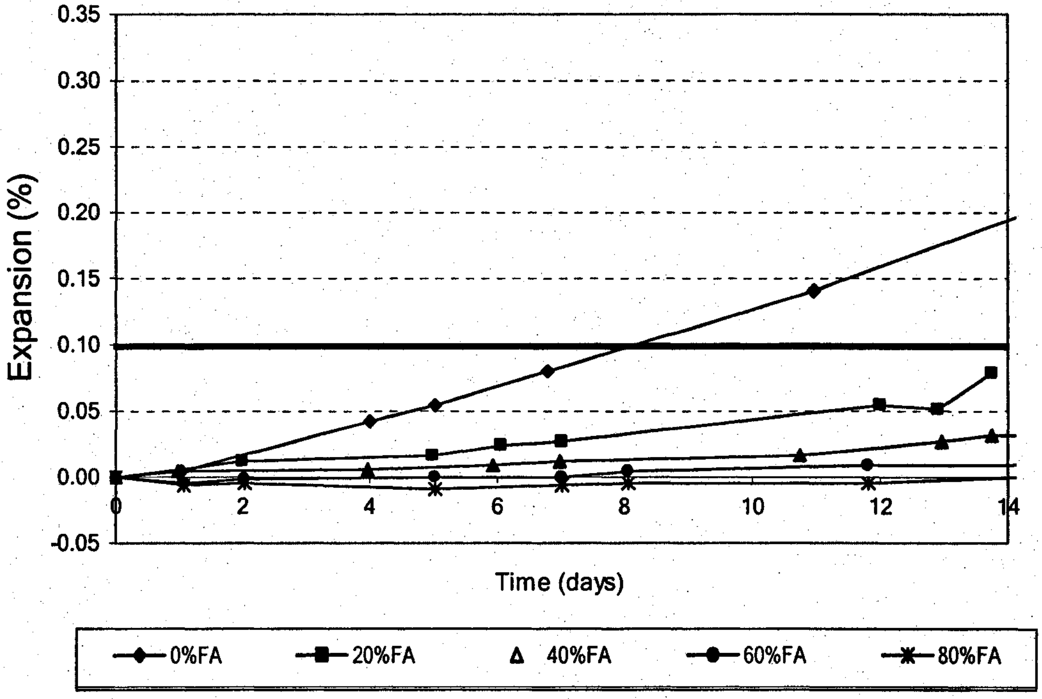


Figure 4.26: Expansion versus Time of Mixtures of Brookfield with Rockport Fly Ash

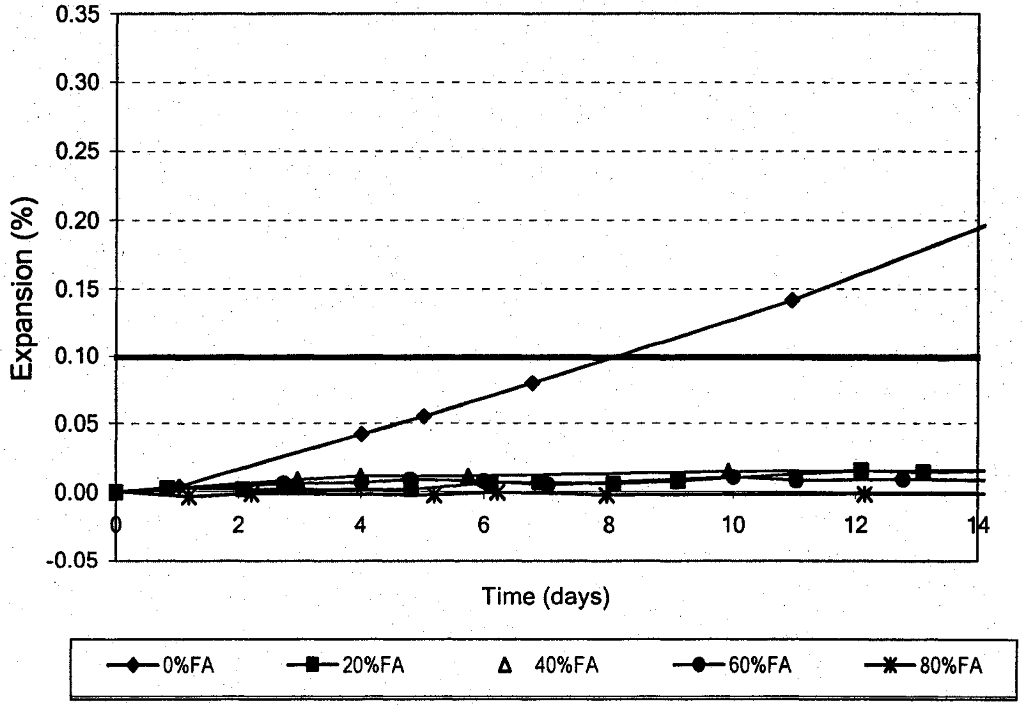


Figure 4.27: Expansion versus Time of Mixtures of Brookfield with Sundance Fly Ash

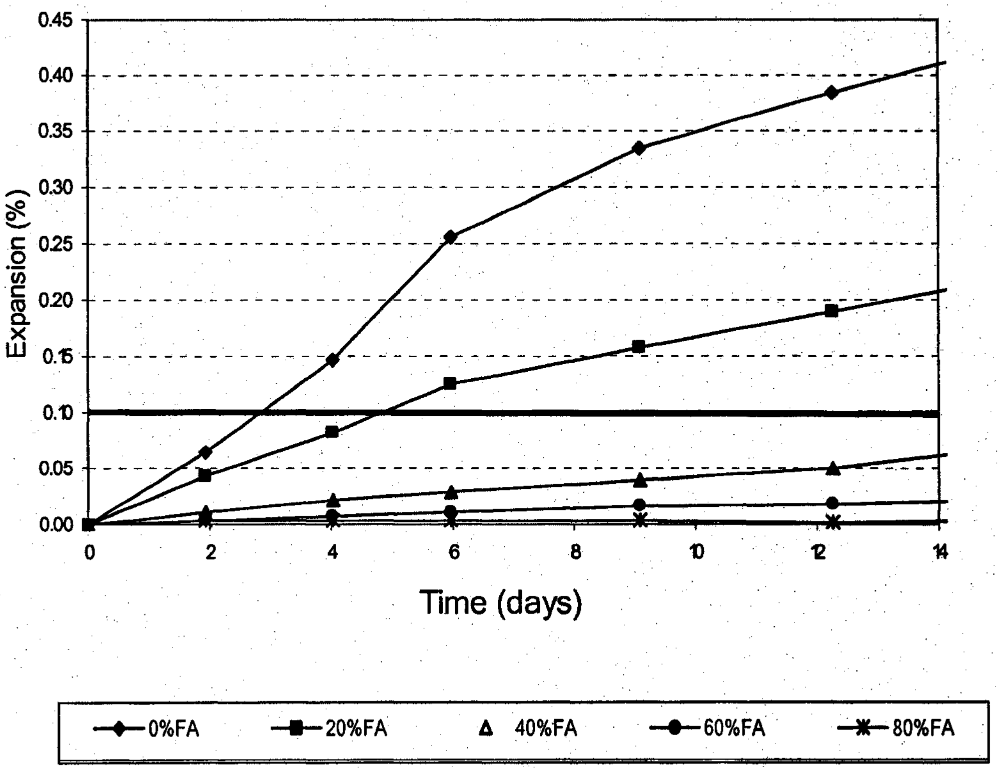


Figure 4.28: Expansion versus Time of Mixtures of Herndon with Rockport Fly Ash

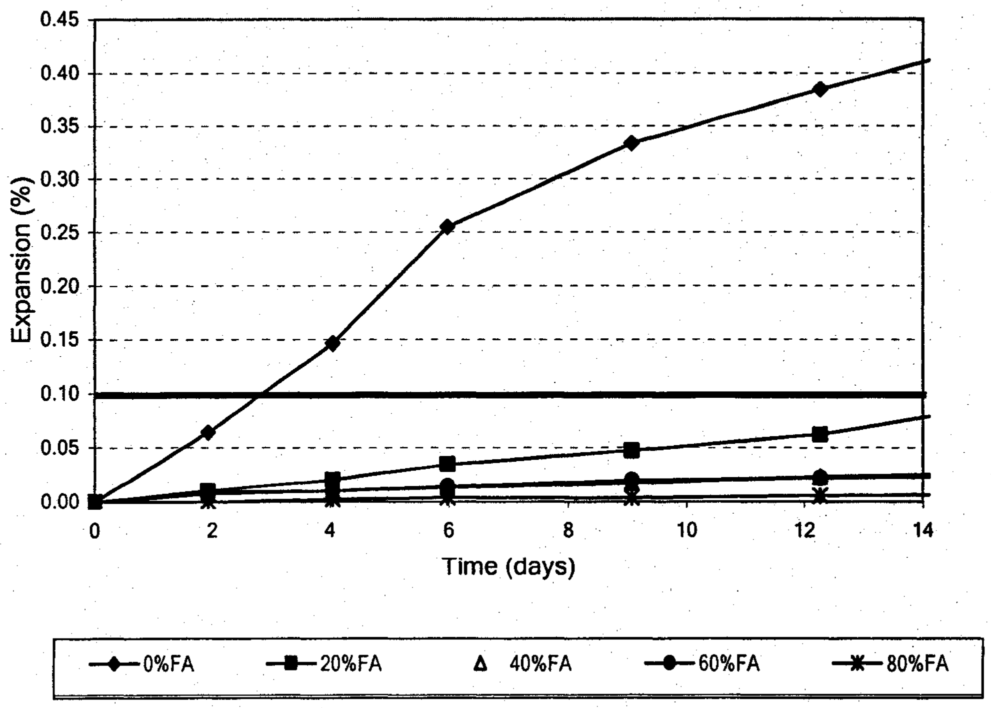


Figure 4.29: Expansion versus Time of Mixtures of Herndon with Sundance Fly Ash

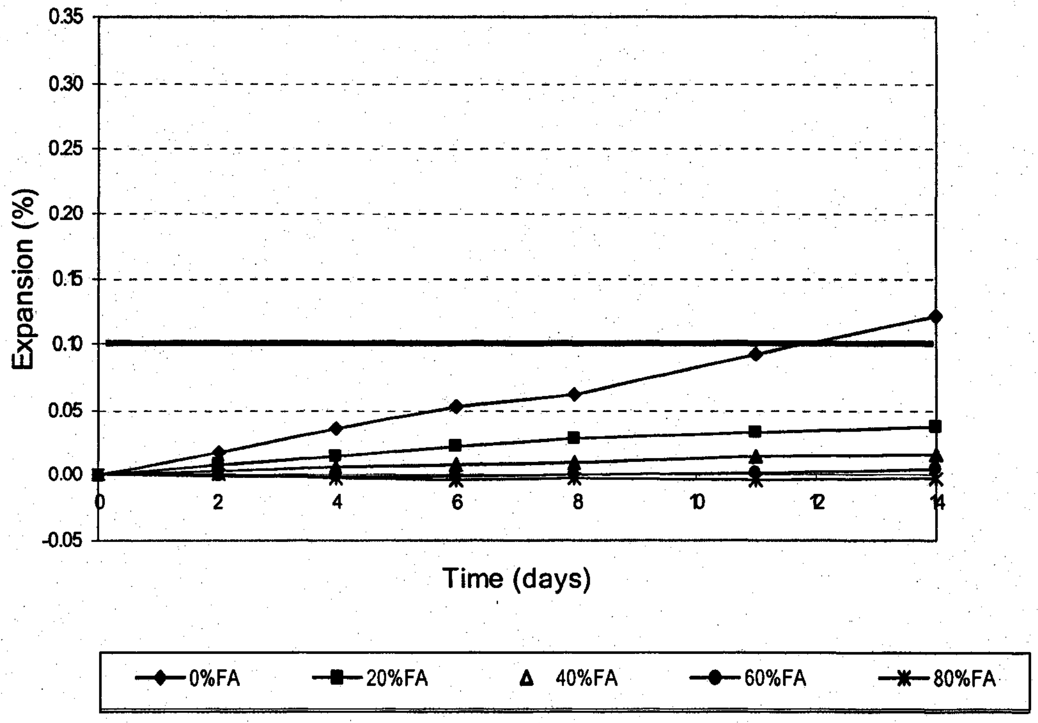


Figure 4.30: Expansion versus Time of Mixtures of St. Constant SF with Rockport Fly Ash

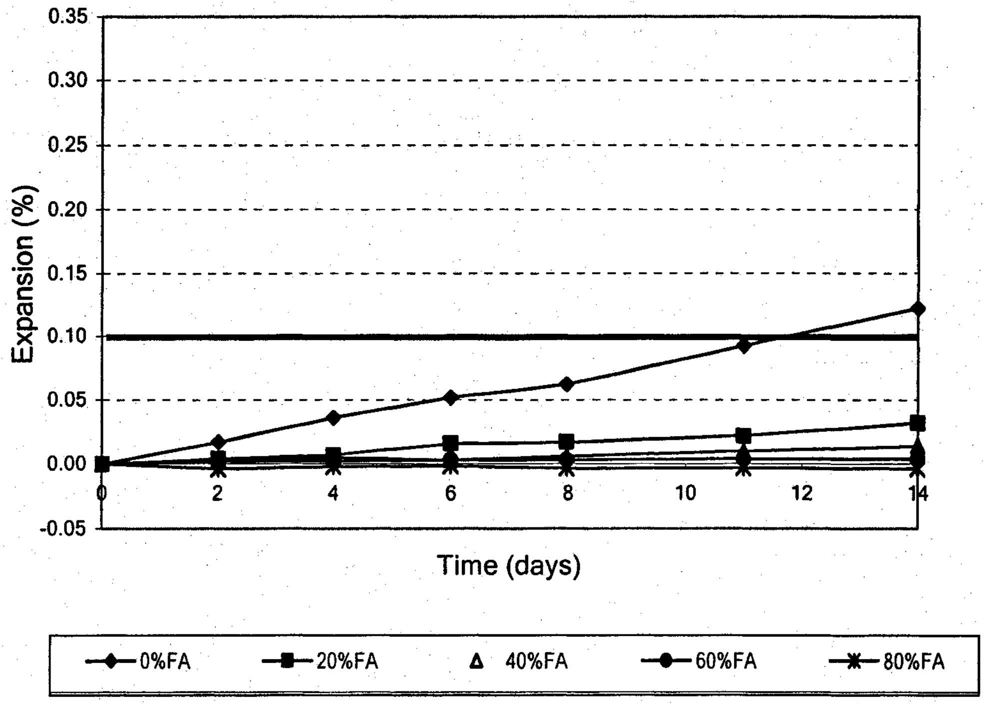


Figure 4.31: Expansion versus Time of Mixtures of St. Constant SF with Sundance Fly Ash

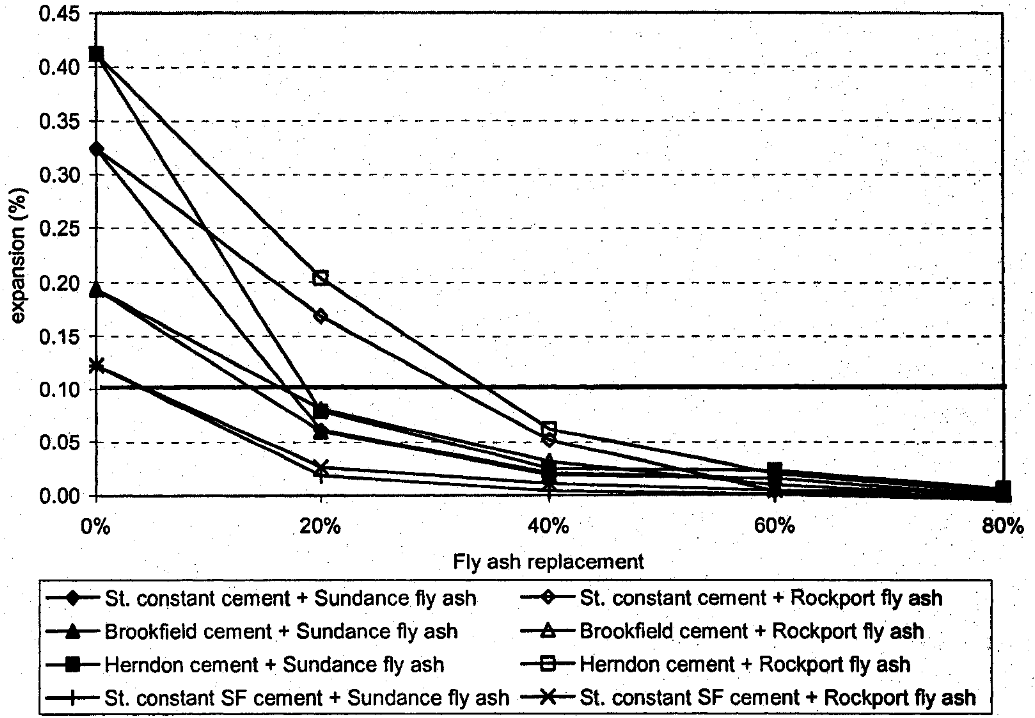


Figure 4.32: Expansion vs. Fly Ash % after 14 days in the ASR Test

4.3. Possible Sources of Errors

Some minor errors could have occurred through the testing process; however, it is thought that these errors were not so severe that they jeopardized the test results. In sulfate resistance test, curing time of specimens until they reached the required 20MPa prior to immersion in sulfate varied widely depending on the fly ash content. Accordingly, the effect of inconsistency in curing time on the expansion was investigated and found to be insignificant as discussed in section 4.1.5. In the sulfate resistance test, for mixture of St. Constant GU cement with Rockport fly ash at 60% and mixture of Brookfield cement with Rockport fly ash at 60%, one of the four bars made for the C 1012 test experienced unusual expansion or much less expansion than the other bars, the comparator readings taken for that bar were ignored and the average reading of the other three bars were considered. For Alkali-Silica reaction test, all specimens were dried and measured within 15± 5 s in compliance with ASTM C1260. Nevertheless, slight errors could have happened in the length change measurement due to the five seconds tolerance for the time of the drying and measuring process. However, the effect of those errors on test results can be ignored since three bars of each mixture were measured and no inconsistency in the result of the three bars was found.

5. Conclusions

Based on the test results the following conclusions can be drawn:

1. Mixtures containing cements with blended silica fume showed considerably less expansion than mixtures of normal Portland cements in both sulfate resistance and ASR tests mainly due to silica fume's effect in alkali reduction and decreasing microporosity and permeability.

2. It was clearly noticed that the increased use of fly ash replacement controlled the alkali-silica reaction in all the mixtures and reduced the resulting expansion. The adequate levels of replacement of Sundance and Rockport fly ash at which expansion did not exceed the limit of 0.1% at 14 days were 20% and 40% respectively. In addition, it dramatically increased resistance to sulfate attack when normal Portland cements where utilized.

3. In the mixtures containing silica fume blended cements, the fly ash replacement did not considerably improve the sulfate resistance of specimens; they already showed a very low expansion without any replacement. Incorporating fly ash in mortars with silica fume blended cement may have a slight negative effect on sulfate resistance when utilized at replacement level of around 40% where the expansion of specimens of silica fume blended cements slightly increased.

4. For all replacement levels, Sundance fly ash performed better than Rockport fly ash in both sulfate resistance and ASR tests due to its lower calcium content.

5. In both tests, the major expansion reduction occurred with fly ash replacement levels between 0% and 20% mainly due to the permeability reduction of specimens. Higher replacement levels may not decrease the permeability much further.

6. In the ASR test, the higher the fly ash content in mixtures the lower the resulting expansion which mainly results from reducing the porosity of the mortars. Accordingly, high replacement levels of fly ash are recommended when highly reactive aggregates are used taking into account to reach the required strength.

7. Replacement of cement for Sundance fly ash at 20% replacement level is considered an adequate replacement level for high sulfate resistance. Higher replacement levels of Rockport fly ash up to 40% should be considered to increase sulfate resistance of mortars made of normal Portland cement to meet the moderate sulfate resistant cement requirements. Higher replacement levels do not markedly reduce expansion, but may dramatically reduce the early strength of the mixtures.

8. For fly ashes of calcium content less than 11%, replacement level at 20% is effective in controlling sulfate related expansion. For fly ashes of higher calcium content, higher replacement levels should be considered.

9. Fly ash replacement levels at 80% proved to be very effective in suppressing expansion of mortars exposed to sulfate attack or in case of the use of highly reactive aggregates with all types of cements and fly ash utilized.

10. ASR-related expansion is more sensitive to the type of cement used than the type of fly ash.

11. The use of low water to cement ratio increases the sulfate resistance of mortars of fly ash at 80% replacement level.

12. Incorporating fly ash in mortar dramatically increases its workability and reduces its water requirement.

13. The time at which specimens are immersed in exposure solution has a minor effect on the long term sulfate-related expansion; it may slightly increase or decrease the expansion.

14. Fly ash replacement level of 20% slightly reduced the early strength of mortars, a compressive strength of 20 MPa was reached after maximum 3 days of curing. However, higher replacement levels dramatically reduced the early strength; mixtures of 80% fly ash replacement did not reach the 20 MPa limit after 28 days of curing.

6. Recommendations

1. Mixtures of low water to cementing materials ratio have performed markedly well in terms of sulfate resistance. It is suggested that lower w/c than 0.4 should be investigated for sulfate resistance for several fly ash replacement levels considering using superplasticizers to maintain adequate workability of the mixtures.

2. Mixtures of 80% fly ash replacements showed excellent performance in sulfate resistance test. However, exposure of specimens to higher sulfate concentrations can be considerable approach in future studies to investigate the effect of sulfate solution concentrations on sulfate resistance of high volume fly ash mortars.

3. Since the expansion of mortars of 80% fly ash replacement tested in this research was very low regardless the time of immersing, investigating the effect of the time of immersing in sulfate on sulfate resistance of mortars of low fly ash content should be considered in future studies.

4. Since low early strength mortar and concrete is a major concern when fly ash is used, strength gaining of fly ash mortars of low w/c should be researched with the use of superplasticizers. The effect of curing temperature on the strength gaining and sulfate resistance of mortars incorporating fly ash replacements should be studied; the optimum curing conditions should be addressed.

5. In future studies, mortars of silica fume blends at 10% and fly ash replacement at 80% should be investigated; they are expected to yield in acceptable early compressive strength and excellent sulfate resistance.

6. Sulfate resistance and alkali-silica reactivity of mortars incorporating high CaO fly ash at 60% - 80% replacement levels should be investigated since high calcium fly ash has better effect on strength gaining than low calcium fly ash.

7. Other deterioration mechanisms should be investigated in high volume fly ash mixtures. Chloride resistance, deicer salt scaling resistance and freezing and thawing resistance should be investigated.

7. References

1. Malhotra, V. M., and Mehta, P. K. "High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories" Supplementary Cementing Materials for Sustainable Development Inc., Second Edition, Supplementary Cementing Materials for Sustainable Development Inc., Ottawa. 2005.

2. Malhotra, V. M. "Making Concrete Greener with Fly Ash"; Concrete International, V. 21, No. 5: 61-66, May 1999.

3. Mehta, P. K. "Concrete Technology for Sustainable Development"; Concrete International, V. 21, No. 11: 47-53, Nov 1999.

4. Detwiler, Rachel J., Bhatty, Javed I., and Bhattacharja S.; "Supplementary Cementing Materials for Use in Blended Cements" Research and Development Bulletin, RD112; Portland Cement Association, 1996.

5. Mehta, P. K. and Monteiro, P. J. M. "Concrete: Structure, Properties, and Materials" Prentice Hall, New Jersey, 1993.

6. Skalny, J., Marchand, J. and Older, I. "Sulfate Attack on Concrete" Spon Press. New York USA, 2002.

7. Malhotra, V. M., and Ramezanianpour, A. A. "Fly Ash in Concrete" CANMET, Ottawa, ON, Canada. Second Edition 1994.

8. Johansen, V. and Thaulow, N. "Heat Curing and Late Formation of Ettringite" ACI International SP177, Ettringite: The Sometimes Host of Destruction: 47-64, 1999.

9. Bye, G. C. "Portland Cement - Composition, Production, and Properties," Thomas Telford Limited, London, 1999.

10. Kosmatka, S., Kerkhoff, B., Panarese, W., MacLoed, N., and Mcgrath, R. "Design and Control of Concrete Mixtures," 7th Canadian Edition, Portland Cement Association, Ottawa, 2002.

11. Lawrence, C. D. "Long-Term Expansion of Mortars and Concretes" ACI International, SP 177, Ettringite: The Sometimes Host of Destruction: 105-123, 1999.

12. Hobbs, D. W. "Expansion and Cracking in Concrete Associated with Delayed Ettringite Formation" ACI International, SP 177, Ettringite: The Sometimes Host of Destruction: 159-182, 1999.

13. Cohen, M. D., and Mather, B. "Sulfate Attack on Concrete – Research Needs" *ACI Material Journal*, V. 88, No. 1: 62-69. 1991.

14. Mehta, P. K. "Mechanism of Sulfate Attack on Portland Cement Concrete – Another Look" *Cement and Concrete Research*, V. 13, pp. 401-406, 1983.

15. Canadian Standards Association. "Concrete Materials and Methods of Construction." A23, CSA, Toronto ON, Canada. 2000.

16. American Concrete Institute "Guide to Durable Concrete" ACI 201.2R-01. Farmington Hills, MI, USA. 2001.

17. Mehta, P.K., "Sulfate Attack on Concrete - A Critical Review", *Materials Science of Concrete III*, Ed. J. Skalny, The American Ceramic Society, Westerville, OH, 1992: 105-130.

18. Lawrence, C. D., "Influence of Binder Type on Sulfate Resistance" *Cement and Concrete Research*. V. 22, no. 6: 1047-1058. 1992.

19. Raymar, K. and Inan, G. "Sodium Sulfate Attack on Plain and Blended Cements" *Building and Environment*, V. 42: 1368-1372, 2007.

20. Al-Dulaijan, S. U., Maslehuddin, M., Al-Zahrani, M. M., Sharif, A. M., Shameem, M., Ibrahim, M. " Sulfate Resistance of Plain and Blended Cements Exposed to Varying Concentrations of Sodium Sulfate" *Cement & Concrete Composites*, V. 25: 429-437, 2003.

21. Santhanam, M., Cohen, M. D., and Olek, J. "Modeling the Effect of Solution Temperature and Concentration during Sulfate Attack on Cement Mortars" *Cement and Concrete Research*, V. 32: 585-592, 2002.

22. Santhanam, M., Cohen, M. D., and Olek, J. "Mechanism of Sulfate Attack: A Fresh Look – Part 2: Proposed Mechanisms." *Cement and Concrete Research*, V. 33: 341-346. 2003.

23. Akoz, F., Turker, F., Koral, S., and Yuzer, N. "Effects of Sodium Sulfate Concentration on the Sulfate Resistance of Mortars with and without Silica Fume." *Cement and Concrete Research*, V. 25, No. 6: 1360-1368. 1995.

24. Gallop, R. S. and Taylor, H. F. W. "Sulfate Resisting Portland Cement: Reaction with Sodium and Magnesium Sulfate Solutions" Cement *and Concrete Research*, V. 25: 1581-1590. 1995.

25. Santhanam, M., Cohen, M. D., and Olek, J. "Mechanism of Sulfate Attack: A Fresh Look – Part 1: Summary of Experimental Results" *Cement and Concrete Research*, V. 32: 915-921, 2002.

26. Akoz, F., Turker, F., Koral, S., and Yuzer, N. "Effects of Raised Temperature of Sulfate Solutions on Sulfate Resistance of Mortars with and without Silica Fume." *Cement and Concrete Research*, V. 29, No. 4: 537-544. 1999.

27. Paglia, C., Wombacher, F., and Bohni, H. "The Influence of Alkali-Free and Alkaline Shotcrete Accelerators within Cement Systems – Influence of The Temperature on The Sulfate Attack Mechanisms and Damage" *Cement and Concrete Research*, V. 33: 387-395, 2003.

28. Brown, P.W. "An Evaluation of The Sulfate Resistance of Cement in a Controlled Environment." *Cement and Concrete Research* V. 11: 719-727. 1981.

29. Ferraris, C. F., Clifton, J. R., Stutzman, P. E., and Garboczi, E.J. "Mechanism of Degradation of Portland Cement-Based Systems by Sulfate Attack" Materials Research Society's Symposium on Mechanisms of Chemical Degradation of Cement-Based Systems: 185-192, E & FN Spon. London UK. 1997.

30. Khatri, R. P., Sirivivatnanon, V., and Yang, J. L. "Role of Permeability in Sulfate Attack" *Cement and Concrete Research*, V. 27, No. 8: 1179-1189, 1997.

31. Young, J.F., Mindess, S., Gray, R.J., and Bentur, A. "The Science and Technology of Civil Engineering Materials" Prentice Hall; New Jersey, USA, 1998.

32. Al-Amoudi, O. S. B. "Attack on Plain and Blended Cements Exposed to Aggressive Sulfate Environments" *Cement Concrete and Research*, V. 24: 305-316, 2002.

33. Rasheeduzzafar "Influence of Cement Composition on Concrete Durability" *ACI Materials Journal*, V. 89, No. 6: 574-586, November-December 1992.

34. Monteiro, J. M. and Kurtis, K. E. "Time to Failure for Concrete Exposed to Severe Sulfate Attack" *Cement and Concrete Research* V. 33: 987-993, 2003.

35. Rasheeduzzafar, Al-Amoudi, O. S. B., Alduljawad, S. N., and Maslehuddin, M. "Magnesium- Sodium Sulfate Attack in Plain and Blended Cements" *Journal of Materials in Civil Engineering*, 6(2): 201-222, 1994.

36. Naik, N. N., Jupe, A. C., Stock, S. R., Wilkinson, A. P., Lee, P. L., and Kurtis, K. E. " Sulfate Attack Monitored by Micro CT and EDXRD: Influence of Cement Type, Water-to- Cement Ratio, and Aggregate" *Cement and Concrete Research*, V. 36: 144-159, 2006.

37. Irassar, E. F., Gonzalez, M., and Rahhal, V. "Sulfate Resistance of type V Cements with Limestone Filler and Natural Pozzolan " *Cement & Concrete Composites*, V. 22: 361- 368, 2000.

38. Mehta, P. K. "Mechanism of Expansion Associated with Ettringite Formation" *Cement and Concrete Research*, V. 3 (1): 1-6, 1973.

39. Tikalsky, P. J., Roy, D., Scheetz, B., and Krize, T. "Redefining Cement Characteristic for Sulfate-Resistant Portland Cement" *Cement and Concrete Research*, V. 32: 1239-1246, 2002.

40. Neville, A. "The Confused World of Sulfate Attack on Concrete "Cement *and Concrete Research*, V. 34: 1275-1296, 2004.

41. Sahmaran, M., Kasap, O., Duru, K., and Yaman, I. O. "Effects of Mix Composition and Water-Cement Ratio on The Sulfate Resistance of Blended Cements" *Cement & Concrete Composites*, V. 29: 159-167, 2007.

42. Boyd, A. J. and Mindess, S. "The Use of Tension Testing to Investigate The Effect of W/C Ratio and Cement Type on the Resistance of Concrete to Sulfate Attack" *Cement and Concrete Research*, V. 34: 373-377, 2004.

43. Shah, S. P., Wang, K., and Weiss, W. J. "Mix Proportioning for Durable Concrete" ACI Concrete International, V. 12 (9): 73-78, 2000.

44. Planel, D., Sercombe, J., Le Bescop, P., Adenot, F., and Torrenti, J. M. "Long-Term Performance of Cement Paste during Combined Calcium Leaching – Sulfate Attack: Kinetics and Size Effect" *Cement and Concrete Research*, V. 36: 137-143, 2006.

45. Hobbs, D.W. "Alkali-Silica Reaction in Concrete" Thomas Telford, London, United Kingdom, 1988.

46. Bérubé, M.A., Durand, B., Vézina, D., and Fournier, B. "Alkali-Aggregate Reactivity in Quebec" *Canadian Journal of Civil Engineering*, V. 27: 226-245, 2000.

47. Hou, X., Struble, L.J., and Kirkpatrick, R.J. "Formation of ASR Gel and the Roles of C-S-H and Portlandite" *Cement and Concrete Research*, V. 34: 1683–1696, 2004.

48. Mather, B. "How to Make Concrete That Will Not Suffer Deleterious Alkali-Silica Reaction" *Cement and Concrete Research*, V. 29: 1277-1280, 1999.

49. Tambelli, C.E., Schneider, J.F., Hasparyk, N.P., and Monteiro, P.J.M. "Study of the Structure of Alkali-Silica Reaction Gel by High-Resolution NMR Spectroscopy" *Journal of Non-Crystalline Solids*, V. 352: 3429-3436, 2006.

50. Thomas, M. D. A., Fournier, B., Folliard, K., Ideker, J., and Shehata, M. " Test Methods for Evaluating Preventive Measures for Controlling Expansion due to Alkali-Silica Reaction in Concrete" *Cement and Concrete Research*, V. 36: 1842-1856, 2006.

51. Poyet, S., Sellier, A., Capra B., Thèvenin-Foray, G., Torrenti, J.M., Tournier-Cognon, H., and Bourdarot, E. "Influence of Water on Alkali-Silica Reaction: Experimental Study and Numerical Simulations" *ASCE Journal of Materials in Civil Engineering*, V. 18 (4): 588-596, 2006.

52. Nielson, A., "Development of Alkali Silica Reactions in Concrete Structures with Time" *Cement and Concrete Research*, V. 24: 83-85, 1994.

53. Karakouzian, M., Okuyan, M.N., and Hudyma, N. "Alkali-Silica Reaction – Possible Cause of Map Cracking in Gunite" *Journal of Performance of Constructed Facilities*, V. 17(3): 118-125, 2003.

54. Carse, A. and Dux, P.F. "Development of an Accelerated Test on Concrete Prisms to Determine Their Potential for Alkali-Silica Reaction" *Cement and Concrete Research*, V. 20: 869-874, 1990.

55. Thomas, M. D. A., Shehata, M., "Use of Blended Cements to Control Expansion of Concrete Due to Alkali–Silica Reaction" Proc. 8th CANMET/ACI International Conference: 591–607 Las Vegas, 2004.

56. Davies, G., and Oberholster, R.E., "Alkali-Silica Reaction Products and Their Development" *Cement and Concrete Research*, V. 18: 621-635, 1988.

57. Jones, F.E. and Tarleton, R.D., "Reaction between Aggregates and Cements" National Building Studies Research Papers, London UK, 1958.

58. Rivard, P. and Ballivy, G. "Assessment of the Expansion Related to Alkali-Silica Reaction by the Damage Rating Index Method" *Construction and Building Materials Journal*, V. 19: 83-90, 2005.

59. Binal, A. "Investigation of mixing ratio and restraint condition effects on alkali–silica gel pressure in mortar by using a uniaxial alkali–silica gel pressure measuring device (ASGPM-D)" *Construction and Building Materials Journal*, V. 21: 1218-1228, 2007.

60. Oberholster, R.E. and Davies, G. "An Accelerated Method for Testing the Potential Alkali Reactivity of Siliceous Aggregates" *Cement & Concrete Research*; V. 16(2):181–189, 1986.

61. Mehta, P.K. "Effect of Cement Composition on Corrosion of Reinforcing Steel in Concrete" American Society of Testing and Materials; Special Technical Publication 629: 12-19, 1980.

62. Diamond, S. and Thaulow, N. "A Study of Expansion Due to Alkali-Silica Reaction and Conditioned by the Grain Size of the Reactive Aggregate" *Cement & Concrete Research*; V. 4: 591–607, 1974.

63. Hobbs, D.W. and Gutteridge, W.A. "Particle Size of Aggregate and its Influence upon the Expansion Caused by the Alkali-Silica Reaction" *Magazine of Concrete Research*, V. 31: 235-242, 1979.

64. Rogers, C. A. "Alkali-Aggregate Reactions in Ontario" Proceedings of the 7th International Conference on Alkali Aggregate Reaction in Concrete, Ottawa: 5–16, 1986.

65. Raymar, K., Topal, A., and Andic, O. "Effects of Aggregate Size and Angularity on Alkali-Silica Reaction" *Cement & Concrete Research*; V. 35:2165–2169, 2005.

66. Carette, G.G. and Malhotra, V.M. "Characterization of Canadian Fly Ashes and Their Relative Performance in Concrete" Energy, Mines and Resources Canada, Ottawa, ON, CANMET Report 86-6E, 1986.

67. ACI Committee 232 "Use of Fly Ash in Concrete" ACI 232.2R-96, American Concrete Institute, Michigan, USA, 1996.

68. Helmuth, R.A. "Fly Ash in Cement and Concrete" Portland Cement Association, SP040T: 203, Skokie, Illinois, USA, 1987.

69. American Society for Testing and Materials, "Standard Specification for Blended Hydraulic Cements" ASTM C595, Annual Book of ASTM standards V. 13: 353, 1975.

70. Berry, E.E. and Malhotra, V.M. "Fly Ash in Concrete" Energy, Mines and Resources Canada, Ottawa, ON, CANMET, Special Publication SP85-3, 1986.

71. Mehta, .K. "Testing and Correlation of Fly Ash Properties with Respect to the Pozzolanic Behavior" Electric Power Research Institute, California USA, report CS3314, 1994.

72. Diamond, S. "Effects of Fly Ash Incorporation in Cement and Concrete" Technical Report, Annual Meeting of the Material Research Society, Boston, MA, USA, 1981.

73. Manz, O.E., McCarthy, G.J., Stevenson, R.J., Dockter, B.A., Hassett, D.G., and Thedchanamorthy, A. "Characterization and Classification of North American Lignite Fly Ashes for Use in Concrete" 3rd CANMET/ACI International Conference Proceedings, Trondheim, Norway. Supplementary papers: 16-32, 1989.

74. Davis, R.E., Carlson, R.W., Kelly, J. and Davis, H.E "Properties of Cements and Concretes Containing Fly Ash" *Journal of the American Concrete Institute*, V.33: 577-612, 1937.

75. Naik, T.R. and Ramme, B.W. "Effect of High-Lime Fly Ash Content on Water Demand, Time of Set, and Compressive Strength of Concrete" *ACI Material Journal*, V. 87: 619-626, 1990.

76. Lane, R.O. and Best, J.F. "Properties and Use of Fly Ash in Portland Cement Concrete" Concrete International, V. 4 (7): 81-92, 1982.

77. Johnson, B.D.G. "The Use of Fly Ash in Cape Town RMC Operations" Proceedings of 5th International Conference on Alkali-Aggregate Reaction in Concrete" Cape Town, South Africa, S252: 33, 1981.

78. Malhotra, V. M., and Mehta, P. K. "Pozzolanic and Cementitious Materials" Gordon and Breech Publishers, 1999.

79. Monk, M. "Portland-PFA Cement: A Comparison between Intergrading and blending" *Magazine of Concrete Research*, V. 35(124): 131-141, 1983.

80. Yuan, R.L. and Cook, J.E. "Study of Class C Fly Ash Concrete" Proceedings of 1st International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete, SP-79: 307-319, Montebello, PQ, Canada, 1983.

81. Neville, A.M. "Properties of Concrete" 4th edition, John Wiley, New York, NY, USA, 1996.

82. Ghosh, R.S. and Timusk, J. "Creep of Fly Ash Concrete" *Journal of the American Concrete Institute*, V. 78: 351-357, 1981.

83. Ghosh, A. and Pratt, P.L. "Studies of the Hydration Reaction and Microstructure of Cement – Fly Ash Paste" Proceedings, Annual Meeting of the Materials Research Society, Boston, MA, USA, 1981.

84. Watt, J.D. and Thorne, D.J. "Composition and Pozzolanic Properties of Pulverized Fly Ashes" *Journal of Applied Chemistry*, V. 15: 585-594, 1965.

85. Brizzi, A., Puccio, M., and Valnti, G.L. "Correlation between Physico-Chemical Characteristics of Fly Ash and its Technical Properties for Use in Concrete" Proceedings, 3rd CANMET International Conference, supplementary papers: 139- 156, Trondheim, Norway, 1989.

86. Ushikawa, H., Uchida, S. and Hanibara, S. "Effects of Character of Amorphous Phase in Blending Components on their Reactivity in Calcium Hydroxide Mixture" Proceedings, 8th International Congress on the Chemistry of Cement, V. IV: 245-250; Rio De Janeiro, Brazil, 1986.

87. Chindaprasirt, P., Homwuttiwong, S., and Sirivivatnanon, V. "Influence of Fly Ash Fineness on Strength, Drying Shrinkage and Sulfate Resistance of Blended Cement Mortar" *Cement & Concrete Research*; V. 34:1087–1092, 2004.

88. Irassar, F., Batic, O. "Effects of Low Calcium Fly Ash on Sulfate Resistance of OPC Cement" *Cement & Concrete Research*; V. 19:194–202, 1989.

89. Mortureux, B., Hornain, H., Gautier, E., and Regourd, M. "Comparison of the Reactivity of Different Pozzolans" Proceedings, 7th International Congress on the Chemistry of Cements" Vol. III: 66-71, Paris, France, 1980.

90. Nehdi, M. and Hayek, M. "Behavior of Blended Cement Mortar Exposed to Sulfate Attack Solutions Cycling Humidity" *Concrete Research*; V. 35:731–742, 2005.

91. Freeman, R.B. and Carrasquillo, R.L. "Influence of the Method of Fly Ash Incorporation on the Sulfate Resistance of Fly Ash Concrete" *Cement and Concrete Composites*; V. 13: 209–217, 1991.

92. Shashiprakash, S.G. and Thomas, M. D.A. "Sulfate Resistance of Mortars containing High-Calcium Fly Ashes and Combination of Highly Reactive Pozzolans and Fly Ash" Seventh CANMENT/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, V. I, SP 199: 221-237, Michigan, USA 2001.

93. Binici, H. and Aksogan, O. "Sulfate Resistance of Plain and Blended Cement" *Cement and Concrete Composites*; V. 28:39–46, 2006.

94. Torii, K. and Kawamura, M. "Effect of Fly Ash and Silica Fume on the Resistance of Mortar to Sulfuric Acid and Sulfate Attack" *Cement and Concrete Composites*; V. 24 (2): 361–370, 1994.

95. Bilodeau, A., Sivasundaram, V., Painter, K.E. and Malhotra, V. M. "Durability of Concrete Incorporating High Volumes of Fly Ash from Sources in the U.S." ACI *Materials Journal*, V. 91, No. 1: 3-12, 1994.

96. Bilodeau, A. and Malhotra, V. M. "High-Volume Fly Ash System: Concrete Solution for Sustainable Development" ACI *Materials Journal*, V. 97, No. 1: 41-48, 2000.

97. Cohen, M. D., Mather B. "Sulfate attack on concrete-research needs" *ACI Material Journal*; V. 88 (1):62–9, 1991.

98. Lodeiro, I.G., Palomo, A., and Fernandez-Jimennez, A. "Alkali-Aggregate Reaction in Activated Fly Ash Systems" *Cement and Concrete Composites*; V. 37: 175–183, 2007.

99. Sibbick, R.G. and Page, C.L. "Effects of Pulverized Fuel Ash on Alkali-Silica Reaction in Concrete" *Construction and Building Materials Journal*, v. 9 (5): 289-293. 1995.

100. Shehata, M. H. and Thomas, M. D. A. "The Effect of Fly Ash Composition on the Expansion of Concrete due to Alkali-Silica Reaction" Cement and Concrete Research 30: 1063-1072, 2000.

101. Hobbs, D.W. "The Alkali-Silica Reaction – A Model for Predicting Expansion in Mortars". *Magazine of Concrete Research*, V. 33, No. 117: 208-220, 1981.

102. Duchesne, J. and Bérubé, M.A. "Long Term Effectiveness of Supplementary Cementing Materials against Alkali-Silica Reaction" *Cement and Concrete Composites*; V. 31: 1057–1063, 2001.

103. Rogers, C.A., Booth, D., and Jiang, J. "Multi-Laboratory Study of the Accelerated Mortar Bar Test for Alkali-Silica Reaction". Technical Report. Ministry of Transportation, Ontario, Canada 1996.

104. Fournier, B. "The Role of Fly Ash in Controlling Alkali-Silica Reaction in Concrete" Proceedings, CANMET/ACI International Symposium on Sustainable Development of the Cement and Concrete Industry: 411-422, Ottawa, Canada, 1998.

105. Alasali, M.M., Malhotra, V.M. " Role of Concrete Incorporating High Volume of Fly Ash in Controlling Expansion due to Alkali-Aggregate Reaction" *ACI Material Journal,* V. 88, No. 2: 159-163, 1991.

106. Holland, T.C. "Silica Fume User's Manual" US Department of Transportation, Federal Highway Administration, FHWA-IF-05-016; National Technical Information Services, Springfield, USA, 2005.

107. Duchene, J. and Bérubé, M.A. "The Effectiveness of Supplementary Cementing Materials in Suppressing Expansion Due to ASR: Another Look at the Reaction Mechanisms; Part 1: Concrete Expansion and Portlandite Depletion" *Cement and Concrete Research;* V.24: 73-82, 1994.

108. Lee, S.T., Moon, H.Y., and Swamy, R.N. "Sulfate Attack and Role of Silica Fume in Resisting Strength Loss" *Cement and Concrete Composites;* V. 27: 65-76, 2005.

109. Wee, T.H., Suryavanshi, A.K., Wong, S.F., and Anisur Rahman, A.K.M. "Sulfate Resistance of Concrete Containing Mineral Admixtures" *ACI Material Journal*, V. 97, No.5: 536-549, 2000.

110. Durand, B., Bérard J., Roux, R., and Soles, J. A. "Alkali-Silica Reaction: The Relation between Pore Solution Characteristics and Expansion Test Results" *Cement and Concrete Research;* V. 20: 419-428, 1990.

111. Gillott, J.E. and Wang, H. "Improved Control of Alkali-Silica Reaction by Combined Use of Admixtures" *Cement and Concrete Research;* V. 23: 973-980, 1993.

112. Boddy, A.M., Hooton, R.D., and Thomas, M.D.A. "The Effect of the Silica Content of Silica Fume on its Ability to Control Alkali-Silica Reaction" *Cement and Concrete Research;* V. 33: 1263-1268, 2003.

113. Juenger, M.C.G. and Ostertag, C.P. "Alkali-Silica Reactivity of Large Silica Fume-Derived Particles" *Cement and Concrete Research;* V. 34: 1389-1402, 2004.

114. Boddy, A.M., Hooton, R.D., and Thomas, M.D.A. "The Effect of Product Form of Silica Fume on its Ability to Control Alkali-Silica Reaction" *Cement and Concrete Research;* V. 30: 1139-1150, 2000.

115. Lane, D.S. and Ozyildirim, C. "Preventive Measures for Alkali-Silica Reaction (Binary and Ternary Systems)" *Cement and Concrete Research;* V. 29: 1281-1288, 1999.

116. Shehata, M. H. and Thomas, M.D.A. "Use of Ternary Blends Containing Silica Fume and Fly Ash to Suppress Expansion Due to Alkali-Silica Reaction in Concrete" *Cement and Concrete Research;* V. 32: 341-349, 2002.

Appendix A:

ASTM C 1012 Mortar Bar Length Change Readings

Cement: St. Constant

Fly Ash: No Content%: 0

Date and Time Cast 11/22/05 13:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
11/23/2005 14:30	0.000	0.744	1.026	1.506	1.422	0.000	0.000	0.000	0.000	0.000
11/30/2005 14:45	1.001	0.782	1.060	1.544	1.456	0.015	0.013	0.015	0.013	0.014
12/7/2005 14:45	2.001	0.794	1.070	1.554	1.468	0.020	0.017	0.019	0.018	0.019
12/14/2005 14:45	3.001	0.800	1.086	1.572	1.484	0.022	0.024	0.026	0.024	0.024
12/21/2005 14:50	4.002	0.820	1.112	1.600	1.510	0.030	0.034	0.037	0.035	0.034
1/18/2006 14:45	8.001	0.852	1.150	1.648	1.554	0.043	0.049	0.056	0.052	0.050
2/22/2006 15:15	13.004	0.898	1.218	1.742	1.624	0.061	0.076	0.093	0.080	0.077
3/8/2006 14:45	15.001	0.934	1.280	1.820	1.684	0.075	0.100	0.124	0.103	0.100
3/22/2006 16:15	17.010	1.108	1.504	2.098	1.920	0.143	0.188	0.233	0.196	0.190
5/24/2006 14:45	26.001	1.144	1.564	2.142	1.960	0.157	0.212	0.250	0.212	0.208
8/24/2006 17:00	39.158	1.518	2.004	2.616	2.382	0.305	0.385	0.437	0.378	0.376
11/24/2006 14:45	52.287	1.884	2.404	2.996	2.744	0.449	0.543	0.587	0.520	0.525
2/24/2006 15:30	13.292	2.352	2.918	3.474	3.196	0.633	0.745	0.775	0.698	0.713
5/24/2006 15:30										

Cement: St. Constant
Fly Ash: Rockport Content%: 20

Date and Time Cast 11/29/05 13:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
12/1/2005 11:00	0	-0.362	-0.6	-0.75	-0.542	0	0	0	0	0
12/8/2005 10:45	1.00	-0.334	-0.56	-0.71	-0.51	0.011	0.016	0.016	0.013	0.014
12/15/2005 11:00	2.00	-0.32	-0.548	-0.698	-0.49	0.017	0.020	0.020	0.020	0.019
12/22/2005 11:00	3.00	-0.306	-0.538	-0.688	-0.494	0.022	0.024	0.024	0.019	0.022
12/29/2005 11:00	4.00	-0.302	-0.532	-0.674	-0.486	0.024	0.027	0.030	0.022	0.026
1/26/2006 11:00	8.00	-0.222	-0.454	-0.598	-0.41	0.055	0.057	0.060	0.052	0.056
3/2/2006 14:40	13.02	-0.174	-0.41	-0.548	-0.364	0.074	0.075	0.080	0.070	0.075
3/16/2006 17:00	15.04	-0.16	-0.39	-0.528	-0.344	0.080	0.083	0.087	0.078	0.082
3/30/2006 10:15	17.00	-0.138	-0.364	-0.502	-0.308	0.088	0.093	0.098	0.092	0.093
6/2/2006 10:45	26.14	-0.096	-0.32	-0.418	-0.244	0.105	0.110	0.131	0.117	0.116
8/31/2006 11:00	39.00	0.020	-0.212	-0.294	-0.132	0.150	0.153	0.180	0.161	0.161
11/30/2006 11:00	52.00	0.132	-0.100	-0.152	0.006	0.194	0.197	0.235	0.216	0.211
3/2/2007 11:30	65.15	0.280	0.050	0.050	0.194	0.253	0.256	0.315	0.290	0.278

Cement: St. Constant
Fly Ash: Rockport Content%: 40

Date and Time Cast 12/5/05 11:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
12/8/2005 10:30	0	-1.004	-1.202	-1.020		0.000	0.000	0.000		0.000
12/15/2005 11:00	1.00	-0.962	-1.162	-0.976		0.017	0.016	0.017		0.017
12/22/2005 11:00	2.00	-0.952	-1.148	-0.960		0.020	0.021	0.024		0.022
12/29/2005 11:00	3.00	-0.942	-1.140	-0.948		0.024	0.024	0.028		0.026
1/5/2006 11:00	4.00	-0.908	-1.104	-0.922		0.038	0.039	0.039		0.038
2/2/2006 10:30	8.00	-0.898	-1.094	-0.910		0.042	0.043	0.043		0.043
3/9/2006 10:00	13.00	-0.876	-1.070	-0.886		0.050	0.052	0.053		0.052
3/23/2006 10:00	15.00	-0.870	-1.064	-0.880		0.053	0.054	0.055		0.054
4/6/2006 10:15	17.00	-0.862	-1.054	-0.870		0.056	0.058	0.059		0.058
6/11/2006 15:45	26.46	-0.838	-1.028	-0.844		0.065	0.069	0.069		0.068
9/13/2006 11:00	39.86	-0.806	-0.992	-0.812		0.078	0.083	0.082		0.081
12/8/2006 11:00	52.15	-0.764	-0.940	-0.770		0.094	0.103	0.098		0.099
3/9/2007 13:00	65.16	-0.738	-0.914	-0.750		0.105	0.113	0.106		0.108

Cement: St. Constant
Fly Ash: Rockport Content%: 60

Date and Time Cast 1/10/06 12:00

bar 3, yeiled differently=>
delete

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
1/19/2006 10:25	0	-1.144	-1.284	-1.678	-1.272	0.000	0.000	0.000	0.000	0.000
1/26/2006 10:30	1.00	-1.098	-1.248	-1.672	-1.228	0.018	0.014		0.017	0.017
2/9/2006 10:30	3.00	-1.092	-1.242	-1.668	-1.218	0.020	0.017		0.021	0.019
2/16/2006 10:30	4.00	-1.076	-1.228	-1.662	-1.208	0.027	0.022		0.025	0.025
3/16/2006 10:30	8.00	-1.050	-1.206	-1.650	-1.200	0.037	0.031		0.028	0.032
4/20/2006 15:25	13.03	-1.054	-1.198	-1.632	-1.160	0.035	0.034		0.044	0.038
5/3/2006 15:25	14.89	-1.042	-1.188	-1.628	-1.160	0.040	0.038		0.044	0.041
5/22/2006 15:00	17.60	-1.046	-1.182	-1.620	-1.158	0.039	0.040		0.045	0.041
7/22/2006 16:00	26.32	-1.020	-1.158	-1.614	-1.132	0.049	0.050		0.055	0.051
10/19/2006 10:00	39.00	-1.012	-1.148	-1.576	-1.120	0.052	0.054		0.060	0.055
1/19/2007 10:00	52.14	-1.000	-1.138	-1.582	-1.108	0.057	0.057		0.065	0.060
4/19/2007 11:00	65.00	-1.000	-1.140	-1.578	-1.108	0.057	0.057		0.065	0.059

Cement: St. Constant
Fly Ash: Rockport Content%: 80

Date and Time Cast 1/18/06 16:00

		Comparator Readings				Expansion (%)				
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	Average
3/8/2006 16:00	0	-1.256	-1.188			0.000	0.000			0.000
3/15/2006 16:15	1.00	-1.220	-1.152			0.014	0.014			0.014
3/22/2006 16:00	2.00	-1.216	-1.150			0.016	0.015			0.015
3/29/2006 16:00	3.00	-1.214	-1.150			0.017	0.015			0.016
4/5/2006 15:35	4.00	-1.214	-1.144			0.017	0.017			0.017
5/3/2006 17:55	8.01	-1.206	-1.140			0.020	0.019			0.019
6/7/2006 15:00	12.99	-1.200	-1.138			0.022	0.020			0.021
6/21/2006 16:20	15.00	-1.198	-1.132			0.023	0.022			0.022
7/8/2006 17:00	17.43	-1.200	-1.132			0.022	0.022			0.022
9/8/2006 16:30	26.29	-1.198	-1.130			0.023	0.023			0.023
12/8/2006 17:00	39.29	-1.192	-1.128			0.025	0.024			0.024
3/8/2007 17:30	52.15	-1.182	-1.116			0.029	0.028			0.029

Cement: Brookfield
Fly Ash: Rockport Content%: 80

Date and Time Cast 3/14/06 15:30

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
4/3/2006 14:30	0	-0.632	-0.744	-0.706	-0.750	0.000	0.000	0.000	0.000	0.000
4/10/2006 14:00	1.00	-0.596	-0.706	-0.670	-0.716	0.014	0.015	0.014	0.013	0.014
4/17/2006 15:40	2.01	-0.596	-0.708	-0.670	-0.716	0.014	0.014	0.014	0.013	0.014
4/24/2006 10:00	2.97	-0.588	-0.698	-0.664	-0.706	0.017	0.018	0.017	0.017	0.017
5/2/2006 16:00	4.15	-0.584	-0.692	-0.654	-0.700	0.019	0.020	0.020	0.020	0.020
5/29/2006 15:00	8.00	-0.576	-0.690	-0.644	-0.692	0.022	0.021	0.024	0.023	0.023
7/3/2006 16:00	13.01	-0.576	-0.682	-0.646	-0.690	0.022	0.024	0.024	0.024	0.023
7/17/2006 15:00	15.00	-0.580	-0.686	-0.650	-0.692	0.020	0.023	0.022	0.023	0.022
8/3/2006 15:00	17.43	-0.578	-0.684	-0.646	-0.692	0.021	0.024	0.024	0.023	0.023
10/3/2006 14:00	26.14	-0.576	-0.682	-0.646	-0.692	0.022	0.024	0.024	0.023	0.023
1/3/2007 14:30	39.29	-0.568	-0.678	-0.632	-0.692	0.025	0.026	0.029	0.023	0.026
4/3/2007 15:30	52.15	-0.568	-0.686	-0.652	-0.692	0.025	0.023	0.021	0.023	0.023

Cement: Brookfield
Fly Ash: Rockport Content%: 60

Date and Time Cast 1/18/06 16:00

bar 1, delete

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
2/8/2006 15:15	0.00	-1.656	-1.586	-1.388	-1.266	0.000	0.000	0.000	0.000	0.000
2/15/2006 15:20	1.00	-1.658	-1.562	-1.360	-1.238		0.009	0.011	0.011	0.010
2/22/2006 16:00	2.00	-1.648	-1.548	-1.350	-1.230		0.015	0.015	0.014	0.015
3/1/2006 16:00	3.00	-1.638	-1.538	-1.340	-1.220		0.019	0.019	0.018	0.019
3/8/2006 16:00	4.00	-1.630	-1.530	-1.330	-1.210		0.022	0.023	0.022	0.022
4/5/2006 15:35	8.00	-1.620	-1.524	-1.322	-1.200		0.024	0.026	0.026	0.025
5/10/2006 12:30	12.98	-1.614	-1.520	-1.320	-1.198		0.026	0.027	0.027	0.027
5/24/2006 10:20	14.97	-1.604	-1.508	-1.314	-1.188		0.031	0.029	0.031	0.030
6/9/2006 16:00	17.29	-1.604	-1.506	-1.312	-1.184		0.031	0.030	0.032	0.031
8/10/2006 17:00	26.15	-1.596	-1.498	-1.294	-1.170		0.035	0.037	0.038	0.036
11/14/2006 15:30	39.86	-1.582	-1.488	-1.290	-1.162		0.039	0.039	0.041	0.039
2/14/2007 15:30	53.00	-1.582	-1.488	-1.290	-1.164		0.039	0.039	0.040	0.039

Cement: Brookfield
Fly Ash: - Content%: 0

Date and Time Cast 1/17/06 11:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
1/18/2006 16:00	0.0	-0.624	-0.784	-1.144	-1.020	0.000	0.000	0.000	0.000	0.000
1/25/2006 16:00	1.0	-0.598	-0.758	-1.120	-0.992	0.010	0.010	0.009	0.011	0.010
2/1/2006 16:00	2.0	-0.598	-0.754	-1.122	-0.988	0.010	0.012	0.009	0.013	0.011
2/8/2006 15:30	3.0	-0.590	-0.746	-1.108	-0.982	0.013	0.015	0.014	0.015	0.014
2/15/2006 15:30	4.0	-0.594	-0.754	-1.114	-0.982	0.012	0.012	0.012	0.015	0.013
3/15/2006 15:15	8.0	-0.584	-0.738	-1.104	-0.974	0.016	0.018	0.016	0.018	0.017
4/19/2006 15:05	13.0	-0.588	-0.746	-1.114	-0.964	0.014	0.015	0.012	0.022	0.016
5/3/2006 18:00	15.0	-0.578	-0.734	-1.096	-0.964	0.018	0.020	0.019	0.022	0.020
5/20/2006 15:00	17.4	-0.584	-0.734	-1.106	-0.970	0.016	0.020	0.015	0.020	0.018
7/20/2006 16:00	26.1	-0.562	-0.712	-1.082	-0.954	0.024	0.028	0.024	0.026	0.026
10/22/2006 16:00	39.6	-0.558	-0.706	-1.078	-0.944	0.026	0.031	0.026	0.030	0.028
1/18/2007 16:00	52.1	-0.548	-0.692	-1.066	-0.934	0.030	0.036	0.031	0.034	0.033
4/20/2007 16:30	65.3	-0.540	-0.688	-1.058	-0.926	0.033	0.038	0.034	0.037	0.035

Cement: Brookfield
Fly Ash: Rockport Content%: 40

Date and Time Cast 1/24/06 12:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
2/1/2006 16:15	0	-1.328	-1.320	-1.500	-1.424	0.000	0.000	0.000	0.000	0.000
2/8/2006 15:30	1.00	-1.312	-1.296	-1.482	-1.402	0.006	0.009	0.007	0.009	0.008
2/15/2006 15:30	2.00	-1.304	-1.290	-1.468	-1.390	0.009	0.012	0.013	0.013	0.012
2/22/2006 15:30	3.00	-1.296	-1.280	-1.460	-1.380	0.013	0.016	0.016	0.017	0.015
3/1/2006 15:30	4.00	-1.286	-1.272	-1.452	-1.376	0.017	0.019	0.019	0.019	0.018
3/29/2006 16:30	8.00	-1.266	-1.252	-1.434	-1.350	0.024	0.027	0.026	0.029	0.027
5/3/2006 16:30	13.00	-1.256	-1.244	-1.422	-1.340	0.028	0.030	0.031	0.033	0.031
5/17/2006 11:15	14.97	-1.254	-1.244	-1.422	-1.342	0.029	0.030	0.031	0.032	0.031
6/3/2006 16:00	17.43	-1.248	-1.234	-1.410	-1.334	0.031	0.034	0.035	0.035	0.034
8/3/2006 17:00	26.15	-1.226	-1.214	-1.384	-1.312	0.040	0.042	0.046	0.044	0.043
11/1/2006 16:00	39.00	-1.216	-1.206	-1.380	-1.304	0.044	0.045	0.047	0.047	0.046
2/1/2007 16:00	52.14	-1.206	-1.190	-1.360	-1.286	0.048	0.051	0.055	0.054	0.052
5/3/2007 16:00	65.14									

Cement: Brookfield
Fly Ash: Rockport Content%: 20

Date and Time Cast 1/23/06 13:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
1/26/2006 10:30	0	-0.966	-1.266	-1.094	-1.254	0.000	0.000	0.000	0.000	0.000
2/2/2006 10:30	1.00	-0.946	-1.248	-1.074	-1.230	0.008	0.007	0.008	0.009	0.008
2/9/2006 10:30	2.00	-0.942	-1.244	-1.074	-1.234	0.009	0.009	0.008	0.008	0.008
2/16/2006 10:30	3.00	-0.934	-1.234	-1.064	-1.224	0.013	0.013	0.012	0.012	0.012
2/23/2006 17:00	4.04	-0.932	-1.230	-1.060	-1.220	0.013	0.014	0.013	0.013	0.014
3/23/2006 10:05	8.00	-0.922	-1.220	-1.050	-1.210	0.017	0.018	0.017	0.017	0.018
4/27/2006 11:00	13.00	-0.916	-1.216	-1.044	-1.204	0.020	0.020	0.020	0.020	0.020
5/11/2006 10:05	15.00	-0.914	-1.216	-1.042	-1.202	0.020	0.020	0.020	0.020	0.020
5/29/2006 12:00	17.58	-0.906	-1.208	-1.036	-1.196	0.024	0.023	0.023	0.023	0.023
7/28/2006 10:30	26.14	-0.894	-1.192	-1.028	-1.186	0.028	0.029	0.026	0.027	0.028
10/26/2006 10:00	39.00	-0.888	-1.190	-1.020	-1.180	0.031	0.030	0.029	0.029	0.030
1/26/2007 10:30	52.14	-0.872	-1.178	-1.016	-1.168	0.037	0.035	0.031	0.034	0.034
4/26/2007 10:30	65.00	-0.868	-1.176	-1.004	-1.164	0.039	0.035	0.035	0.035	0.036

Cement: St Constant

Fly Ash: Sundance Content%: 80

Date and Time Cast 1/29/06 13:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
2/27/2006 16:30	0	-0.718	-0.59	-0.642	-0.814	0	0	0	0	0
3/6/2006 16:30	1.00	-0.678	-0.556	-0.606	-0.782	0.016	0.013	0.014	0.013	0.014
3/13/2006 16:05	2.00	-0.67	-0.546	-0.596	-0.774	0.019	0.017	0.018	0.016	0.018
3/20/2006 15:00	2.99	-0.67	-0.546	-0.598	-0.776	0.019	0.017	0.017	0.015	0.017
3/27/2006 13:15	3.98	-0.674	-0.548	-0.596	-0.776	0.017	0.017	0.018	0.015	0.017
4/24/2006 10:00	7.96	-0.672	-0.550	-0.600	-0.784	0.018	0.016	0.017	0.012	0.016
5/29/2006 15:00	12.99	-0.668	-0.542	-0.596	-0.768	0.020	0.019	0.018	0.018	0.019
6/12/2006 15:45	15.00	-0.668	-0.538	-0.592	-0.766	0.020	0.020	0.020	0.019	0.020
6/30/2006 15:45	17.57	-0.664	-0.54	-0.588	-0.766	0.021	0.020	0.021	0.019	0.020
8/29/2006 16:30	26.14	-0.654	-0.532	-0.586	-0.762	0.025	0.023	0.022	0.020	0.023
11/27/2006 16:30	39.00	-0.650	-0.534	-0.584	-0.764	0.027	0.022	0.023	0.020	0.023
2/27/2007 16:30	52.14	-0.646	-0.526	-0.584	-0.762	0.028	0.025	0.023	0.020	0.024
5/28/2007 17:00	65.00									

Cement: St Constant
Fly Ash: Sundance Content%: 60

Date and Time Cast 1/29/06 15:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
2/27/2006 16:30	0	-0.840	-0.792	-1.132	-1.094	0.000	0.000	0.000	0.000	0.000
3/6/2006 16:30	1.00	-0.812	-0.764	-1.106	-1.066	0.011	0.011	0.010	0.011	0.011
3/13/2006 16:15	2.00	-0.802	-0.756	-1.098	-1.056	0.015	0.014	0.013	0.015	0.014
3/20/2006 16:00	3.00	-0.802	-0.756	-1.096	-1.054	0.015	0.014	0.014	0.016	0.015
3/27/2006 13:00	3.98	-0.800	-0.754	-1.094	-1.050	0.016	0.015	0.015	0.017	0.016
4/24/2006 10:00	7.96	-0.794	-0.748	-1.092	-1.048	0.018	0.017	0.016	0.018	0.017
5/29/2006 15:00	12.99	-0.774	-0.736	-1.070	-1.026	0.026	0.022	0.024	0.027	0.025
6/12/2006 15:00	14.99	-0.772	-0.726	-1.066	-1.024	0.027	0.026	0.026	0.028	0.027
6/29/2006 15:45	17.42	-0.774	-0.722	-1.066	-1.026	0.026	0.028	0.026	0.027	0.027
8/30/2006 16:30	26.29	-0.768	-0.718	-1.058	-1.010	0.028	0.029	0.029	0.033	0.030
11/27/2006 16:00	39.00	-0.758	-0.712	-1.050	-1.004	0.032	0.031	0.032	0.035	0.033
2/27/2007 16:30	52.14	-0.754	-0.706	-1.046	-1.000	0.034	0.034	0.034	0.037	0.035
5/28/2007 17:00	65.00									

Cement: St Constant
Fly Ash: Sundance Content%: 40

Date and Time
Cast 2/6/06 12:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
2/13/2006 16:00	0	-0.614	-0.992	-0.744	-0.492	0.000	0.000	0.000	0.000	0.000
2/20/2006 16:00	1.00	-0.576	-0.888	-0.716	-0.458	0.015	0.041	0.011	0.013	0.020
2/27/2006 16:00	2.00	-0.566	-0.878	-0.706	-0.448	0.019	0.045	0.015	0.017	0.024
3/6/2006 16:00	3.00	-0.552	-0.866	-0.694	-0.434	0.024	0.050	0.020	0.023	0.029
3/13/2006 16:00	4.00	-0.542	-0.858	-0.688	-0.428	0.028	0.053	0.022	0.025	0.032
4/10/2006 14:00	7.99	-0.540	-0.854	-0.684	-0.424	0.029	0.054	0.024	0.027	0.033
5/15/2006 10:00	12.96	-0.520	-0.840	-0.670	-0.406	0.037	0.060	0.029	0.034	0.040
5/29/2006 15:00	14.99	-0.518	-0.834	-0.664	-0.402	0.038	0.062	0.031	0.035	0.042
6/14/2006 16:00	17.29	-0.514	-0.828	-0.658	-0.398	0.039	0.065	0.034	0.037	0.044
8/14/2006 16:00	26.00	-0.492	-0.812	-0.642	-0.382	0.048	0.071	0.040	0.043	0.051
11/14/2006 16:00	39.14	-0.480	-0.794	-0.622	-0.368	0.053	0.078	0.048	0.049	0.057
2/14/2007 16:00	52.29	-0.466	-0.790	-0.624	-0.362	0.058	0.080	0.047	0.051	0.059
5/14/2007 16:00	65.00									

Cement: St Constant
Fly Ash: Sundance Content%: 20
Date and Time Cast 2/6/06 13:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
2/8/2006 15:15	0	-0.258	-0.462	-0.814	-0.438	0.000	0.000	0.000	0.000	0.000
2/15/2006 15:15	1.00	-0.228	-0.440	-0.784	-0.410	0.012	0.009	0.012	0.011	0.011
2/22/2006 15:15	2.00	-0.220	-0.424	-0.772	-0.400	0.015	0.015	0.017	0.015	0.015
3/1/2006 15:15	3.00	-0.210	-0.410	-0.758	-0.388	0.019	0.020	0.022	0.020	0.020
3/8/2006 15:15	4.00	-0.200	-0.400	-0.748	-0.378	0.023	0.024	0.026	0.024	0.024
4/5/2006 15:25	8.00	-0.180	-0.388	-0.734	-0.362	0.031	0.029	0.031	0.030	0.030
5/10/2006 12:30	12.98	-0.176	-0.382	-0.728	-0.364	0.032	0.031	0.034	0.029	0.032
5/25/2006 12:30	15.13	-0.166	-0.374	-0.722	-0.352	0.036	0.035	0.036	0.034	0.035
6/10/2006 16:00	17.43	-0.168	-0.372	-0.720	-0.352	0.035	0.035	0.037	0.034	0.035
8/10/2006 15:00	26.14	-0.154	-0.360	-0.702	-0.336	0.041	0.040	0.044	0.040	0.041
11/8/2006 15:00	39.00	-0.138	-0.332	-0.680	-0.314	0.047	0.051	0.053	0.049	0.050
2/8/2007 15:00	52.14	-0.110	-0.308	-0.664	-0.294	0.058	0.061	0.059	0.057	0.059
5/9/2007 15:30	65.00	-0.070	-0.284	-0.636	-0.278	0.074	0.070	0.070	0.063	0.069

Cement: Brookfield
Fly Ash: Sundance
Content%: 60

Date and Time Cast 2/7/06 13:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
3/15/2006 15:00	0	-1.218	-1.210	-0.616	-1.116	0.000	0.000	0.000	0.000	0.000
3/22/2006 15:35	1.00	-1.200	-1.196	-0.600	-1.096	0.007	0.006	0.006	0.008	0.007
3/29/2006 16:30	2.01	-1.192	-1.186	-0.598	-1.096	0.010	0.009	0.007	0.008	0.009
4/5/2006 15:35	3.00	-1.186	-1.178	-0.588	-1.086	0.013	0.013	0.011	0.012	0.012
4/12/2006 14:30	4.00	-1.186	-1.176	-0.586	-1.084	0.013	0.013	0.012	0.013	0.013
5/10/2006 12:30	7.99	-1.182	-1.172	-0.584	-1.084	0.014	0.015	0.013	0.013	0.014
6/14/2006 15:30	13.00	-1.170	-1.164	-0.570	-1.070	0.019	0.018	0.018	0.018	0.018
6/28/2006 16:00	15.01	-1.164	-1.160	-0.566	-1.066	0.021	0.020	0.020	0.020	0.020
7/15/2006 15:30	17.43	-1.162	-1.160	-0.564	-1.066	0.022	0.020	0.020	0.020	0.020
9/15/2006 15:00	26.29	-1.160	-1.154	-0.560	-1.056	0.023	0.022	0.022	0.024	0.023
12/15/2006 15:30	39.29	-1.158	-1.144	-0.558	-1.052	0.024	0.026	0.023	0.025	0.024
3/15/2007 15:30	52.15	-1.154	-1.140	-0.552	-1.048	0.025	0.028	0.025	0.027	0.026
6/14/2007 14:30	65.14									

Cement: Brookfield
Fly Ash: Sundance
Content%: 80

Date and Time Cast 3/13/06 13:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
4/3/2006 16:00	0	-0.126	0.190	-0.490	-0.514	0.000	0.000	0.000	0.000	0.000
4/10/2006 14:00	0.99	-0.104	0.214	-0.480	-0.504	0.009	0.009	0.004	0.004	0.006
4/17/2006 16:00	2.00	-0.080	0.214	-0.468	-0.500	0.018	0.009	0.009	0.006	0.010
4/24/2006 18:00	3.01	-0.092	0.222	-0.466	-0.492	0.013	0.013	0.009	0.009	0.011
5/1/2006 16:00	4.00	-0.092	0.220	-0.466	-0.492	0.013	0.012	0.009	0.009	0.011
5/29/2006 15:30	8.00	-0.088	0.228	-0.458	-0.480	0.015	0.015	0.013	0.013	0.014
7/3/2006 16:00	13.00	-0.090	0.226	-0.458	-0.482	0.014	0.014	0.013	0.013	0.013
7/17/2006 16:00	15.00	-0.080	0.228	-0.458	-0.490	0.018	0.015	0.013	0.009	0.014
8/3/2006 16:30	17.43	-0.080	0.226	-0.452	-0.486	0.018	0.014	0.015	0.011	0.015
10/3/2006 16:00	26.14	-0.086	0.232	-0.452	-0.484	0.016	0.017	0.015	0.012	0.015
1/3/2007 16:45	39.29	-0.082	0.230	-0.452	-0.492	0.017	0.016	0.015	0.009	0.014
4/3/2007 16:45	52.15	-0.080	0.232	-0.450	-0.480	0.018	0.017	0.016	0.013	0.016

Cement: Brookfield

Fly Ash: Sundance Content%: 40

Date and Time Cast 3/6/06 13:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
3/9/2006 10:30	0	-1.190	-0.832	-1.086	-1.198	0.000	0.000	0.000	0.000	0.000
3/16/2006 17:15	1.04	-1.150	-0.796	-1.050	-1.152	0.016	0.014	0.014	0.018	0.016
3/23/2006 10:30	2.00	-1.154	-0.792	-1.042	-1.150	0.014	0.016	0.017	0.019	0.017
3/30/2006 10:15	3.00	-1.150	-0.792	-1.038	-1.148	0.016	0.016	0.019	0.020	0.018
4/6/2006 10:20	4.00	-1.142	-0.786	-1.032	-1.140	0.019	0.018	0.021	0.023	0.020
5/4/2006 15:20	8.03	-1.148	-0.786	-1.038	-1.140	0.017	0.018	0.019	0.023	0.019
6/8/2006 15:40	13.03	-1.116	-0.764	-1.008	-1.120	0.029	0.027	0.031	0.031	0.029
6/22/2006 16:00	15.03	-1.114	-0.766	-1.004	-1.120	0.030	0.026	0.032	0.031	0.030
7/9/2006 13:00	17.44	-1.114	-0.762	-1.004	-1.114	0.030	0.028	0.032	0.033	0.031
9/9/2006 11:00	26.29	-1.122	-0.766	-1.010	-1.120	0.027	0.026	0.030	0.031	0.028
12/9/2006 11:00	39.29	-1.094	-0.746	-0.986	-1.094	0.038	0.034	0.039	0.041	0.038
3/9/2007 12:30	52.15	-1.096	-0.746	-0.984	-1.094	0.037	0.034	0.040	0.041	0.038
6/8/2007 11:30	65.15									

Cement: Brookfield

Fly Ash: Sundance

Content%: 20

Date and Time Cast 3/6/06 13:00

		Comparator Readings				Expansion (%)				
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	Average
3/9/2006 10:30	0	-0.960	-1.666	-1.040	-1.414	0.000	0.000	0.000	0.000	0.000
3/16/2006 17:15	1.04	-0.928	-1.650	-1.016	-1.386	0.013	0.006	0.009	0.011	0.010
3/23/2006 10:30	2.00	-0.932	-1.656	-1.016	-1.384	0.011	0.004	0.009	0.012	0.009
3/30/2006 10:15	3.00	-0.928	-1.652	-1.016	-1.384	0.013	0.006	0.009	0.012	0.010
4/6/2006 10:10	4.00	-0.928	-1.642	-1.018	-1.386	0.013	0.009	0.009	0.011	0.010
5/4/2006 15:20	8.03	-0.918	-1.626	-1.010	-1.378	0.017	0.016	0.012	0.014	0.015
6/8/2006 15:45	13.03	-0.910	-1.634	-0.998	-1.366	0.020	0.013	0.017	0.019	0.017
6/22/2006 18:00	15.04	-0.906	-1.628	-0.990	-1.360	0.021	0.015	0.020	0.021	0.019
7/9/2006 18:00	17.47	-0.908	-1.630	-0.992	-1.358	0.020	0.014	0.019	0.022	0.019
9/9/2006 18:00	26.33	-0.906	-1.628	-0.992	-1.360	0.021	0.015	0.019	0.021	0.019
12/9/2006 18:00	39.33	-0.884	-1.574	-0.972	-1.344	0.030	0.036	0.027	0.028	0.030
3/9/2007 18:30	52.19	-0.880	-1.572	-0.970	-1.338	0.031	0.037	0.028	0.030	0.031
6/8/2007 15:30	65.17									

Cement: Herndon
Fly Ash: - Content%: 0

Date and Time Cast 4/24/2006 18:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
4/25/2006 15:00	0	0.946	1.022	1.267	1.196	0	0	0	0	0
5/2/2006 15:00	1.00	0.984	1.060	1.314	1.244	0.015	0.015	0.019	0.019	0.017
5/9/2006 21:00	2.04	1.000	1.076	1.332	1.258	0.021	0.021	0.026	0.024	0.023
5/16/2006 19:00	3.02	1.012	1.088	1.342	1.270	0.026	0.026	0.030	0.029	0.028
5/23/2006 19:00	4.02	1.022	1.092	1.342	1.282	0.030	0.028	0.030	0.034	0.030
6/20/2006 17:00	8.01	1.064	1.132	1.394	1.324	0.046	0.043	0.050	0.050	0.048
7/25/2006 19:00	13.02	1.124	1.182	1.460	1.388	0.070	0.063	0.076	0.076	0.071
8/8/2006 19:00	15.02	1.180	1.228	1.518	1.442	0.092	0.081	0.099	0.097	0.092
8/25/2006 16:00	17.43	1.266	1.282	1.610	1.530	0.126	0.102	0.135	0.131	0.124
10/25/2006 15:00	26.14	1.662	1.578	2.006	1.982	0.282	0.219	0.291	0.309	0.275
1/25/2007 16:00	39.29	2.460	2.242	2.852	2.872	0.596	0.480	0.624	0.660	0.590
4/24/2007 15:30	52.00	3.690	3.248	4.238	4.366	1.080	0.876	1.170	1.248	1.094

Cement: Herndon

Fly Ash: Sundance   Content%: 20

Date and Time Cast 4/21/2006 20:30

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
4/24/2006 15:00	0	-0.784	-0.612	-0.644	-0.514	0	0	0	0	0
5/1/2006 15:00	1.00	-0.754	-0.580	-0.614	-0.482	0.012	0.013	0.012	0.013	0.012
5/8/2006 21:00	2.04	-0.744	-0.570	-0.604	-0.474	0.016	0.017	0.016	0.016	0.016
5/15/2006 19:00	3.02	-0.740	-0.562	-0.598	-0.464	0.017	0.020	0.018	0.020	0.019
5/22/2006 19:00	4.02	-0.734	-0.560	-0.594	-0.456	0.020	0.020	0.020	0.023	0.021
6/19/2006 19:00	8.02	-0.708	-0.538	-0.576	-0.438	0.030	0.029	0.027	0.030	0.029
7/24/2006 19:00	13.02	-0.698	-0.524	-0.562	-0.426	0.034	0.035	0.032	0.035	0.034
8/7/2006 19:00	15.02	-0.694	-0.520	-0.558	-0.424	0.035	0.036	0.034	0.035	0.035
8/24/2006 16:00	17.43	-0.692	-0.522	-0.560	-0.426	0.036	0.035	0.033	0.035	0.035
10/24/2006 15:00	26.14	-0.670	-0.504	-0.546	-0.408	0.045	0.043	0.039	0.042	0.042
1/25/2007 16:00	39.43	-0.652	-0.490	-0.528	-0.392	0.052	0.048	0.046	0.048	0.048
4/24/2007 15:00	52.14	-0.644	-0.476	-0.518	-0.386	0.055	0.054	0.050	0.050	0.052

Cement: Herndon

Fly Ash: Sundance

Content%: 40

Date and Time Cast 4/16/2006 20:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
4/21/2006 17:45	0	-0.306		-0.850	-0.662	0	0	0	0	0
4/28/2006 17:45	1.00	-0.266		-0.816	-0.632	0.016		0.013	0.012	0.014
5/5/2006 17:45	2.00	-0.258		-0.806	-0.616	0.019		0.017	0.018	0.018
5/12/2006 20:00	3.01	-0.238		-0.792	-0.600	0.027		0.023	0.024	0.025
5/19/2006 20:00	4.01	-0.236		-0.786	-0.600	0.028		0.025	0.024	0.026
6/16/2006 20:30	8.02	-0.218		-0.764	-0.584	0.035		0.034	0.031	0.033
7/21/2006 20:30	13.02	-0.204		-0.756	-0.568	0.040		0.037	0.037	0.038
8/4/2006 20:15	15.01	-0.204		-0.752	-0.568	0.040		0.039	0.037	0.039
8/21/2006 20:30	17.44	-0.202		-0.750	-0.568	0.041		0.039	0.037	0.039
10/20/2006 20:00	26.01	-0.194		-0.738	-0.556	0.044		0.044	0.042	0.043
1/20/2007 19:00	39.15	-0.184		-0.730	-0.548	0.048		0.047	0.045	0.047
4/21/2007 18:00	52.14	-0.166		-0.722	-0.530	0.055		0.050	0.052	0.052

Cement: Herndon
Fly Ash: Sundance
Content%: 60

Date and Time Cast 4/21/2006 22:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/1/2006 21:00	0	-0.352	-0.070	-0.662		0	0	0		0
5/8/2006 21:00	1.00	-0.326	-0.032	-0.626		0.010	0.015	0.014		0.013
5/15/2006 21:00	2.00	-0.320	-0.024	-0.608		0.013	0.018	0.021		0.017
5/22/2006 21:00	3.00	-0.308	-0.014	-0.604		0.017	0.022	0.023		0.021
5/29/2006 17:00	3.98	-0.302	-0.004	-0.598		0.020	0.026	0.025		0.024
6/26/2006 11:00	7.94	-0.286	0.012	-0.580		0.026	0.032	0.032		0.030
7/31/2006 16:00	12.97	-0.286	0.014	-0.580		0.026	0.033	0.032		0.030
8/15/2006 15:20	15.11	-0.276	0.020	-0.574		0.030	0.035	0.035		0.033
9/1/2006 15:20	17.54	-0.276	0.038	-0.568		0.030	0.043	0.037		0.036
11/1/2006 15:20	26.25	-0.268	0.030	-0.560		0.033	0.039	0.040		0.038
2/1/2007 15:30	39.40	-0.258	0.034	-0.558		0.037	0.041	0.041		0.040
5/1/2007 15:30	52.11	-0.260	0.034	-0.560		0.036	0.041	0.040		0.039

Cement: Herndon
Fly Ash: Sundance Content%: 80
Date and Time Cast 4/18/2006 21:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
5/15/2006 17:45	0	-0.390	-0.908	-0.910		0	0	0		0
5/22/2006 20:30	1.02	-0.360	-0.876	-0.872		0.012	0.013	0.015		0.013
5/29/2006 14:00	1.98	-0.352	-0.868	-0.870		0.015	0.016	0.016		0.015
6/5/2006 16:00	2.99	-0.350	-0.866	-0.868		0.016	0.017	0.017		0.016
6/12/2006 20:00	4.01	-0.350	-0.866	-0.868		0.016	0.017	0.017		0.016
7/10/2006 19:00	8.01	-0.350	-0.862	-0.866		0.016	0.018	0.017		0.017
8/14/2006 20:00	13.01	-0.346	-0.862	-0.866		0.017	0.018	0.017		0.018
8/28/2006 18:00	15.00	-0.356	-0.876	-0.880		0.013	0.013	0.012		0.013
9/15/2006 17:00	17.57	-0.352	-0.868	-0.870		0.015	0.016	0.016		0.015
11/15/2006 17:45	26.29	-0.350	-0.868	-0.870		0.016	0.016	0.016		0.016
2/15/2007 17:30	39.43	-0.352	-0.872	-0.872		0.015	0.014	0.015		0.015
5/14/2007 17:30	52.00	-0.354	-0.872	-0.872		0.014	0.014	0.015		0.014

Cement: Herndon

Fly Ash: Rockport

Content%: 40

Date and Time Cast 5/4/2006 20:00

Date and time	Elapsed weeks	Comparator Readings				Expansion (%)				Average
		1	2	3	4	1	2	3	4	
5/9/2006 20:00	0	-0.210	0.014	-0.062	0.540	0	0	0	0	0
5/16/2006 19:30	1.00	-0.182	0.038	-0.032	0.570	0.011	0.009	0.012	0.012	0.011
5/23/2006 19:30	2.00	-0.156	0.052	-0.012	0.590	0.021	0.015	0.020	0.020	0.019
5/30/2006 20:00	3.00	-0.138	0.082	0.006	0.610	0.028	0.027	0.027	0.028	0.027
6/6/2006 21:00	4.01	-0.134	0.086	0.012	0.610	0.030	0.028	0.029	0.028	0.029
7/4/2006 21:00	8.01	-0.116	0.106	0.034	0.636	0.037	0.036	0.038	0.038	0.037
8/8/2006 21:15	13.01	-0.100	0.120	0.048	0.644	0.043	0.042	0.043	0.041	0.042
8/22/2006 20:30	15.00	-0.096	0.132	0.050	0.654	0.045	0.046	0.044	0.045	0.045
9/9/2006 20:30	17.57	-0.086	0.142	0.060	0.664	0.049	0.050	0.048	0.049	0.049
11/9/2006 20:00	26.29	-0.058	0.174	0.088	0.694	0.060	0.063	0.059	0.061	0.061
2/8/2007 18:00	39.27	0.032	0.292	0.160	0.746	0.095	0.109	0.087	0.081	0.093
5/8/2007 19:30	52.00	0.198	0.466	0.306	0.872	0.161	0.178	0.145	0.131	0.154

Cement: Herndon

Fly Ash: Rockport

Content%: 60

Date and Time Cast 4/28/06 21:15

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/26/2006 19:30	0	0.990	0.414	1.358	1.408	0	0	0	0	0
6/2/2006 17:10	0.99	1.030	0.466	1.396	1.464	0.016	0.020	0.015	0.022	0.018
6/9/2006 18:00	1.99	1.056	0.480	1.418	1.480	0.026	0.026	0.024	0.028	0.026
6/16/2006 18:30	2.99	1.058	0.484	1.424	1.488	0.027	0.028	0.026	0.031	0.028
6/23/2006 18:30	3.99	1.070	0.496	1.434	1.500	0.031	0.032	0.030	0.036	0.032
7/21/2006 18:00	7.99	1.088	0.508	1.454	1.518	0.039	0.037	0.038	0.043	0.039
8/25/2006 19:00	13.00	1.088	0.514	1.456	1.520	0.039	0.039	0.039	0.044	0.040
9/8/2006 19:00	15.00	1.102	0.534	1.470	1.538	0.044	0.047	0.044	0.051	0.047
9/26/2006 18:00	17.56	1.108	0.540	1.478	1.540	0.046	0.050	0.047	0.052	0.049
11/26/2006 19:15	26.28	1.118	0.550	1.490	1.564	0.050	0.054	0.052	0.061	0.054
2/25/2007 20:30	39.29	1.136	0.560	1.500	1.576	0.057	0.057	0.056	0.066	0.059
5/25/2007 19:30	52.00	1.142	0.574	1.508	1.580	0.060	0.063	0.059	0.068	0.062

Cement: Herndon
Fly Ash: Rockport Content%: 80
Date and Time Cast 4/28/2006 18:30

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/26/2006 17:00	0	0.184	-0.070	-0.458		0	0	0		0
6/2/2006 17:10	1.00	0.230	-0.024	-0.412		0.018	0.018	0.018		0.018
6/9/2006 17:00	2.00	0.238	-0.022	-0.410		0.021	0.019	0.019		0.020
6/16/2006 17:30	3.00	0.242	-0.022	-0.410		0.023	0.019	0.019		0.020
6/23/2006 18:00	4.01	0.246	-0.016	-0.406		0.024	0.021	0.020		0.022
7/21/2006 18:00	8.01	0.242	-0.016	-0.406		0.023	0.021	0.020		0.022
8/25/2006 18:30	13.01	0.240	-0.022	-0.414		0.022	0.019	0.017		0.019
9/8/2006 18:00	15.01	0.248	-0.012	-0.406		0.025	0.023	0.020		0.023
9/26/2006 17:30	17.57	0.242	-0.014	-0.406		0.023	0.022	0.020		0.022
11/26/2006 17:00	26.29	0.250	-0.010	-0.402		0.026	0.024	0.022		0.024
2/25/2007 17:00	39.29	0.248	-0.010	-0.398		0.025	0.024	0.024		0.024
5/25/2007 17:00	52.00	0.246	-0.010	-0.400		0.024	0.024	0.023		0.024

Cement: St. constant SF

Fly Ash: - Content%: 0

Date and Time Cast 5/14/2006 18:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/15/2006 14:30	0	1.46	1.442	2.136	1.362	0	0	0	0	0
5/22/2006 18:00	1.02	1.49	1.464	2.166	1.404	0.012	0.009	0.012	0.017	0.012
5/29/2006 14:30	2.00	1.496	1.474	2.174	1.404	0.014	0.013	0.015	0.017	0.015
6/5/2006 18:00	3.02	1.51	1.478	2.184	1.412	0.020	0.014	0.019	0.020	0.018
6/12/2006 18:30	4.02	1.502	1.48	2.174	1.396	0.017	0.015	0.015	0.013	0.015
7/10/2006 16:30	8.01	1.492	1.49	2.184	1.404	0.013	0.019	0.019	0.017	0.017
8/14/2006 15:00	13.00	1.500	1.500	2.194	1.414	0.016	0.023	0.023	0.020	0.020
8/28/2006 15:30	15.01	1.490	1.488	2.180	1.406	0.012	0.018	0.017	0.017	0.016
9/15/2006 14:00	17.57	1.500	1.498	2.194	1.416	0.016	0.022	0.023	0.021	0.020
11/15/2006 16:30	26.30	1.506	1.508	2.194	1.416	0.018	0.026	0.023	0.021	0.022
2/13/2007 16:00	39.15	1.506	1.506	2.198	1.416	0.018	0.025	0.024	0.021	0.022
5/14/2007 15:00	52.00	1.516	1.512	2.204	1.420	0.022	0.028	0.027	0.023	0.025

Cement: St. constant SF

Fly Ash: Sundance Content%: 20

Date and Time Cast 5/8/2006 22:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/10/2006 22:30	0	-1.569	-1.333	-1.334	-1.149	0	0	0	0	0
5/17/2006 21:00	0.99	-1.558	-1.310	-1.308	-1.130	0.004	0.009	0.010	0.007	0.008
5/24/2006 21:00	1.99	-1.534	-1.292	-1.286	-1.102	0.014	0.016	0.019	0.019	0.017
5/31/2006 18:00	2.97	-1.544	-1.276	-1.282	-1.108	0.010	0.022	0.020	0.016	0.017
6/7/2006 20:00	3.99	-1.536	-1.296	-1.300	-1.106	0.013	0.015	0.013	0.017	0.014
7/5/2006 20:30	7.99	-1.524	-1.282	-1.284	-1.094	0.018	0.020	0.020	0.022	0.020
8/9/2006 21:00	12.99	-1.524	-1.280	-1.284	-1.094	0.018	0.021	0.020	0.022	0.020
8/23/2006 22:00	15.00	-1.524	-1.282	-1.284	-1.096	0.018	0.020	0.020	0.021	0.020
9/10/2006 22:00	17.57	-1.520	-1.282	-1.280	-1.096	0.019	0.020	0.021	0.021	0.020
11/10/2006 21:30	26.28	-1.510	-1.274	-1.270	-1.084	0.023	0.023	0.025	0.026	0.024
2/8/2007 22:30	39.14	-1.512	-1.276	-1.272	-1.088	0.022	0.022	0.024	0.024	0.023
5/9/2007 22:30	52.00	-1.506	-1.270	-1.266	-1.082	0.025	0.025	0.027	0.026	0.026

Cement: St. constant SF

Fly Ash: Sundance Content%: 40

Date and Time Cast 5/10/2006 23:45

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/15/2006 18:00	0	1.840	1.338	1.818	1.950	0	0	0	0	0
5/22/2006 20:45	1.02	1.864	1.366	1.846	1.976	0.009	0.011	0.011	0.010	0.010
5/29/2006 18:00	2.00	1.882	1.388	1.866	1.988	0.017	0.020	0.019	0.015	0.018
6/5/2006 19:30	3.01	1.886	1.398	1.866	1.990	0.018	0.024	0.019	0.016	0.019
6/12/2006 19:15	4.01	1.894	1.398	1.874	1.992	0.021	0.024	0.022	0.017	0.021
7/10/2006 20:00	8.01	1.906	1.414	1.888	2.008	0.026	0.030	0.028	0.023	0.027
8/14/2006 18:00	13.00	1.924	1.422	1.904	2.020	0.033	0.033	0.034	0.028	0.032
8/28/2006 18:00	15.00	1.912	1.412	1.894	2.016	0.028	0.029	0.030	0.026	0.028
9/15/2006 18:30	17.57	1.924	1.424	1.902	2.020	0.033	0.034	0.033	0.028	0.032
11/15/2006 17:00	26.28	1.930	1.426	1.906	2.026	0.035	0.035	0.035	0.030	0.034
2/13/2007 18:00	39.14	1.926	1.426	1.904	2.026	0.034	0.035	0.034	0.030	0.033
5/14/2007 18:30	52.00	1.942	1.436	1.914	2.038	0.040	0.039	0.038	0.035	0.038

Cement: St. constant SF

Fly Ash: Sundance Content%: 60

Date and Time Cast 5/10/2006 18:30

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
6/9/06 18:00	0	0.138	0.298	0.078	0.360	0	0	0	0	0
6/16/06 19:00	1.01	0.154	0.312	0.100	0.382	0.006	0.006	0.009	0.009	0.007
6/23/06 18:30	2.00	0.164	0.320	0.114	0.392	0.010	0.009	0.014	0.013	0.011
6/30/06 17:00	2.99	0.166	0.322	0.114	0.392	0.011	0.009	0.014	0.013	0.012
7/7/06 18:00	4.00	0.172	0.324	0.120	0.396	0.013	0.010	0.017	0.014	0.014
8/4/06 18:00	8.00	0.180	0.326	0.124	0.398	0.017	0.011	0.018	0.015	0.015
9/8/06 18:00	13.00	0.186	0.326	0.128	0.410	0.019	0.011	0.020	0.020	0.017
9/22/06 17:30	15.00	0.186	0.330	0.128	0.410	0.019	0.013	0.020	0.020	0.018
10/9/06 17:00	17.42	0.180	0.322	0.118	0.402	0.017	0.009	0.016	0.017	0.015
12/9/06 16:00	26.13	0.178	0.322	0.116	0.402	0.016	0.009	0.015	0.017	0.014
3/9/07 17:30	39.00	0.182	0.328	0.124	0.408	0.017	0.012	0.018	0.019	0.017
6/8/07 18:00	52.00	0.184	0.330	0.126	0.410	0.018	0.013	0.019	0.020	0.017

Cement: St. constant SF

Fly Ash: Sundance Content%: 80

Date and Time Cast 5/24/2006 22:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
6/21/06 16:15	0	-0.994	-0.240	-0.568		0	0	0	0	0
6/28/06 16:00	1.00	-0.964	-0.212	-0.548		0.012	0.011	0.008		0.010
7/5/06 16:00	2.00	-0.970	-0.212	-0.546		0.009	0.011	0.009		0.010
7/12/06 17:00	3.00	-0.972	-0.214	-0.546		0.009	0.010	0.009		0.009
7/19/06 16:00	4.00	-0.970	-0.212	-0.550		0.009	0.011	0.007		0.009
8/16/06 16:30	8.00	-0.972	-0.214	-0.548		0.009	0.010	0.008		0.009
9/20/06 16:00	13.00	-0.972	-0.212	-0.550		0.009	0.011	0.007		0.009
10/4/06 16:30	15.00	-0.972	-0.212	-0.550		0.009	0.011	0.007		0.009
10/21/06 17:30	17.44	-0.972	-0.212	-0.556		0.009	0.011	0.005		0.008
12/21/06 18:30	26.16	-0.966	-0.210	-0.552		0.011	0.012	0.006		0.010
3/21/07 18:30	39.01	-0.962	-0.202	-0.530		0.013	0.015	0.015		0.014
6/20/07 18:00	52.01	-0.948	-0.192	-0.510		0.018	0.019	0.023		0.020

Cement: St. constant SF

Fly Ash: Sundance

Content%: 80

Date and Time Cast 7/5/2006 20:00

Immersed in Sulphate solution after 2 days of casting

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
7/8/06 17:00	0	0.616	0.974	-0.550		0	0	0	0	0
7/15/06 19:00	1.01	0.654	1.008	-0.514		0.015	0.013	0.014		0.014
7/22/06 18:00	2.01	0.662	1.012	-0.508		0.018	0.015	0.017		0.017
7/29/06 17:00	3.00	0.654	1.010	-0.510		0.015	0.014	0.016		0.015
8/5/06 17:30	4.00	0.656	1.016	-0.508		0.016	0.017	0.017		0.016
9/2/06 17:30	8.00	0.658	1.020	-0.502		0.017	0.018	0.019		0.018
10/7/06 17:00	13.00	0.652	1.018	-0.502		0.014	0.017	0.019		0.017
10/21/06 17:00	15.00	0.652	1.010	-0.504		0.014	0.014	0.018		0.015
11/8/06 17:30	17.57	0.650	1.010	-0.512		0.013	0.014	0.015		0.014
1/8/07 19:30	26.30	0.644	1.002	-0.518		0.011	0.011	0.013		0.012
4/7/07 19:30	39.01	0.642	1.000	-0.520		0.010	0.010	0.012		0.011

Cement: St. constant SF

Fly Ash: Sundance Content%: 80

Date and Time Cast 7/5/2006 22:00

Low water to cement ratio of 0.4

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
8/18/06 17:00	0	1.390	0.726	-0.333	1.396	0	0	0	0	0
8/25/06 17:00	1.00	1.396	0.732	-0.330	1.396	0.002	0.002	0.001	0.000	0.001
9/1/06 17:00	2.00	1.406	0.738	-0.326	1.404	0.006	0.005	0.003	0.003	0.004
9/8/06 17:30	3.00	1.408	0.738	-0.324	1.406	0.007	0.005	0.004	0.004	0.005
9/15/06 17:00	4.00	1.408	0.738	-0.324	1.404	0.007	0.005	0.004	0.003	0.005
10/13/06 17:15	8.00	1.402	0.730	-0.330	1.396	0.005	0.002	0.001	0.000	0.002
11/17/06 17:00	13.00	1.396	0.726	-0.334	1.390	0.002	0.000	0.000	-0.002	0.000
11/30/06 18:00	14.86	1.394	0.722	-0.340	1.388	0.002	-0.002	-0.003	-0.003	-0.001
12/18/06 17:00	17.43	1.388	0.718	-0.344	1.384	-0.001	-0.003	-0.004	-0.005	-0.003
2/18/07 17:00	26.29	1.394	0.722	-0.340	1.386	0.002	-0.002	-0.003	-0.004	-0.002
5/18/07 17:00	39.00									

Cement: St. constant SF

Fly Ash: Rockport

Content%: 20

Date and Time Cast 5/16/2006 13:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/17/2006 22:00	0	2.125	2.328	1.753	2.667	0	0	0	0	0
5/24/2006 21:00	0.99	2.158	2.362	1.784	2.704	0.013	0.013	0.012	0.015	0.013
5/31/2006 19:30	1.99	2.166	2.364	1.790	2.706	0.016	0.014	0.015	0.015	0.015
6/7/2006 16:35	2.97	2.170	2.368	1.794	2.712	0.018	0.016	0.016	0.018	0.017
6/14/2006 16:00	3.96	2.174	2.372	1.794	2.716	0.019	0.017	0.016	0.019	0.018
7/12/2006 16:30	7.97	2.180	2.382	1.800	2.726	0.022	0.021	0.019	0.023	0.021
8/15/2006 20:00	12.85	2.186	2.386	1.808	2.732	0.024	0.023	0.022	0.026	0.024
8/28/2006 21:00	14.71	2.180	2.376	1.794	2.730	0.022	0.019	0.016	0.025	0.020
9/17/2006 18:00	17.55	2.184	2.378	1.802	2.734	0.023	0.020	0.019	0.026	0.022
11/17/2006 17:30	26.26	2.178	2.376	1.800	2.732	0.021	0.019	0.019	0.026	0.021
2/17/2007 18:30	39.41	2.192	2.390	1.810	2.744	0.026	0.024	0.022	0.030	0.026
5/16/2007 21:30	52.00	2.194	2.392	1.808	2.748	0.027	0.025	0.022	0.032	0.026

Cement: St. constant SF

Fly Ash: Rockport Content%: 40

Date and Time Cast 5/15/2006 0:45

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
5/17/2006 23:05	0	3.088	0.890	0.938	0.186	0	0	0	0	0
5/24/2006 21:15	0.99	3.134	0.928	0.974	0.228	0.018	0.015	0.014	0.017	0.016
5/31/2006 22:00	1.99	3.136	0.936	0.990	0.236	0.019	0.018	0.020	0.020	0.019
6/7/2006 22:30	3.00	3.148	0.944	0.990	0.246	0.024	0.021	0.020	0.024	0.022
6/14/2006 22:30	4.00	3.152	0.948	0.994	0.250	0.025	0.023	0.022	0.025	0.024
7/12/2006 22:00	7.99	3.168	0.964	1.010	0.266	0.031	0.029	0.028	0.031	0.030
8/15/2006 22:30	12.85	3.180	0.974	1.020	0.276	0.036	0.033	0.032	0.035	0.034
8/28/2006 22:00	14.71	3.182	0.972	1.022	0.276	0.037	0.032	0.033	0.035	0.034
9/17/2006 23:30	17.57	3.184	0.976	1.028	0.278	0.038	0.034	0.035	0.036	0.036
11/17/2006 21:00	26.27	3.192	0.984	1.032	0.284	0.041	0.037	0.037	0.039	0.038
2/17/2007 20:00	39.41	3.204	0.998	1.048	0.296	0.046	0.043	0.043	0.043	0.044
5/16/2007 21:30	51.99	3.210	1.002	1.054	0.300	0.048	0.044	0.046	0.045	0.046

Cement: St. constant SF

Fly Ash: Rockport

Content%: 60

Date and Time Cast 5/17/2006 17:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
6/20/06 20:00	0	1.566	1.750	1.218	1.132	0	0	0	0	0
6/27/06 20:30	1.00	1.596	1.778	1.224	1.160	0.012	0.011	0.002	0.011	0.009
7/4/06 19:30	2.00	1.610	1.788	1.256	1.172	0.017	0.015	0.015	0.016	0.016
7/11/06 19:00	2.99	1.614	1.792	1.260	1.178	0.019	0.017	0.017	0.018	0.018
7/18/06 18:00	3.99	1.616	1.794	1.264	1.180	0.020	0.017	0.018	0.019	0.019
8/15/06 18:00	7.99	1.624	1.804	1.274	1.190	0.023	0.021	0.022	0.023	0.022
9/19/06 20:00	13.00	1.628	1.810	1.276	1.198	0.024	0.024	0.023	0.026	0.024
10/3/06 19:00	14.99	1.632	1.812	1.280	1.198	0.026	0.024	0.024	0.026	0.025
10/20/06 18:30	17.42	1.632	1.812	1.282	1.200	0.026	0.024	0.025	0.027	0.026
12/20/06 19:00	26.14	1.632	1.812	1.284	1.200	0.026	0.024	0.026	0.027	0.026
3/20/07 19:30	39.00	1.634	1.814	1.288	1.202	0.027	0.025	0.028	0.028	0.027
6/19/07 20:30	52.00	1.634	1.814	1.286	1.204	0.027	0.025	0.027	0.028	0.027

Cement: St. constant SF

Fly Ash: Rockport Content%: 80

Date and Time Cast 5/24/2006 1:00

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
21-Jun	0	1.214	2.100	1.262		0	0	0		0
28-Jun	1.00	1.246	2.132	1.296		0.013	0.013	0.013		0.013
5-Jul	1.99	1.250	2.138	1.298		0.014	0.015	0.014		0.014
12-Jul	2.98	1.248	2.136	1.296		0.013	0.014	0.013		0.014
19-Jul	3.99	1.244	2.132	1.296		0.012	0.013	0.013		0.013
16-Aug	7.99	1.248	2.138	1.298		0.013	0.015	0.014		0.014
20-Sep	12.88	1.248	2.142	1.300		0.013	0.017	0.015		0.015
4-Oct	14.88	1.248	2.142	1.300		0.013	0.017	0.015		0.015
21-Oct	17.31	1.246	2.138	1.298		0.013	0.015	0.014		0.014
21-Dec	26.02	1.238	2.128	1.288		0.009	0.011	0.010		0.010
22-Mar	39.02	1.238	2.128	1.288		0.009	0.011	0.010		0.010
21-Jun	52.02	1.238	2.128	1.288		0.009	0.011	0.010		0.010

Cement: Herndon

Fly Ash: Rockport

Content%: 80

Date and Time Cast 9/6/2006 17:00

Low water to cement ratio of 0.39

		Comparator Readings				Expansion (%)				Average
Date and time	Elapsed weeks	1	2	3	4	1	2	3	4	
10/3/06 18:00	0	2.036	1.350	0.020		0	0	0	0	0
10/10/06 18:30	1.00	2.058	1.388	0.042		0.009	0.015	0.009		0.011
10/17/06 18:30	2.00	2.064	1.390	0.048		0.011	0.016	0.011		0.013
10/24/06 18:00	3.00	2.066	1.392	0.048		0.012	0.017	0.011		0.013
10/31/06 18:00	4.00	2.066	1.388	0.048		0.012	0.015	0.011		0.013
11/28/06 18:00	8.00	2.066	1.388	0.050		0.012	0.015	0.012		0.013
1/2/07 18:30	13.00	2.066	1.388	0.050		0.012	0.015	0.012		0.013
1/16/07 19:30	15.01	2.066	1.388	0.050		0.012	0.015	0.012		0.013
2/3/07 18:30	17.57	2.066	1.388	0.044		0.012	0.015	0.009		0.012
4/3/07 19:00	26.01	2.058	1.384	0.042		0.009	0.013	0.009		0.010

Appendix B:

ASTM C 1260 Mortar Bar Length Change Readings

Cement: St Constant

Fly Ash: Sundance Content%: 0

Date and Time Cast: 28/02/2005 14:00:00 AM

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
3/1/2006 16:20	0	-0.914	-0.904	-0.776				
3/2/2006 16:05	0.00	-0.782	-0.776	-0.652	0.000	0.000	0.000	0.000
3/6/2006 16:00	3.99	-0.452	-0.448	-0.33	0.130	0.129	0.127	0.129
3/8/2006 16:00	5.99	-0.294	-0.228	-0.16	0.192	0.216	0.194	0.201
3/13/2006 16:00	10.99	-0.078	-0.07	0.052	0.277	0.278	0.277	0.277
3/15/2006 16:00	12.99	-0.006	0.006	0.128	0.306	0.308	0.307	0.307
3/20/2006 16:00	17.99	0.25	0.264	0.368	0.406	0.409	0.402	0.406

Cement: St Constant
Fly Ash: Sundance
Content%: 20

Date and Time Cast: 07/03/2005 13:50:00 AM

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
3/8/2006 15:00	0	-1.126	-0.502	-0.416				
3/9/2006 16:00	0.04	-0.988	-0.372	-0.274	0.000	0.000	0.000	0.000
3/13/2006 16:00	4.04	-0.946	-0.322	-0.232	0.017	0.020	0.017	0.018
3/15/2006 16:15	6.05	-0.88	-0.296	-0.212	0.043	0.030	0.024	0.032
3/20/2006 15:30	11.02	-0.898	-0.278	-0.19	0.035	0.037	0.033	0.035
3/22/2006 15:30	13.02	-0.858	-0.238	-0.146	0.051	0.053	0.050	0.051
3/27/2006 13:30	17.94	-0.768	-0.136	-0.04	0.087	0.093	0.092	0.091
3/29/2006 17:00	20.08	-0.692	-0.058	0.052	0.117	0.124	0.128	0.123

Cement: St Constant

Fly Ash: Sundance Content%: 40

Date and Time Cast: 07/03/2005 14:00:00 AM

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
3/8/2006 15:00	0	-0.972	-1.182	-0.66				
3/9/2006 16:00	0.04	-0.852	-1.06	-0.546	0.000	0.000	0.000	0.000
3/13/2006 16:00	4.04	-0.838	-1.054	-0.534	0.006	0.002	0.005	0.004
3/15/2006 16:15	6.05	-0.828	-1.046	-0.522	0.009	0.006	0.009	0.008
3/20/2006 15:30	11.02	-0.816	-1.026	-0.494	0.014	0.013	0.020	0.016
3/22/2006 15:30	13.02	-0.794	-1.026	-0.508	0.023	0.013	0.015	0.019
3/27/2006 13:30	17.94	-0.776	-1.002	-0.48	0.030	0.023	0.026	0.026
3/29/2006 17:00	20.08	-0.778	-0.994	-0.464	0.029	0.026	0.032	0.029

Cement: St Constant

Fly Ash: Sundance

Content%: 60

Date and Time Cast: 20/03/2005 12:00:00 AM

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
3/21/2006 11:45	0	-1.292	-1.074	-1.02				
3/22/2006 15:35	0.16	-1.172	-0.956	-0.91	0.000	0.000	0.000	0.000
3/27/2006 13:25	5.07	-1.162	-0.948	-0.898	0.004	0.003	0.005	0.004
3/29/2006 17:00	7.22	-1.152	-0.938	-0.886	0.008	0.007	0.009	0.008
3/30/2006 10:25	7.94	-1.152	-0.926	-0.877	0.008	0.012	0.013	0.011
3/31/2006 15:30	9.16	-1.154	-0.936	-0.896	0.007	0.008	0.006	0.007
4/3/2006 15:00	12.14	-1.152	-0.918	-0.866	0.008	0.015	0.017	0.013
4/5/2006 15:00	14.14	-1.136	-0.916	-0.868	0.014	0.016	0.017	0.015

Cement: St Constant
Fly Ash: Sundance
Content%: 80

Date and Time Cast: 20/03/2005 12:00:00 AM

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
3/21/2006 11:45	0	-1.65	-1.33					
3/22/2006 15:35	0.16	-1.528	-1.208		0.000	0.000		0.000
3/27/2006 13:25	5.07	-1.534	-1.216		-0.002	-0.003		-0.003
3/29/2006 17:00	7.22	-1.528	-1.21		0.000	-0.001		0.000
3/30/2006 10:25	7.94	-1.53	-1.214		-0.001	-0.002		-0.002
3/31/2006 15:30	9.16	-1.528	-1.21		0.000	-0.001		0.000
4/3/2006 15:00	12.14	-1.526	-1.21		0.001	-0.001		0.000
4/5/2006 15:00	14.14	-1.526	-1.21		0.001	-0.001		0.000
4/6/2006 16:00	15.18	-1.52	-1.202		0.003	0.002		0.003
4/10/2006 14:00	19.09	-1.524	-1.196		0.002	0.005		0.003

Cement: St Constant
Fly Ash: Rockport

Content%: 20

Date and Time Cast: 4/4/05 0:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/5/2006 15:00	0	-1.634	-1.624	-1.464				
4/6/2006 16:00	0.04	-1.65	-1.59	-1.426	0.000	0.000	0.000	0.000
4/10/2006 14:00	3.92	-1.662	-1.436	-1.282	-0.005	0.061	0.057	0.038
4/12/2006 14:30	5.94	-1.644	-1.376	-1.284	0.002	0.084	0.056	0.048
4/13/2006 16:00	7.00	-1.62	-1.348	-1.192	0.012	0.095	0.092	0.066
4/14/2006 15:00	7.96	-1.574	-1.304	-1.148	0.030	0.113	0.109	0.084
4/17/2006 15:45	10.99	-1.484	-1.2	-1.036	0.065	0.154	0.154	0.124
4/19/2006 15:00	12.96	-1.402	-1.13	-0.97	0.098	0.181	0.180	0.153
4/20/2006 15:30	13.98	-1.36	-1.088	-0.932	0.114	0.198	0.194	0.169
4/24/2006 10:00	17.75	-1.244	-1.054	-0.802	0.160	0.211	0.246	0.206

Cement: St Constant
Fly Ash: Rockport
Content%: 40

Date and Time Cast: 4/23/05 15:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/25/2006 15:50	0	-0.8	-1.652	-0.844				
4/26/2006 11:00	0.00	-0.664	-1.66	-0.698	0.000	0.000	0.000	0.000
4/27/2006 16:00	1.21	-0.646	-1.644	-0.688	0.007	0.006	0.004	0.006
4/29/2006 16:30	3.23	-0.632	-1.62	-0.664	0.013	0.016	0.013	0.014
5/2/2006 18:00	6.29	-0.594	-1.61	-0.636	0.028	0.020	0.024	0.024
5/3/2006 18:00	7.29	-0.586	-1.616	-0.628	0.031	0.017	0.028	0.025
5/4/2006 16:00	8.21	-0.562	-1.622	-0.608	0.040	0.015	0.035	0.030
5/9/2006 16:00	13.21	-0.494	-1.594	-0.534	0.067	0.026	0.065	0.052
5/10/2006 16:00	14.21	-0.486	-1.594	-0.548	0.070	0.026	0.059	0.052
5/11/2006 16:00	15.21	-0.444	-1.564	-0.504	0.087	0.038	0.076	0.067

Cement: St Constant
Fly Ash: Rockport Content%: 60

Date and Time Cast: 4/4/05 15:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/5/2006 15:00	0	-1.638	-1.64	-1.64				
4/6/2006 16:00	0.04	-1.648	-1.648	-1.648	0.000	0.000	0.000	0.000
4/10/2006 14:00	3.92	-1.66	-1.66	-1.663	-0.005	-0.005	-0.006	-0.005
4/12/2006 14:30	5.94	-1.648	-1.648	-1.644	0.000	0.000	0.002	0.001
4/13/2006 16:00	7.00	-1.662	-1.668	-1.666	-0.006	-0.008	-0.007	-0.007
4/14/2006 15:00	7.96	-1.662	-1.662	-1.662	-0.006	-0.006	-0.006	-0.006
4/17/2006 15:45	10.99	-1.678	-1.678	-1.678	-0.012	-0.012	-0.012	-0.012
4/19/2006 15:00	12.96	-1.65	-1.65	-1.65	-0.001	-0.001	-0.001	-0.001
4/20/2006 15:30	13.98	-1.638	-1.64	-1.638	0.004	0.003	0.004	0.004
4/24/2006 10:00	17.75	-1.65	-1.652	-1.65	-0.001	-0.002	-0.001	-0.001

Cement: St Constant
Fly Ash: Rockport Content%: 80
Date and Time Cast: 4/4/05 15:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/5/2006 15:00	0	-1.640	-1.640					
4/6/2006 16:00	0.04	-1.648	-1.558		0.000	0.000		0.000
4/10/2006 14:00	3.92	-1.660	-1.568		-0.005	-0.004		-0.004
4/12/2006 14:30	5.94	-1.646	-1.568		0.001	-0.004		-0.002
4/13/2006 16:00	7.00	-1.662	-1.612		-0.006	-0.021		-0.013
4/14/2006 15:00	7.96	-1.666	-1.558		-0.007	0.000		-0.004
4/17/2006 15:45	10.99	-1.678	-1.574		-0.012	-0.006		-0.009
4/19/2006 15:00	12.96	-1.648	-1.558		0.000	0.000		0.000
4/20/2006 15:30	13.98	-1.634	-1.554		0.006	0.002		0.004
4/24/2006 10:00	17.75	-1.650	-1.566		-0.001	-0.003		-0.002

Cement: Brookfield
Fly Ash: Rockport
Content%: 80

Date and Time Cast: 4/10/05 15:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/11/2006 18:15	0	-1.22	-1.244					
4/12/2006 14:30	0.00	-1.108	-1.136		0.000	0.000		0.000
4/13/2006 16:00	1.06	-1.124	-1.148		-0.006	-0.005		-0.006
4/14/2006 15:00	2.02	-1.12	-1.148		-0.005	-0.005		-0.005
4/17/2006 15:45	5.05	-1.13	-1.16		-0.009	-0.009		-0.009
4/19/2006 15:00	7.02	-1.126	-1.148		-0.007	-0.005		-0.006
4/20/2006 15:30	8.04	-1.12	-1.144		-0.005	-0.003		-0.004
4/24/2006 10:00	11.81	-1.122	-1.148		-0.006	-0.005		-0.005
4/26/2006 15:30	14.04	-1.108	-1.136		0.000	0.000		0.000
4/27/2006 10:00	14.81	-1.114	-1.14		-0.002	-0.002		-0.002

Cement: Brookfield

Fly Ash: Rockport

Content%: 60

Date and Time Cast: 4/10/05 15:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
4/11/2006 18:15	0	-0.706	-1.134	-1.088				
4/12/2006 14:30	0.00	-0.624	-1.056	-1.012	0.000	0.000	0.000	0.000
4/13/2006 16:00	1.06	-0.64	-1.066	-1.022	-0.006	-0.004	-0.004	-0.005
4/14/2006 15:00	2.02	-0.626	-1.06	-1.018	-0.001	-0.002	-0.002	-0.002
4/17/2006 15:45	5.05	-0.618	-1.056	-1.016	0.002	0.000	-0.002	0.000
4/19/2006 15:00	7.02	-0.622	-1.058	-1.016	0.001	-0.001	-0.002	-0.001
4/20/2006 15:30	8.04	-0.606	-1.046	-1.002	0.007	0.004	0.004	0.005
4/24/2006 10:00	11.81	-0.6	-1.032	-0.99	0.009	0.009	0.009	0.009
4/26/2006 15:30	14.04	-0.598	-1.032	-0.99	0.010	0.009	0.009	0.009
4/27/2006 10:00	14.81	-0.588	-1.028	-0.984	0.014	0.011	0.011	0.012
4/29/2006 16:00	17.06	-0.596	-1.032	-0.984	0.011	0.009	0.011	0.010
5/2/2006 16:00	20.06	-0.578	-1.016	-0.972	0.018	0.016	0.016	0.017
5/3/2006 18:00	21.15	-0.57	-1.002	-0.962	0.021	0.021	0.020	0.021
5/4/2006 16:00	22.06	-0.566	-1.002	-0.964	0.023	0.021	0.019	0.021
5/9/2006 16:00	27.06	-0.548	-0.984	-0.942	0.030	0.028	0.028	0.029

Cement: Brookfield
Fly Ash: Rockport
Content%: 40

Date and Time Cast: 4/11/05 15:00

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/12/2006 14:30	0.00	-0.890	-0.324	-0.462				
4/13/2006 16:00	0.00	-0.772	-0.210	-0.360	0.000	0.000	0.000	0.000
4/14/2006 15:00	0.96	-0.764	-0.198	-0.340	0.003	0.005	0.008	0.005
4/17/2006 15:45	3.99	-0.758	-0.194	-0.340	0.006	0.006	0.008	0.007
4/19/2006 15:00	5.96	-0.754	-0.184	-0.330	0.007	0.010	0.012	0.010
4/20/2006 15:30	6.98	-0.740	-0.184	-0.324	0.013	0.010	0.014	0.012
4/24/2006 10:00	10.75	-0.730	-0.174	-0.316	0.017	0.014	0.017	0.016
4/26/2006 15:30	12.98	-0.702	-0.142	-0.286	0.028	0.027	0.029	0.028
4/27/2006 10:00	13.75	-0.690	-0.132	-0.280	0.032	0.031	0.031	0.031
4/29/2006 16:00	16.00	-0.698	-0.128	-0.276	0.029	0.032	0.033	0.031
5/2/2006 16:00	19.00	-0.674	-0.098	-0.258	0.039	0.044	0.040	0.041
5/3/2006 18:00	20.08	-0.646	-0.070	-0.214	0.050	0.055	0.057	0.054
5/4/2006 16:00	21.00	-0.632	-0.054	-0.210	0.055	0.061	0.059	0.059

Cement: Brookfield
Fly Ash: Rockport
Content%: 20

Date and Time Cast: 4/25/05 15:50

		Comparator Readings			Expansion (%)			Average
Date and time	Elapsed days	1	2	3	1	2	3	
4/26/2006 11:30	0.00	0.916	0.726	0.608				
4/27/2006 16:00	0.00	1.058	0.86	0.754	0.000	0.000	0.000	0.000
4/29/2006 16:00	2.00	1.09	0.896	0.788	0.013	0.014	0.013	0.013
5/2/2006 16:00	5.00	1.132	0.936	0.824	0.029	0.030	0.028	0.029
5/3/2006 18:00	6.08	1.132	0.932	0.822	0.029	0.028	0.027	0.028
5/4/2006 16:00	7.00	1.158	0.964	0.854	0.039	0.041	0.039	0.040
5/9/2006 16:00	12.00	1.252	1.086	0.982	0.076	0.089	0.090	0.085
5/10/2006 14:00	12.92	1.282	1.112	0.998	0.088	0.099	0.096	0.094
5/11/2006 10:00	13.75	1.314	1.148	1.028	0.101	0.113	0.108	0.107

Cement: Herndon

Fly Ash: - Content%: 0

Date and Time Cast: 6/20/2006 16:30

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/22/2006 16:30	0	2.016	1.850	1.450	0	0	0	0
6/24/2006 15:00	1.94	2.170	2.020	1.614	0.061	0.067	0.065	0.064
6/26/2006 17:30	4.04	2.376	2.226	1.828	0.142	0.148	0.149	0.146
6/28/2006 16:00	5.98	2.644	2.502	2.112	0.247	0.257	0.261	0.255
7/1/2006 18:00	9.06	2.838	2.702	2.316	0.324	0.335	0.341	0.333
7/4/2006 23:00	12.27	2.964	2.832	2.448	0.373	0.387	0.393	0.384
7/7/2006 18:00	15.06	3.064	2.940	2.556	0.413	0.429	0.435	0.426
7/10/2006 17:00	18.02	3.190	3.068	2.682	0.462	0.480	0.485	0.476
7/15/2006 16:30	23.00	3.420	3.288	2.880	0.553	0.566	0.563	0.561
7/20/2006 16:30	28.00	3.690	3.486	3.110	0.659	0.644	0.654	0.652
7/24/2006 16:30	32.00	3.860	3.690	3.308	0.726	0.724	0.731	0.727
7/29/2006 16:30	37.00	4.065	3.910	3.538	0.807	0.811	0.822	0.813
8/4/2006 16:00	42.98	4.362	4.206	3.834	0.924	0.928	0.939	0.930
8/7/2006 16:30	46.00	4.518	4.346	3.958	0.985	0.983	0.987	0.985
8/12/2006 16:30	51.00	4.704	4.528	4.136	1.058	1.054	1.057	1.057
8/17/2006 16:30	56.00	4.760	4.684	4.286	1.080	1.116	1.117	1.104
8/22/2006 16:30	61.00	5.006	4.830	4.436	1.177	1.173	1.176	1.175

Cement: Herndon

Fly Ash: Sundance

Content%: 20

Date and Time Cast: 6/20/2006 18:10

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/22/2006 16:30	0	1.450	2.174	2.128	0	0	0	0
6/24/2006 15:00	1.94	1.472	2.202	2.156	0.009	0.011	0.011	0.010
6/26/2006 17:30	4.04	1.498	2.230	2.178	0.019	0.022	0.020	0.020
6/28/2006 16:00	5.98	1.530	2.264	2.222	0.031	0.035	0.037	0.035
7/1/2006 18:00	9.06	1.558	2.298	2.254	0.043	0.049	0.050	0.047
7/4/2006 23:00	12.27	1.594	2.340	2.290	0.057	0.065	0.064	0.062
7/7/2006 18:00	15.06	1.656	2.406	2.354	0.081	0.091	0.089	0.087
7/10/2006 17:00	18.02	1.714	2.466	2.410	0.104	0.115	0.111	0.110
7/15/2006 16:30	23.00	1.818	2.574	2.524	0.145	0.157	0.156	0.153
7/20/2006 16:30	28.00	1.938	2.680	2.638	0.192	0.199	0.201	0.197
7/24/2006 16:30	32.00	2.030	2.780	2.730	0.228	0.239	0.237	0.235
7/29/2006 16:30	37.00	2.140	2.886	2.838	0.272	0.280	0.280	0.277
8/4/2006 16:00	42.98	2.302	3.060	3.012	0.335	0.349	0.348	0.344
8/7/2006 16:30	46.00	2.380	3.138	3.092	0.366	0.380	0.380	0.375
8/12/2006 16:30	51.00	2.532	3.280	3.238	0.426	0.435	0.437	0.433
8/17/2006 16:30	56.00	2.692	3.442	3.392	0.489	0.499	0.498	0.495
8/22/2006 16:30	61.00	2.854	3.604	3.550	0.553	0.563	0.560	0.559

Cement: Herndon

Fly Ash: Sundance

Content%: 40

Date and Time Cast: 6/21/2006 16:30

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/23/2006 16:30	0	0.226	1.648	1.068	0	0	0	0
6/25/2006 15:00	1.94	0.248	1.676	1.088	0.009	0.011	0.008	0.009
6/28/2006 16:00	4.98	0.238	1.686	1.092	0.005	0.015	0.009	0.010
7/1/2006 18:00	8.06	0.250	1.698	1.108	0.009	0.020	0.016	0.015
7/4/2006 19:00	11.10	0.270	1.712	1.122	0.017	0.025	0.021	0.021
7/7/2006 18:00	14.06	0.280	1.718	1.132	0.021	0.028	0.025	0.025
7/10/2006 17:00	17.02	0.292	1.732	1.140	0.026	0.033	0.028	0.029
7/15/2006 16:30	22.00	0.316	1.754	1.160	0.035	0.042	0.036	0.038
7/20/2006 16:30	27.00	0.340	1.778	1.180	0.045	0.051	0.044	0.047
7/24/2006 16:30	31.00	0.384	1.814	1.226	0.062	0.065	0.062	0.063
7/29/2006 16:30	36.00	0.438	1.874	1.282	0.083	0.089	0.084	0.086
8/4/2006 16:00	41.98	0.530	1.958	1.362	0.120	0.122	0.116	0.119
8/7/2006 16:30	45.00	0.568	1.998	1.392	0.135	0.138	0.128	0.133
8/12/2006 16:30	50.00	0.634	2.072	1.464	0.161	0.167	0.156	0.161
8/17/2006 16:30	55.00	0.720	2.156	1.552	0.194	0.200	0.191	0.195
8/22/2006 16:30	60.00	0.806	2.240	1.648	0.228	0.233	0.228	0.230

Cement: Herndon

Fly Ash: Sundance

Content%: 60

Date and Time Cast: 6/21/2006 20:30

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/23/2006 16:30	0	2.378	1.480	2.020	0	0	0	0
6/25/2006 15:00	1.94	2.400	1.496	2.034	0.009	0.006	0.006	0.007
6/28/2006 16:00	4.98	2.410	1.510	2.044	0.013	0.012	0.009	0.011
7/1/2006 18:00	8.06	2.416	1.522	2.062	0.015	0.017	0.017	0.016
7/4/2006 23:00	11.27	2.426	1.528	2.074	0.019	0.019	0.021	0.020
7/7/2006 18:00	14.06	2.430	1.530	2.082	0.020	0.020	0.024	0.022
7/10/2006 17:00	17.02	2.436	1.534	2.082	0.023	0.021	0.024	0.023
7/15/2006 16:30	22.00	2.438	1.534	2.084	0.024	0.021	0.025	0.023
7/19/2006 16:30	26.00	2.440	1.536	2.084	0.024	0.022	0.025	0.024
7/24/2006 16:30	31.00	2.448	1.544	2.100	0.028	0.025	0.031	0.028
7/29/2006 16:30	36.00	2.456	1.556	2.118	0.031	0.030	0.039	0.033
8/4/2006 16:00	41.98	2.472	1.566	2.122	0.037	0.034	0.040	0.037
8/7/2006 16:30	45.00	2.482	1.576	2.128	0.041	0.038	0.043	0.040
8/12/2006 16:30	50.00	2.490	1.590	2.134	0.044	0.043	0.045	0.044
8/17/2006 16:30	55.00	2.504	1.602	2.150	0.050	0.048	0.051	0.050
8/22/2006 16:30	60.00	2.522	1.612	2.168	0.057	0.052	0.058	0.056

Cement: Herndon

Fly Ash: Sundance

Content%: 80

Date and Time Cast: 6/21/2006 18:20

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/23/2006 16:30	0	-0.778	1.498	1.826	0	0	0	0
6/25/2006 15:00	1.94	-0.788	1.498	1.836	-0.004	0.000	0.004	0.000
6/28/2006 16:00	4.98	-0.768	1.496	1.844	0.004	-0.001	0.007	0.003
7/1/2006 18:00	8.06	-0.772	1.502	1.848	0.002	0.002	0.009	0.004
7/4/2006 23:00	11.27	-0.772	1.502	1.844	0.002	0.002	0.007	0.004
7/7/2006 18:00	14.06	-0.772	1.508	1.850	0.002	0.004	0.009	0.005
7/10/2006 17:00	17.02	-0.766	1.510	1.850	0.005	0.005	0.009	0.006
7/20/2006 16:30	27.00	-0.778	1.490	1.840	0.000	-0.003	0.006	0.001

Cement: Herndon

Fly Ash: Rockport

Content%: 20

Date and Time Cast: 6/23/2006 21:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/25/2006 16:30	0	1.206	1.196	1.804	0	0	0	0
6/28/2006 16:00	2.98	1.362	1.360	1.960	0.061	0.065	0.061	0.062
7/1/2006 18:00	6.06	1.528	1.516	2.120	0.127	0.126	0.124	0.126
7/4/2006 23:00	9.27	1.612	1.600	2.198	0.160	0.159	0.155	0.158
7/7/2006 18:00	12.06	1.690	1.686	2.278	0.191	0.193	0.187	0.190
7/10/2006 17:00	15.02	1.766	1.754	2.348	0.220	0.220	0.214	0.218
7/15/2006 16:30	20.00	1.926	1.910	2.508	0.283	0.281	0.277	0.281
7/22/2006 16:30	27.00	2.128	2.104	2.706	0.363	0.357	0.355	0.359
7/29/2006 16:30	34.00	2.368	2.330	2.942	0.457	0.446	0.448	0.451
8/4/2006 16:00	39.98	2.626	2.580	3.194	0.559	0.545	0.547	0.550
8/7/2006 16:30	43.00	2.748	2.696	3.318	0.607	0.591	0.596	0.598
8/12/2006 16:30	48.00	2.926	2.876	3.496	0.677	0.661	0.666	0.668
8/22/2006 16:30	58.00	3.220	3.270	3.880	0.793	0.817	0.817	0.809

Cement: Herndon

Fly Ash: Rockport

Content%: 40

Date and Time Cast: 6/22/2006 22:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/24/2006 16:30	0	2.448	0.510	1.342	0	0	0	0
6/26/2006 15:00	1.94	2.476	0.534	1.370	0.011	0.009	0.011	0.010
6/28/2006 16:00	3.98	2.500	0.558	1.402	0.020	0.019	0.024	0.021
7/1/2006 18:00	7.06	2.530	0.588	1.432	0.032	0.031	0.035	0.033
7/4/2006 23:00	10.27	2.558	0.612	1.460	0.043	0.040	0.046	0.043
7/7/2006 18:00	13.06	2.580	0.640	1.482	0.052	0.051	0.055	0.053
7/10/2006 17:00	16.02	2.636	0.692	1.536	0.074	0.072	0.076	0.074
7/15/2006 16:30	21.00	2.710	0.766	1.594	0.103	0.101	0.099	0.101
7/20/2006 16:30	26.00	2.820	0.876	1.716	0.146	0.144	0.147	0.146
7/24/2006 16:30	30.00	2.906	0.920	1.792	0.180	0.161	0.177	0.173
7/29/2006 16:30	35.00	3.006	1.056	1.886	0.220	0.215	0.214	0.216
8/4/2006 16:00	40.98	3.126	1.196	2.020	0.267	0.270	0.267	0.268
8/7/2006 16:30	44.00	3.202	1.270	2.090	0.297	0.299	0.294	0.297
8/12/2006 16:30	49.00	3.318	1.396	2.214	0.343	0.349	0.343	0.345
8/22/2006 16:30	59.00	3.552	1.642	2.442	0.435	0.446	0.433	0.438

Cement: Herndon

Fly Ash: Rockport

Content%: 60

Date and Time Cast: 6/23/2006 18:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/25/2006 16:30	0	1.616	0.134	-0.396	0	0	0	0
6/28/2006 16:00	2.98	1.628	0.152	-0.386	0.005	0.007	0.004	0.005
7/1/2006 18:00	6.06	1.638	0.164	-0.366	0.009	0.012	0.012	0.011
7/4/2006 23:00	9.27	1.652	0.174	-0.352	0.014	0.016	0.017	0.016
7/7/2006 18:00	12.06	1.656	0.182	-0.350	0.016	0.019	0.018	0.018
7/10/2006 17:00	15.02	1.666	0.192	-0.344	0.020	0.023	0.020	0.021
7/15/2006 16:30	20.00	1.676	0.204	-0.330	0.024	0.028	0.026	0.026
7/22/2006 16:30	27.00	1.690	0.232	-0.308	0.029	0.039	0.035	0.034
7/25/2006 16:30	30.00	1.706	0.240	-0.298	0.035	0.042	0.039	0.039
7/29/2006 16:30	34.00	1.726	0.248	-0.280	0.043	0.045	0.046	0.045
8/4/2006 16:00	39.98	1.764	0.280	-0.256	0.058	0.057	0.055	0.057
8/7/2006 16:30	43.00	1.790	0.308	-0.238	0.069	0.069	0.062	0.066
8/12/2006 16:30	48.00	1.816	0.342	-0.198	0.079	0.082	0.078	0.080
8/17/2006 16:30	53.00	1.862	0.378	-0.158	0.097	0.096	0.094	0.096
8/22/2006 16:30	58.00	1.902	0.426	-0.124	0.113	0.115	0.107	0.112

Cement: Herndon

Fly Ash: Rockport

Content%: 80

Date and Time Cast: 6/24/2006 22:20

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/26/2006 16:30	0	2.010	0.466	1.416	0	0	0	0
6/28/2006 16:00	1.98	2.014	0.482	1.430	0.002	0.006	0.006	0.004
7/1/2006 18:00	5.06	2.016	0.480	1.424	0.002	0.006	0.003	0.004
7/4/2006 23:00	8.27	2.012	0.480	1.424	0.001	0.006	0.003	0.003
7/7/2006 18:00	11.06	2.012	0.470	1.416	0.001	0.002	0.000	0.001
7/10/2006 17:00	14.02	2.018	0.482	1.424	0.003	0.006	0.003	0.004
7/20/2006 16:30	24.00	2.010	0.474	1.408	0.000	0.003	-0.003	0.000
7/25/2006 16:30	29.00	2.012	0.474	1.408	0.001	0.003	-0.003	0.000
7/29/2006 16:30	33.00	2.010	0.474	1.408	0.000	0.003	-0.003	0.000
8/4/2006 16:00	38.98	2.024	0.484	1.432	0.006	0.007	0.006	0.006
8/7/2006 16:30	42.00	2.028	0.490	1.432	0.007	0.009	0.006	0.008
8/12/2006 16:30	47.00	2.028	0.484	1.432	0.007	0.007	0.006	0.007
8/17/2006 16:30	52.00	2.034	0.488	1.434	0.009	0.009	0.007	0.008
8/22/2006 16:30	57.00	2.038	0.494	1.442	0.011	0.011	0.010	0.011

Cement: St. Constant SF

Fly Ash: Sundance

Content%: 0

Date and Time Cast: 6/23/2006 21:30

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
6/25/2006 16:30	0	1.038	0.706	0.886	0	0	0	0
6/28/2006 16:00	2.98	1.104	0.768	0.946	0.026	0.024	0.024	0.025
7/1/2006 18:00	5.06	1.158	0.826	0.994	0.047	0.047	0.043	0.046
7/4/2006 19:00	8.10	1.210	0.858	1.038	0.068	0.060	0.060	0.062
7/7/2006 18:00	11.06	1.282	0.940	1.114	0.096	0.092	0.090	0.093
7/10/2006 17:00	14.02	1.358	1.016	1.188	0.126	0.122	0.119	0.122
7/22/2006 16:30	26.00	1.734	1.402	1.570	0.274	0.274	0.269	0.272
7/29/2006 16:30	33.00	2.004	1.670	1.846	0.380	0.380	0.378	0.379
8/4/2006 16:00	38.98	2.288	1.950	2.140	0.492	0.490	0.494	0.492
8/7/2006 16:30	42.00	2.432	2.092	2.288	0.549	0.546	0.552	0.549
8/12/2006 16:30	47.00	2.688	2.352	2.556	0.650	0.648	0.657	0.652
8/21/2006 16:30	56.00	3.198	2.866	3.088	0.850	0.850	0.867	0.856
9/5/2006 16:30	71.00	3.786	3.468	3.698	1.082	1.087	1.107	1.092
9/25/2006 16:30	91.00	4.502	4.162	4.400	1.364	1.361	1.383	1.369

Cement: St. Constant SF

Fly Ash: Sundance

Content%: 20

Date and Time Cast: 9/26/2006 21:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
9/28/2006 16:30	0	0.220	2.378	-0.828	0	0	0	0
9/30/2006 16:30	2.00	0.232	2.388	-0.818	0.005	0.004	0.004	0.004
10/2/2006 16:00	3.98	0.232	2.392	-0.816	0.005	0.006	0.005	0.005
10/4/2006 16:30	6.00	0.238	2.398	-0.810	0.007	0.008	0.007	0.007
10/6/2006 16:00	7.98	0.248	2.404	-0.800	0.011	0.010	0.011	0.011
10/9/2006 17:00	11.02	0.254	2.414	-0.780	0.013	0.014	0.019	0.015
10/12/2006 16:30	14.00	0.264	2.424	-0.776	0.017	0.018	0.020	0.019
10/15/2006 16:30	17.00	0.278	2.438	-0.770	0.023	0.024	0.023	0.023
10/18/2006 17:00	20.02	0.288	2.454	-0.756	0.027	0.030	0.028	0.028
10/23/2006 16:00	24.98	0.306	2.472	-0.728	0.034	0.037	0.039	0.037
10/28/2006 16:00	29.98	0.314	2.472	-0.712	0.037	0.037	0.046	0.040
11/2/2006 17:00	35.02	0.396	2.582	-0.640	0.069	0.080	0.074	0.075
11/7/2006 17:00	40.02	0.466	2.646	-0.574	0.097	0.106	0.100	0.101
11/13/2006 17:30	46.04							
11/16/2006 16:30	49.00							
11/21/2006 18:00	54.06							
11/26/2006 18:00	59.06							

Cement: St. Constant SF

Fly Ash: Sundance

Content%: 40

Date and Time Cast: 9/26/2006 22:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
9/28/2006 16:30	0	2.154	0.218	0.754	0	0	0	0
9/30/2006 16:30	2.00	2.168	0.222	0.758	0.006	0.002	0.002	0.003
10/2/2006 16:00	3.98	2.168	0.222	0.758	0.006	0.002	0.002	0.003
10/4/2006 16:30	6.00	2.162	0.222	0.758	0.003	0.002	0.002	0.002
10/6/2006 16:00	7.98	2.160	0.222	0.756	0.002	0.002	0.001	0.002
10/9/2006 17:00	11.02	2.172	0.226	0.760	0.007	0.003	0.002	0.004
10/12/2006 16:30	14.00	2.172	0.230	0.766	0.007	0.005	0.005	0.006
10/15/2006 16:30	17.00	2.176	0.234	0.770	0.009	0.006	0.006	0.007
10/18/2006 17:00	20.02	2.184	0.238	0.768	0.012	0.008	0.006	0.008
10/23/2006 16:00	24.98	2.198	0.248	0.770	0.017	0.012	0.006	0.012
10/28/2006 16:00	29.98	2.214	0.268	0.816	0.024	0.020	0.024	0.023
11/2/2006 17:00	35.02	2.236	0.284	0.816	0.032	0.026	0.024	0.028
11/7/2006 17:00	40.02	2.254	0.306	0.838	0.039	0.035	0.033	0.036

Cement: St. Constant SF

Fly Ash: Sundance

Content%: 60

Date and Time Cast: 9/26/2006 23:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
9/28/2006 16:30	0	0.750	1.356		0	0	0	0
9/30/2006 16:30	2.00	0.760	1.358		0.004	0.001		0.002
10/2/2006 16:00	3.98	0.758	1.360		0.003	0.002		0.002
10/4/2006 16:30	6.00	0.760	1.362		0.004	0.002		0.003
10/6/2006 16:00	7.98	0.760	1.362		0.004	0.002		0.003
10/9/2006 17:00	11.02	0.764	1.362		0.006	0.002		0.004
10/12/2006 16:30	14.00	0.762	1.364		0.005	0.003		0.004
10/15/2006 16:30	17.00	0.766	1.368		0.006	0.005		0.006
10/18/2006 17:00	20.02	0.770	1.372		0.008	0.006		0.007
10/23/2006 16:00	24.98	0.772	1.376		0.009	0.008		0.008
10/28/2006 16:00	29.98	0.788	1.384		0.015	0.011		0.013
11/2/2006 17:00	35.02	0.788	1.390		0.015	0.013		0.014
11/7/2006 17:00	40.02	0.794	1.402		0.017	0.018		0.018

Cement: St. Constant SF

Fly Ash: Sundance

Content%: 80

Date and Time Cast: 9/27/2006 20:00

Date and time	Elapsed days	Comparator Readings			Expansion (%			Average
		1	2	3	1	2	3	
9/29/2006 16:30	0	1.076	0.880	1.860	0	0	0	0
10/1/2006 16:30	2.00	1.062	0.872	1.852	-0.006	-0.003	-0.003	-0.004
10/3/2006 17:00	4.02	1.070	0.874	1.854	-0.002	-0.002	-0.002	-0.002
10/5/2006 16:30	6.00	1.072	0.874	1.856	-0.002	-0.002	-0.002	-0.002
10/7/2006 16:30	8.00	1.064	0.872	1.854	-0.005	-0.003	-0.002	-0.003
10/10/2006 16:00	10.98	1.066	0.872	1.854	-0.004	-0.003	-0.002	-0.003
10/13/2006 16:30	14.00	1.062	0.872	1.854	-0.006	-0.003	-0.002	-0.004
10/16/2006 16:30	17.00	1.066	0.872	1.852	-0.004	-0.003	-0.003	-0.003
10/19/2006 17:00	20.02	1.066	0.876	1.856	-0.004	-0.002	-0.002	-0.002
10/24/2006 16:30	25.00	1.072	0.878	1.862	-0.002	-0.001	0.001	-0.001
10/29/2006 16:30	30.00	1.078	0.884	1.866	0.001	0.002	0.002	0.002
11/3/2006 16:30	35.00	1.082	0.886	1.870	0.002	0.002	0.004	0.003
11/8/2006 17:30	40.04	1.084	0.892	1.872	0.003	0.005	0.005	0.004

Cement: St. Constant SF
Fly Ash: Rockport Content%: 20

Date and Time Cast: 9/27/2006 23:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
9/29/2006 16:30	0	-0.038	1.602	0.060	0	0	0	0
10/1/2006 16:30	2.00	-0.012	1.628	0.074	0.010	0.010	0.006	0.009
10/3/2006 17:00	4.02	-0.006	1.632	0.080	0.013	0.012	0.008	0.011
10/5/2006 16:30	6.00	0.000	1.636	0.088	0.015	0.013	0.011	0.013
10/7/2006 16:30	8.00	0.008	1.640	0.094	0.018	0.015	0.013	0.015
10/10/2006 16:00	10.98	0.014	1.650	0.098	0.020	0.019	0.015	0.018
10/13/2006 16:30	14.00	0.026	1.660	0.110	0.025	0.023	0.020	0.023
10/16/2006 16:30	17.00	0.040	1.674	0.120	0.031	0.028	0.024	0.028
10/19/2006 17:00	20.02	0.066	1.690	0.146	0.041	0.035	0.034	0.036
10/24/2006 16:30	25.00	0.106	1.744	0.186	0.057	0.056	0.050	0.054
10/29/2006 16:30	30.00	0.172	1.796	0.248	0.083	0.076	0.074	0.078
11/3/2006 16:30	35.00	0.260	1.868	0.326	0.117	0.105	0.105	0.109
11/8/2006 17:30	40.04	0.354	1.972	0.426	0.154	0.146	0.144	0.148

Cement: St. Constant SF
Fly Ash: Rockport Content%: 40

Date and Time Cast: 9/30/2006 20:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
10/2/2006 16:30	0	1.224	0.522	0.088	0	0	0	0
10/4/2006 16:30	2.00	1.226	0.524	0.088	0.001	0.001	0.000	0.001
10/6/2006 17:00	4.02	1.230	0.524	0.092	0.002	0.001	0.002	0.002
10/8/2006 16:30	6.00	1.238	0.528	0.096	0.006	0.002	0.003	0.004
10/10/2006 16:30	8.00	1.238	0.528	0.096	0.006	0.002	0.003	0.004
10/13/2006 16:00	10.98	1.244	0.534	0.098	0.008	0.005	0.004	0.006
10/16/2006 16:30	14.00	1.244	0.544	0.104	0.008	0.009	0.006	0.008
10/19/2006 16:30	17.00	1.256	0.548	0.114	0.013	0.010	0.010	0.011
10/22/2006 17:00	20.02	1.262	0.564	0.128	0.015	0.017	0.016	0.016
10/27/2006 16:30	25.00	1.276	0.580	0.148	0.020	0.023	0.024	0.022
11/1/2006 16:30	30.00	1.304	0.602	0.162	0.031	0.031	0.029	0.031

Cement: St. Constant SF

Fly Ash: Rockport

Content%: 60

Date and Time Cast: 9/30/2006 21:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
10/2/2006 16:30	0	1.270	0.600	2.148	0	0	0	0
10/4/2006 16:30	2.00	1.270	0.598	2.148	0.000	-0.001	0.000	0.000
10/6/2006 17:00	4.02	1.268	0.592	2.148	-0.001	-0.003	0.000	-0.001
10/8/2006 16:30	6.00	1.268	0.590	2.150	-0.001	-0.004	0.001	-0.001
10/10/2006 16:30	8.00	1.272	0.598	2.152	0.001	-0.001	0.002	0.001
10/13/2006 16:00	10.98	1.276	0.604	2.158	0.002	0.002	0.004	0.003
10/16/2006 16:30	14.00	1.282	0.608	2.164	0.005	0.003	0.006	0.005
10/19/2006 16:30	17.00	1.288	0.612	2.168	0.007	0.005	0.008	0.007
10/22/2006 17:00	20.02	1.294	0.618	2.176	0.009	0.007	0.011	0.009
10/27/2006 16:30	25.00	1.308	0.618	2.188	0.015	0.007	0.016	0.013
11/1/2006 16:30	30.00	1.312	0.632	2.190	0.017	0.013	0.017	0.015

Cement: St. Constant SF
Fly Ash: Rockport Content%: 80
Date and Time Cast: 9/28/2006 21:00

Date and time	Elapsed days	Comparator Readings			Expansion (%)			Average
		1	2	3	1	2	3	
10/1/2006 16:30	0	1.526	0.740		0	0		0
10/3/2006 17:00	2.02	1.526	0.746		0.000	0.002		0.001
10/5/2006 16:30	4.00	1.516	0.736		-0.004	-0.002		-0.003
10/7/2006 16:30	6.00	1.516	0.732		-0.004	-0.003		-0.004
10/9/2006 16:00	7.98	1.516	0.734		-0.004	-0.002		-0.003
10/12/2006 16:30	11.00	1.514	0.734		-0.005	-0.002		-0.004
10/15/2006 16:30	14.00	1.518	0.736		-0.003	-0.002		-0.002
10/18/2006 17:00	17.02	1.522	0.740		-0.002	0.000		-0.001
10/21/2006 16:30	20.00	1.524	0.744		-0.001	0.002		0.000
10/26/2006 16:30	25.00	1.528	0.748		0.001	0.003		0.002
10/31/2006 16:30	30.00	1.530	0.748		0.002	0.003		0.002
11/4/2006 17:30	34.04	1.540	0.768		0.006	0.011		0.008